# **Applied Thermodynamics: Software Solutions**

Part-IV Dr. M. Thirumaleshwar



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# Applied Thermodynamics: Software Solutions

Part-IV (Psychrometrics, Reactive systems)

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### Contents

1 1.1 1.2 1.3 1.4 1.5 1.6

| Dedication  | Part I |
|---|--------|
| Preface   | Part I |
| About the Author  | Part I |
| About the Software used                                 | Part I |
| To the Student  | Part I |
| How to use this Book?                                   | Part I |
| Gas Power Cycles  | Part I |
| Definitions, Statements and Formulas used[1-6]:         | Part I |
| Problems on Otto cycle (or, constant volume cycle):     | Part I |
| Problems on Diesel cycle (or, constant pressure cycle): | Part I |
| Problems on Dual cycle (or, limited pressure cycle):    | Part I |
| Problems on Stirling cycle:                             | Part I |
| References:   | Part I |



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| 2     | Cycles for Gas Turbines and Jet propulsion                   | Part II  |
|-------|--|----------|
| 2.1   | Definitions, Statements and Formulas used[1-7]:              | Part II  |
| 2.2   | Problems solved with Mathcad:                                | Part II  |
| 2.3   | Problems solved with EES:                                    | Part II  |
| 2.4   | Problems solved with TEST:                                   | Part II  |
| 2.5   | References:  | Part II  |
| 3     | Vapour Power Cycles  | Part II  |
| 3.1   | Definitions, Statements and Formulas used[1-7]:              | Part II  |
| 3.2   | Problems solved with Mathcad:                                | Part II  |
| 3.4   | Problems solved with TEST:                                   | Part II  |
| 3.5   | References:  | Part II  |
| 4     | Refrigeration Cycles   | Part III |
| 4.1   | Definitions, Statements and Formulas used[1-7]:              | Part III |
| 4.1.1 | Ideal vapour compression refrigeration cycle:                | Part III |
| 4.2   | Problems solved with Mathcad:                                | Part III |
| 4.3   | Problems solved with DUPREX (free software from DUPONT) [8]: | Part III |
| 4.4   | Problems solved with EES:                                    | Part III |

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| 4.5 | Problems solved with TEST:                        | Part III |
|-----|---|----------|
| 4.6 | References:                                       | Part III |
| 5   | Air compressors                                   | Part III |
| 5.1 | Definitions, Statements and Formulas used[1-6]:   | Part III |
| 5.2 | Problems solved with Mathcad:                     | Part III |
| 5.3 | Problems solved with EES:                         | Part III |
| 5.4 | References:                                       | Part III |
| 6   | Thermodynamic relations                           | Part III |
| 6.1 | Summary of Thermodynamic relations [1-6]:         | Part III |
| 6.5 | References:                                       | Part III |
| 7   | Psychrometrics                                    | 8        |
| 7.1 | Definitions, Statements and Formulas used [1-11]: | 8        |
| 7.2 | Problems solved with Mathcad:                     | 31       |
| 7.3 | Problems solved with Psychrometric chart:         | 62       |
| 7.4 | Problems solved with EES:                         | 73       |
| 7.5 | Problems solved with TEST:                        | 96       |
| 7.6 | References:                                       | 141      |

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#### Contents

| 8   | Reactive Systems                                  | 143    |
|-----|---|--------|
| 8.1 | Definitions, Statements and Formulas used [1-11]: | 143    |
| 8.2 | Problems solved with Mathcad:                     | 166    |
| 8.3 | Problems solved with EES:                         | 198    |
| 8.4 | Problems solved with TEST:                        | 228    |
| 8.5 | References:                                       | 288    |
| 9   | Compressible fluid flow                           | Part V |
| 9.1 | Definitions, Statements and Formulas used         | Part V |
| 9.2 | Problems solved with Mathcad, EES and TEST        | Part V |
| 9.3 | References  | Part V |



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# 7 Psychrometrics

#### Learning objectives:

- 1. In this chapter, **'Psychrometrics'** i.e. is the study of properties of air-water vapor mixtures is dealt with.
- 2. We give the definitions of various terms and also the thermodynamic equations to determine various psychrometric properties.
- 3. Psychrometric chart, which is very useful to analyse psychrometric processes, is presented.
- 4. Various psychrometric processes adopted in air-conditioning are explained with the help of Psychrometric chart.
- 5. **Two very good stand-alone calculators** to quickly calculate various Psychrometric properties are explained.
- 6. Usefulness of Psychrometric chart is demonstrated by solving many problems.
- 7. Several very useful Functions are written in Mathcad to calculate various psychrometric properties. A summary of various Mathcad Functions written is also provided.
- 8. Also, many problems are solved in Mathcad, EES and TEST to illustrate the problem solving techniques in this chapter.

\_\_\_\_\_

#### 7.1 Definitions, Statements and Formulas used [1-11]:

#### 7.1.1 'Psychrometrics'

'Psychrometrics' is the study of properties of air-water vapor mixtures. We also study various processes involving the air-water vapor mixtures and the important applications are in the fields of comfort air conditioning , paper and textile engineering processes etc.

#### 7.1.2 Properties of atmospheric air:

Atmospheric air is considered as a mixture of air and water vapor. Further, both air and water vapor are considered as ideal gases (without much error, i.e. less than 0.2%).

Therefore:

#### **Atmospheric pressure:** $p = p_a + p_w$ , where

 $p_a = partial pressure of air, and$ 

 $p_w$  = partial pressure of water vapor.

**Enthalpy of dry air:**  $h_{air} = cp.T = 1.005 * T, kJ/kg$ 

$$\Delta h_{air} = cp. \Delta T = 1.005 * \Delta T, kJ/kg$$

#### Enthalpy of water vapor:

Enthalpy of water vapor at 0 C is 2500.9 kJ/kg.

Average value of cp in the temp range -10 C to 50 C is 1.82 kJ/kg.C.

Therefore, enthalpy of water vapor at temp T is determined as:

 $h_{g}(T) = 2500.9 + 1.82 * T, kJ/kg,... T in deg.C$ 

Total enthalpy of moist air:

h(T) = 1.005 \* T + w \* (2500.9 + 1.82 \* T), kJ/kg

**Sat. pressure of water vapor (psat):** is related to the 'dry bulb temp' (i.e. the ordinary temp measured with a thermometer in atmospheric air. Sat. pressure of water with temp can be read from the Steam Tables [Ref: www.thermofluids.net – TEST Software]

| deg-C | kPa     |
|-------|---------|
| Tomp  | Sat.    |
| remp. | press.  |
| 7 °C  | p_sat@T |
| 0.01  | 0.6113  |
| 5     | 0.8721  |
| 10    | 1.2276  |
| 15    | 1.7051  |
| 20    | 2.339   |
| 25    | 3.169   |
| 30    | 4.246   |
| 35    | 5.628   |
| 40    | 7.384   |
| 45    | 9.593   |
| 50    | 12.349  |
| 55    | 15.758  |
| 60    | 19.940  |
| 65    | 25.03   |
| 70    | 31.19   |

#### Following is the mathematical relation for the vapor pressure(Pa) of water with temp (deg.C) [11]:

$$psat = exp \left[ \frac{-5.8002206 \cdot 10^{3}}{T + 273.15} + 1.3914993 - 48.640239 \cdot 10^{-3} \cdot (T + 273.15) \dots + 41.764768 \cdot 10^{-6} \cdot (T + 273.15)^{2} - 14.452093 \cdot 10^{-9} \cdot (T + 273.15)^{3} + 6.5459673 \cdot \ln(T + 273.15) \right]$$

At T = 20 C, we get: psat = 2339 Pa, which matches very well with the above Table.

#### Specific humidity or humidity ratio (w): is defined as:

$$w = \frac{m_{w}}{m_{a}} \qquad kg \text{ water vap/kg dry air}$$
  
i.e. 
$$w = \frac{\frac{p_{w} \cdot V}{R_{w} \cdot T}}{\frac{p_{a} \cdot V}{R_{a} \cdot T}} \qquad \dots \text{ using Ideal Gas relation}$$
  
i.e. 
$$w = 0.62198 \cdot \frac{p_{w}}{p_{a}}$$

i.e. 
$$w = 0.62198 \cdot \frac{p_W}{p - p_W}$$
 kg water vap/kg dry air

where p is the total pressure = atmospheric pressure = 101325 Pa

Relative humidity (RH or  $\varphi$ ): It is the ratio of amount of water vapor present in air to the max. amount of water vapor that it can hold at that temperature.

$$\phi = \frac{m_{w}}{m_{g}} = \frac{\frac{p_{w} \cdot V}{R_{w} \cdot T}}{\frac{p_{g} \cdot V}{R_{w} \cdot T}} = \frac{p_{w}}{p_{g}} \qquad \text{where } p_{g} = \text{psat at } T$$

Also:

Also: 
$$\phi = \frac{\mathbf{w} \cdot \mathbf{p}}{(0.62198 + \mathbf{w}) \cdot \mathbf{p}_g}$$
  
and  $\mathbf{w} = \frac{0.62198 \cdot \phi \cdot \mathbf{p}_g}{\mathbf{p} - \phi \cdot \mathbf{p}_g}$ 

**Degree of saturation** ( $\mu$ ): It is the ratio of actual specific humidity and the saturated specific humidity, both at the same temp T.

$$\mu = \frac{w}{w_{s}} = \frac{\frac{0.622 \cdot \frac{p_{w}}{p - p_{w}}}{0.622 \cdot \frac{p_{s}}{p - p_{s}}}$$

i.e. 
$$\mu = \frac{p_{\rm W}}{p_{\rm S}} \cdot \frac{p - p_{\rm S}}{p - p_{\rm W}}$$

Also:

$$\mu = \frac{\phi}{1 + \frac{(1 - \phi) \cdot w_s}{0.62198}}$$

For dry air, i.e. when  $\varphi = 0$ , we have:  $\mu = 0$ , and

For sat. air, i.e. when  $\varphi = 100\%$ , we have:  $\mu = 1$ , i.e  $\varphi$  varies between 0 and 1.

**Dew-point temperature (dpt):** It is defined as the temp at which condensation begins when air is cooled at constant pressure.

i.e. dpt is the sat. temp of water corresponding to the vapor pressure.

i.e.  $dpt = T_{sat} at p_w$ 



## Dew point temp (deg.C), between 0 and 70 C, as a function of partial pressure of water vapor in air (pw), is given by following eqn:

Remember that  $p_w$  is related to dry bulb temp and RH. So, dew point temp (dpt) can be written in terms of dry bulb temp (dbt) and RH.

Dry bulb temperature (dbt): It is the temp measured with an ordinary thermometer placed in air.

Wet bulb temperature (wbt): It is the temp measured by a thermometer when its bulb is enveloped with a cotton wick saturated with water and held in a flowing stream of air.

A 'Psychrometer' measures both the dry bulb temp and wet bulb temps.

At any dbt, greater the difference between the dbt and wbt, smaller is the amount of water vapor held in the mixture.

#### Adiabatic saturation temperature[Ref:1]:



When unsaturated air flows over a sheet of water in a long, insulated chamber, water evaporates and the specific humidity of air increases, and both air and water get cooled. If the chamber is long enough, the air comes out saturated. Its equilibrium temp is known as "adiabatic sat. temp." This temp is generally between the dry bulb temp and the dew point temp.

Generally, wet bulb temp is equal to the adiabatic saturation temp. for air-water mixtures at atmospheric pressure.

Making a mass balance and an energy balance and simplifying, we get:

$$\mathbf{w}_1 = \frac{\mathbf{cp} \cdot \left(\mathbf{T}_2 - \mathbf{T}_1\right) + \mathbf{w}_2 \cdot \mathbf{h}_{fg2}}{\mathbf{h}_{g1} - \mathbf{h}_{f2}} \qquad \dots \text{kg H2O/kg dry air}$$

and.

 $w_2 = \frac{0.622 \cdot p_{g2}}{P_2 - p_{g2}}$  ...kg H2O/kg dry air



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In the above,  $h_g$  is the enthalpy of water vapor,  $h_f$  is the enthalpy of liquid water, 1 and 2 refer to inlet and exit of the chamber.  $p_{g2}$  is the sat. pressure of water at T2. While doing calculations, we can substitute wet bulb temp (wbt) for T2, in the above equations.

#### Relative humidity from DBT and WBT:

Method 1: Following simple formula may be used for computer calculations:

 $phi(DBT, WBT) := \frac{[psatt(WBT) - (DBT - WBT) \cdot 63]}{psatt(DBT)}$ 

Ex: phi(20, 15.7) = 0.647 = 64.7%

When the wet thermometer is frozen, the constant in above eqn. changes to 56

Method 2: Using Carrier's Formula to get partial pressure of water:

$$pw = (pw_s)_{wbt} - \frac{\left[P - (pw_s)_{wbt}\right] \cdot (dbt - wbt)}{1527.4 - 1.3 \cdot wbt}$$
 Pa

In the above formula, pressures are in Pa, temps in deg.C

i.e. 
$$pw(dbt,wbt,P) := \left[ psatt(wbt) - \frac{(P - psatt(wbt)) \cdot (dbt - wbt)}{1527.4 - 1.3 \cdot wbt} \right] \dots Pa$$

Ex: 
$$pw(35, 25, 101325) = 2.513 \times 10^3$$
 ... Pa

 $RH = \frac{pw}{pw_s}$ 

And,

Therefore:  $RH(dbt, wbt, P) := \frac{pw(dbt, wbt, P)}{psatt(dbt)}$ 

Ex: RH(20,15,101325) = 0.588 = 58.8%

|   |    |    | Relativ | ve Humidity - R | ?H (%)  |    |    |    |
|---|----|----|---------|-----------------|---|----|----|----|
| Difference<br>Between Dry<br>Bulb<br>and Wet Bulb |    |    | Di      | ry Bulb Tempe   | rature - <i>T<sub>db</sub></i> ( <sup>o</sup> | C) |    |    |
| Temperatures<br>$T_{db} - T_{wb}$<br>(°C)         | 15 | 18 | 20      | 22              | 25  | 27 | 30 | 33 |
| 1   | 90 | 91 | 91      | 92              | 92  | 92 | 93 | 93 |
| 2   | 80 | 82 | 83      | 84              | 85  | 85 | 86 | 87 |
| 3   | 71 | 73 | 75      | 76              | 77  | 78 | 79 | 80 |
| 4   | 62 | 65 | 67      | 68              | 70  | 71 | 73 | 74 |
| 5   | 53 | 57 | 59      | 61              | 64  | 65 | 67 | 69 |
| 6   | 44 | 49 | 52      | 54              | 57  | 59 | 61 | 63 |
| 7   | 36 | 42 | 45      | 47              | 51  | 53 | 55 | 58 |
| 8   | 28 | 34 | 38      | 41              | 45  | 47 | 50 | 53 |
| 9   | 21 | 27 | 31      | 34              | 39  | 41 | 45 | 48 |
| 10  | 13 | 20 | 25      | 28              | 33  | 36 | 40 | 43 |

#### Method 3: Following Table from Engineering Toolbox may be used [Ref: 13]

**For example:** For a DBT = 20 C, WBT = 15 C, difference is = DBT – WBT = 5 C, and from the above table, under the column for DBT = 20 C, we get: RH = 59%

#### Method 4: Use stand-alone Psychrometric calculators ... This is explained later in section 7.1.5

Sp. volume of moist air (m3/kg) is given by:

$$v = \frac{\left(\frac{1}{P}\right) \cdot 287.055 \cdot (dbt + 273.15) \cdot (1 + 1.6078 \cdot w)}{1 + w} \qquad m^{3/kg} \text{ of moist air}$$

where P is the total pressure = atmospheric pressure = 101325 Pa.

#### 7.1.3 Psychrometric chart:

This is a plot with DBT on x-axis and sp. humidity (w) as the ordinate. Volume of mixture ( $m^3 / kg$  dry air), WBT, RH and enthalpy of mixture appear as parameters. Chart is generally plotted for 760 mm Hg (or 1 atm. or 101325 Pa).

#### Following schematic from Ref. 1 shows various lines:



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#### In the Psychrometric chart, for sat. air, DBT, WBT and DPT coincide as shown below:



And, Constant enthalpy line and WBT lines almost coincide in the Psychrometric chart:







**Psychrometrics** 

#### An actual Psychrometric chart given by ASHRAE is shown below:

In the following chart, note that humidity ratio is given on the ordinate as: (grams of moisture per kg of dry air)





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#### And, different zones of temp and humidity are shown in the following fig.:

**Comfort zone** for humans is generally in the following range:

DBT: between 22 C and 27 C

RH: between 40% and 60%



7.1.4 Air-conditioning processes:

Important air-conditioning processes are summarized in following figure:[1]



Generally, **heating and humidifying** is done in winter and **cooling and dehumidifying** is required in summer air conditioning.

a) Sensible heating [5]:



Here, air enters at T1, gets heated to T2, while the heater coils temp is T3. Sp. humidity, w remains constant.

Heat transferred,  $Q = m_a * (h2 - h1)$ , kJ/s

Bypass Factor (BF) is defined as:

$$BF = \frac{DBT_3 - DBT_2}{DBT_3 - DBT_1} = \text{length (2-3) / length (1-3)}$$

Bypass Factor is a function of coil design and air velocity.

Bypass Factor can be considered as the fraction of air which does not come in contact with coil surface.

#### b) Sensible cooling:



Here, air enters at T1, gets cooled to T2, while the cooling coils temp is T3. Sp. humidity, w remains constant.

Heat transferred,  $Q = m_a * (h1 - h2)$ , kJ/s



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#### Bypass Factor (BF) is defined as:

$$BF = \frac{DBT_2 - DBT_3}{DBT_1 - DBT_3} = \text{length (2-3) / length (1-3)} \dots \text{for cooling}$$

#### c) Heating and humidifying:[12]

Here, first, the air is heated from 1 to 2, and then humidified by spraying water. Process is shown on the Psychrometric chart below:



For the above case, we have:

Dry air mass balance:  $m_{a1} = m_{a2} = m_a$ Water mass balance:  $m_{a1} \cdot w_1 = m_{a2} \cdot w_2$  i.e.  $w_1 = w_2$ Energy balance:  $Q_{in} + m_a \cdot h_1 = m_a \cdot h_2$  i.e.  $Q_{in} = m_a \cdot (h_2 - h_1)$ 

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#### d) Cooling and dehumidifying:[12]



Water mass balance:  $m_{a1} \cdot w_1 = m_{a2} \cdot w_2 + m_w$  i.e.  $m_w = m_a \cdot (w_1 - w_2)$ 

Energy balance:  $Q_{out} = m_a \cdot (h_1 - h_2) - m_w \cdot h_w$ 

#### e) Adiabatic Steaming:[12]



Note that in the above case, there is heating and humidification.

f) Evaporative cooling:[12]

#### Evaporative coolers or swamp coolers are used in hot and dry (i.e. desert) climates.

Here, the principle used is: as water evaporates, the latent heat of vaporization is absorbed from the water body and the surrounding air. As a result, both the water and the air are cooled.

The schematic diagram of the apparatus and the process on the Psychrometric chart are shown below.



Note that evaporative cooling process follows a constant wet bulb temp line on the Psychrometric chart.

For the above process (1-2), we can write:

WBT = constant, and, h = constant.

#### g) Adiabatic mixing of air streams [1]:

Schematic diagram and the process on the Psychrometric chart are shown below:



#### For the above case:

Dry air mass balance:  $m_{a1} + m_{a2} = m_{a3}$ 

Water mass balance:  $m_{a1} \cdot w_1 + m_{a2} \cdot w_2 = m_{a3} \cdot w_3$ 

Energy balance:  $m_{a1} \cdot h_1 + m_{a2} \cdot h_2 = m_{a3} \cdot h_3$ 

Then, we get:

$$\frac{m_{a1}}{m_{a2}} = \frac{w_2 - w_3}{w_3 - w_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

**Note:** When two air streams at two different states 1 and 2 are mixed adiabatically, the state of the mixture (i.e. state 3) lies on the straight line connecting states 1 and 2 on the Psychrometric chart, and the ratio of the distances 2-3 and 3-1 is equal to the ratio of mass flow rates  $m_{a1}$  and  $m_{a2}$ .

**Psychrometrics** 

#### h) Wet cooling towers [1]:

Here, warm water is sprayed from top of the tower and air is forced to flow from bottom of tower to the top. A small fraction of water evaporates and cools the remaining water. Temp and moisture content of air increase as air travels to the top of tower. Make up water must be added to the cycle to replace water lost by evaporation.



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**Psychrometrics** 

For the above, we have:

Dry air mass balance:  $m_{a1} = m_{a2} = m_a$ 

Water mass balance:  $m_3 + m_{a1} \cdot w_1 = m_{a2} \cdot w_2 + m_4$ 

Energy balance: 
$$m_{a1} \cdot h_1 + m_3 \cdot h_3 = m_{a2} \cdot h_2 + m_4 \cdot h_4$$

Solving for ma:

$$\mathbf{m}_{\mathbf{a}} = \frac{\mathbf{m}_{3} \cdot (\mathbf{h}_{3} - \mathbf{h}_{4})}{(\mathbf{h}_{2} - \mathbf{h}_{1}) - (\mathbf{w}_{2} - \mathbf{w}_{1}) \cdot \mathbf{h}_{4}} \qquad kg/s$$

Volume flow rate of air in to the cooling tower:

$$V_1 = m_a \cdot v_1$$
 where v1 is the sp. vol. of air (m^3/kg dry air) at state 1

Mass flow rate of make up water:

$$m_{makeup} = m_a \cdot (w_2 - w_1)$$
 kg/s

7.1.5 Two free calculators for Psychrometric properties:

Quite a large number of calculators are available for calculation of Psychrometric properties.

Here, we explain two very good stand-alone calculators. i.e. they don't require to be installed in the PC, but will work if the program is put in a folder.

#### 1. PsychroCalc from <u>www.numlog.ca</u>:

Two inputs have to be provided: one is necessarily the dry bulb temp. Other one is any of the following: wet bulb temp, or dew point temp or RH. Total pressure can be atmospheric or any other Altitude. SI or IP Units can be chosen.

As an example, following screen shot shows the properties when DBT = 20 C and WBT = 15 C are input and Calculate button is pressed:

|                             |  |                                      | _                 | ~  | _                  |                    |                                       |       |      |
|-----------------------------|--|--------------------------------------|-------------------|--|--------------------|--------------------|---------------------------------------|-------|------|
| Dry Bulb Temp.:             | 20   |                                      | °C                | (• Wet B   | ulb Temp.:         | .5                 |                                       | °C    |      |
| • Pressure:                 | 101325                                       |                                      | Pa                | C Dew P  | oint Temp.:        |                    |                                       | °C    |      |
| C Altitude:                 | 0  |                                      | m                 | C Rel. H   | umidity:           | 0.0                |                                       | %     |      |
| SI Units                    | C IP Units                                   |                                      |                   | (  | Calculate          | 1                  | Clear                                 |       |      |
| īdb =<br>īwb =              | 20.0<br>15.0                                 | °C<br>°C                             |                   |  |                    |                    |                                       |       | 1    |
| dp =<br>lelHum =<br>IR =    | 11.8<br>58.9<br>8.58<br>0.842                | °C<br>%<br>gH2O/kgAir<br>m3/kg       |                   |  |                    |                    |                                       |       |      |
| 1U =                        | 0.584  | k1/kg                                |                   |  |                    |                    |                                       |       |      |
| /P =<br>) =                 | 1378.1<br>101325.0                           | Pa<br>Pa                             |                   |  |                    |                    |                                       |       |      |
|                             |  |                                      |                   |  |                    |                    |                                       |       |      |
|                             |  |                                      |                   |  |                    |                    |                                       |       | 1000 |
|                             |  |                                      |                   |  |                    |                    |                                       |       | 2    |
| Tdb = 0<br>Twb =<br>Tdp = 0 | dry bulb tem<br>wet bulb ter<br>dew point te | nperature<br>mperature<br>emperature | RelH<br>HR<br>V = | Hum = relative h<br>= humidity ratio<br>specific volume<br>= degree of sat | umidity<br>uration | h =<br>VP :<br>p = | enthalpy<br>= vapour pres<br>pressure | ssure |      |
|                             |  |                                      | MU                | = degree of sat  | uration            |                    |                                       |       |      |

Note that Dew point temp, RH, humidity ratio, sp. volume, degree of saturation (mu), enthalpy, vap. pressure and the atm. pressure (chosen) are given in output.

2. This is browser based calculator from Sugar Engineers' Library. You have to save the page from the Internet web site (<u>http://www.sugartech.com/engrdata/index.php</u>) just once, and thereafter you can use it without being connected to Internet. Here also, DBT is the necessary input, and for the second input, you can use WBT, RH, or DPT. In addition, you can enter Altitude also, if required. SI or IP units can be chosen.

#### Following screen shot shows the results for DBT = 20 C, WBT = 15 C, Altitude = 0 (i.e. sea level):

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#### **Psychrometric Calculations**

The formulations used here to calculate moist air properties are based on perfect gas relations published in 1989 <u>ASHRAE</u> Fundamentals Handbook, which should be accurate. Nevertheless, It is strongly recommend that you to compare the results calculated by this worksheet with a psychrometric chart. There is **no error checking** so you should use reasonable input values.

| Inj                | outs          |      | Outputs              |               |       |  |
|--------------------|---------------|------|----------------------|---------------|-------|--|
| Unit Chosen:       | ⊙ SI          | OIP  |                      |               |       |  |
| Parameter Name     | Value         | Unit | Atmospheric Press    | 1.0132387597! | bar   |  |
| Dry Bulb Temp.:    | 20            | С    | Sat. Vapor Press.    | 23.387977529  | mbar  |  |
| Wet Bulb Temp.: 💿  | 15            | С    | Partial Vapor Press. | 13.784642579  | mbar  |  |
| Relat. Humidity: O | 58.939010704: | %    | Humidity Ratio       | 0.0085787306  | kg/kg |  |
| Dew Point Temp     | 11.772225697; | С    | Enthalpy             | 41.880514658  | kJ/kg |  |
| Altitude           | 0.0           | m    | Specific Volume      | 0.8410950650! | m3/kg |  |
| Cal                | culate        |      |                      |               | C     |  |



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#### 7.2 Problems solved with Mathcad:

Prob.7.2.1 Write Mathcad Functions for Psychrometric properties:

#### Mathcad Solution:

First, let us write Functions for saturation pressure of water as a function of sat. temp and vice versa. Also, we shall write Functions to determine enthalpies of sat. liquid, sat. vapor and latent heat of vaporization for water:

These Functions use the sat. temp table from TEST [Ref:12]

| Ref: TEST |        |         |           |       |          |       |          |  |
|-----------|--------|---------|-----------|-------|----------|-------|----------|--|
| Units:    | deg.C  | ;       | kPa kJ/kg |       |          | kJ/kg |          |  |
|           | (0.01) |         | 0.6113    |       | ( 0.01 ) |       | (2501.4) |  |
|           | 5      |         | 0.8721    |       | 20.98    |       | 2510.6   |  |
|           | 10     |         | 1.2276    |       | 42.01    |       | 2519.8   |  |
|           | 15     |         | 1.7051    |       | 62.99    |       | 2528.9   |  |
|           | 20     |         | 2.339     |       | 83.96    |       | 2538.1   |  |
|           | 25     |         | 3.169     |       | 104.89   |       | 2547.2   |  |
| tsat :=   | 30     | psat := | 4.246     | hf := | 125.79   | hg := | 2556.3   |  |
|           | 35     |         | 5.628     |       | 146.68   |       | 2565.3   |  |
|           | 40     |         | 7.384     |       | 167.57   |       | 2574.3   |  |
|           | 45     |         | 9.593     |       | 188.45   |       | 2583.2   |  |
|           | 50     |         | 12.349    |       | 209.33   |       | 2592.1   |  |
|           | 55     |         | 15.758    |       | 230.23   |       | 2600.9   |  |
|           | 60     |         | ( 19.94 ) |       | 251.13   |       | (2609.6) |  |

#### In the following Functions: P....in Pascals, T ... in deg.C

| $PSATT(T) := linterp(tsat, psat, T) \cdot 1000$              | Ex: | $PSATT(25) = 3.169 \times 10^3 Pa$  |      |
|--|-----|-------------------------------------|------|
| $TSATP(P) := linterp\left(psat, tsat, \frac{P}{1000}\right)$ | Ex: | TSATP(1754) = 15.386 C              |      |
| HFSATT(T) := linterp(tsat, hf, T)                            | Ex: | HFSATT(30) = 125.79 kJ/kg           |      |
| HGSATT(T) := linterp(tsat, hg, T)                            | Ex: | HGSATT(30) = $2.556 \times 10^3$ kJ | /kg  |
| HFGSATT(T) := HGSATT(T) - HFSATT(T)                          | Ex: | HFGSATT(15) = $2.466 \times 10^3$ k | J/kg |

#### **Other Functions:**

Sal. pressure over water: Range: U to 200 C:

#### T in deg.C, pressure in Pa.

1. Sat. pressure:

$$psatt(T) := exp \left[ \begin{array}{c} \frac{-5.8002206 \cdot 10^3}{T + 273.15} + 1.3914993 - 48.640239 \cdot 10^{-3} \cdot (T + 273.15) \dots \\ + 41.764768 \cdot 10^{-6} \cdot (T + 273.15)^2 - 14.452093 \cdot 10^{-9} \cdot (T + 273.15)^3 + 6.5459673 \cdot \ln(T + 273.15) \end{array} \right]$$

Ex: psatt(20) = 2.339 × 10<sup>3</sup> Pa

#### 2. Sat. temp:

p := 2339 Pa T := 30 C....trial value

Given

psatt(T) = p

$$tsatp(p) := Find(T)$$

i.e. tsatp(p) = 20.001 C

Ex: tsatp(7384) = 40.001 C

#### 2. Relative humidity 4:

 $\phi(pw,dbt) := \frac{pw}{psatt(dbt)} \qquad \dots pw \text{ is the prtial pressure of water at dry bulb temp, dbt}$ 

#### 3. Partial pressure of water, pw:

Pw(dbt,RH) := RH·psatt(dbt) Pa

Ex:  $Pw(20, 0.5) = 1.169 \times 10^3$  Pa

**Psychrometrics** 

#### 4. Humidity ratio, w:

$$\mathrm{w}(\mathtt{P},\mathtt{pw}) \coloneqq \frac{0.622 \cdot \mathtt{pw}}{\mathtt{P} - \mathtt{pw}} \qquad \text{kg H2O/kg dry air} \quad \mathtt{P} \text{ is total pressure = atmosph. pr.}$$

 $W(\texttt{dbt},\texttt{RH},\texttt{P}) \coloneqq \frac{0.622 \cdot \texttt{RH} \cdot \texttt{psatt}(\texttt{dbt})}{(\texttt{P} - \texttt{RH} \cdot \texttt{psatt}(\texttt{dbt}))} \qquad \qquad \texttt{kg H2O/kg dry air } \dots \texttt{P} \dots \texttt{in Pa}$ 

Ex:  $W(20, 0.5, 101325) = 7.262 \times 10^{-3}$  kg water/kg dry air

 $ws(P,dbt) := \frac{0.622 \cdot psatt(dbt)}{P - psatt(dbt)} \qquad \dots \text{ at sat. pressure}$ 

i.e. ws(101325,20) = 0.0147 kg/kg dry air

#### 5. Degree of saturation, µ:

$$mu(dbt, RH, P) := \frac{W(dbt, RH, P)}{ws(P, dbt)}$$

Ex: mu(20,0.5,101325) = 0.494



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\* Figures taken from London Business School's Masters in Management 2010 employment report



#### 6. Dew point temp, deg.C: ... between 0 and 70 C:

#### Also:

7. Dew point temp, deg.C: ... between 0 and 70 C: ... in terms of DBT and RH:

```
dewpt(dbt,RH) := dpt(Pw(dbt,RH)) C.
```

Ex: dewpt(20,0.5) = 9.147 C

8. Sp. volume of moist air (given in Psychrometric charts) ... in m3/kg :

$$v(dbt, RH, P) := \frac{\left(\frac{1}{P}\right) \cdot 287.055 \cdot (dbt + 273.15) \cdot (1 + 1.6078 \cdot W(dbt, RH, P))}{1 + W(dbt, RH, P)}$$
m^3/kg of moist air

Ex: v(20,0.5,101325) = 0.834 m^3/kg of moist air

#### 9. Density of moist air :

 $\texttt{rho}(\texttt{dbt},\texttt{RH},\texttt{P}) \coloneqq \frac{1}{v(\texttt{dbt},\texttt{RH},\texttt{P})} \qquad \dots \texttt{density of moist air } \dots \texttt{kg/m^3}$ 

- Ex: rho(20,0.5,101325) = 1.199 kg/m^3
- 10(a). Enthalpy of water vapor: (0 deg.C is the reference. Enthalpy at 0 deg.C = 2500.9 kJ/kg Average sp. heat (cp) of water vapor between -10 and 50 C is 1.82 kJ/kg.C)

$$h_g(T) := 2500.9 + 1.82 \cdot T$$
 kJ/kg  
Ex:  $h_g(25) = 2.5464 \times 10^3$  kJ/kg

- 10(b). Enthalpy of dry air: (0 deg.C is the reference. Average sp. heat (cp) of air between -10 and 50 C is 1.005 kJ/kg.C)
  - h<sub>drvair</sub>(T) := 1.005·T kJ/kg
  - Ex: h<sub>drvair</sub>(25) = 25.125 kJ/kg

#### 11. Enthalpy of moist air :

 $h_{moist}(dbt,RH,P) := 1.005 \cdot dbt + W(dbt,RH,P) \cdot (2500.9 + 1.82 \cdot dbt) kJ/kg$ 

Ex: h<sub>moist</sub>(20,0.5,101325) = 38.527 kJ/kg

12. RH from DBT and WBT .... :

 $phi(DBT, WBT) := \frac{[psatt(WBT) - (DBT - WBT) \cdot 63]}{psatt(DBT)}$ 

Ex: phi(20, 15.7) = 0.647 = 64.7%

Using Dr. Carrier's eqn for partial pressure of water vapor :

$$pw = (pw_s)_{wbt} - \frac{\left[P - (pw_s)_{wbt}\right] \cdot (dbt - wbt)}{1527.4 - 1.3 \cdot wbt}$$
 Pa

In the above formula, pressures are in Pa, temps in deg.C

i.e. 
$$pw(dbt,wbt,P) := \left[ psatt(wbt) - \frac{(P - psatt(wbt)) \cdot (dbt - wbt)}{1527.4 - 1.3 \cdot wbt} \right] \dots Pa$$

Ex: 
$$pw(20, 15.7, 101325) = 1.5 \times 10^3$$
 ... Pa

And,  $RH = \frac{pw}{pw_s}$ 

Ex: RH(20, 15.7, 101325) = 0.641 = 64.1%
#### Plot RH vs DBT for different "wet bulb depression (DBT-WBT)" values:

DBT := 15,17...36 C....define a range variable

| DBT = | RH(DBT,DBT - 1,101325) | RH(DBT,DBT - 2,101325) | RH(DBT,DBT - 3,101325) |
|-------|------------------------|------------------------|------------------------|
| 15    | 0.899                  | 0.801                  | 0.706                  |
| 17    | 0.904                  | 0.812                  | 0.723                  |
| 19    | 0.909                  | 0.822                  | 0.737                  |
| 21    | 0.914                  | 0.83                   | 0.75                   |
| 23    | 0.918                  | 0.838                  | 0.762                  |
| 25    | 0.921                  | 0.845                  | 0.772                  |
| 27    | 0.924                  | 0.852                  | 0.782                  |
| 29    | 0.927                  | 0.857                  | 0.79                   |
| 31    | 0.93                   | 0.862                  | 0.798                  |
| 33    | 0.932                  | 0.867                  | 0.805                  |
| 35    | 0.934                  | 0.871                  | 0.811                  |



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| 15 0.615 0.526 0.441 |  |
|----------------------|--|
| 17 0.636 0.553 0.473 |  |
| 19 0.656 0.577 0.501 |  |
| 21 0.673 0.598 0.526 |  |
| 23 0.688 0.617 0.549 |  |
| 25 0.702 0.634 0.569 |  |
| 27 0.714 0.649 0.587 |  |
| 29 0.725 0.663 0.603 |  |
| 31 0.735 0.675 0.617 |  |
| 33 0.744 0.686 0.631 |  |
| 35 0.753 0.697 0.643 |  |

| DBT = | RH(DBT,DBT - 7,101325) | RH(DBT,DBT - 8,101325) | RH(DBT,DBT - 9,101325) | RH(DBT,DBT - 10,101325) |
|-------|------------------------|------------------------|------------------------|-------------------------|
| 15    | 0.358                  | 0.278                  | 0.2                    | 0.124                   |
| 17    | 0.395                  | 0.32                   | 0.247                  | 0.176                   |
| 19    | 0.428                  | 0.357                  | 0.288                  | 0.222                   |
| 21    | 0.457                  | 0.39                   | 0.325                  | 0.262                   |
| 23    | 0.483                  | 0.419                  | 0.357                  | 0.298                   |
| 25    | 0.506                  | 0.445                  | 0.386                  | 0.33                    |
| 27    | 0.526                  | 0.468                  | 0.412                  | 0.358                   |
| 29    | 0.545                  | 0.489                  | 0.435                  | 0.384                   |
| 31    | 0.562                  | 0.508                  | 0.456                  | 0.407                   |
| 33    | 0.577                  | 0.525                  | 0.475                  | 0.428                   |
| 35    | 0.591                  | 0.541                  | 0.493                  | 0.446                   |



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#### 13.Humidity from DBT and WBT:

 $W1(dbt,wbt,P) := RH(dbt,wbt,P) \cdot \frac{0.622 \cdot psatt(dbt)}{P - psatt(dbt) \cdot RH(dbt,wbt,P)}$ 

Ex: W1(20,15,101325) = 8.558 × 10<sup>-3</sup> kg H2O/kg. dry air

#### 14. Humidity from DBT & RH:

 $\omega 1(DBT,RH,P) := RH \cdot \frac{0.622 \cdot psatt(DBT)}{P - psatt(DBT) \cdot RH} \qquad \qquad \mbox{kg H2O/kg dry air,} \quad P \mbox{ in Pa, temp (C)}$ 

Ex:  $\omega 1(20, 0.64, 101325) = 9.326 \times 10^{-3}$  kg H2O/kg dry air





39

#### 15. WBT from DBT & RH:

WBT := 10 C....trial value P := 101325 Pa

Given

phi = RH(DBT, WBT, P)

WBT(DBT, phi, P) := Find(WBT) .....Required Function

Ex: WBT(20,0.64,101325) = 15.683 C

#### 16. pw from w & P:

$$p_w(w,P) := \frac{w \cdot P}{w + 0.622}$$
 Pa ... w in kg H2O/kg dry air, P is atm. pressure in Pa

Ex: 
$$p_w(0.0152, 101325) = 2.417 \times 10^3$$
 Pa

#### 17. pw from DBT, WBT & P:

 $p_w(dbt, wbt, P) := \frac{\omega 1(dbt, wbt, P) \cdot P}{\omega 1(dbt, wbt, P) + 0.622} \qquad \begin{array}{c} \mathsf{Pa} \ \dots \ dbt, \ wbt \ in \ \mathsf{C}, \ \mathsf{P} \ is \ atm. \\ pressure \ in \ \mathsf{Pa} \end{array}$ 

Ex: 
$$p_w(25, 15, 101325) = 4.754 \times 10^4$$
 Pa

#### 18. pw from DBT, RH & P:

 $P_w(DBT,RH,P) := \frac{\omega 1(DBT,RH,P) \cdot P}{\omega 1(DBT,RH,P) + 0.622} \qquad \begin{array}{c} \mathsf{Pa} \ \dots \ \mathsf{DBT} \ \mathsf{in} \ \mathsf{C}, \ \mathsf{P} \ \mathsf{is} \ \mathsf{atm}. \\ \mathsf{pressure} \ \mathsf{in} \ \mathsf{Pa} \end{array}$ 

Ex:  $P_w(25, 0.75, 100000) = 2.377 \times 10^3$  Pa

| Function   | Comments   | Example                            |
|------------|--|------------------------------------|
| PSATT(T)   | sat. pr. of water (Pa) as a function of temp (C), data from Steam Tables                       | $PSATT(25) = 3.169 \times 10^3$    |
| TSATP(P)   | sat. temp. of water (C) as a function of pressure (Pa), data from Steam Tables                 | TSATP(1750) = 15.354               |
| HFSATT(T)  | enthalpy of sat. water (kJ/kg) as<br>a function of temp (C), data from<br>Steam Tables         | HFSATT(30) = 125.79                |
| HGSATT(T)  | enthalpy of sat. vapor (kJ/kg) as<br>a function of temp (C), data from<br>Steam Tables         | $HGSATT(30) = 2.556 \times 10^{3}$ |
| HFGSATT(T) | enthalpy vaporization of water (kJ/kg) as<br>a function of temp (C), data from Steam<br>Tables | HFGSATT(15) = $2.466 \times 10^3$  |
| psatt(T)   | sat. pr. of water (Pa) as a function of temp (C), from vap. pressure eqn.                      | $psatt(20) = 2.339 \times 10^3$    |
| tsatp(p)   | sat. temp. of water (C) as a function of pressure (Pa), from vap. pressure eqn.                | tsatp(7384) = 40.001               |
| ∮(pw,dbt)  | Relative humidity from pw(Pa) and dbt (C)  | $\phi(2380, 25) = 0.751$           |

Summary of Mathcad Functions to determine various Psychrometric properties:



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| Pw(dbt,RH)                    | Pw (Pa) from dbt (C) and RH,<br>P = 101325 Pa   | $Pw(20, 0.5) = 1.169 \times 10^3$                   |
|-------------------------------|---|---|
| w(P,pw) W(dbt,RH,P)           | w, W Sp. humidity (kg. water vap/kg<br>dry air)                                       | $W(20, 0.5, 101325) = 7.262 \times 10^{-3}$         |
| ws(P,dbt)                     | ws sp. humidity at saturation, P is atm.<br>pressure (Pa)                             | ws(101325,20) = 0.0147                              |
| mu(dbt,RH,P)                  | degree of saturation  | mu(20, 0.5, 101325) = 0.494                         |
| dpt(pw)                       | dew point temp (C), pw in (Pa)  | dpt(1169.4) = 9.147                                 |
| dewpt(dbt,RH)                 | dew point temp (C) as a function of dbt<br>and RH                                     | dewpt(20, 0.75) = 15.276                            |
| v(dbt,RH,P)                   | sp.vol. (m^3/kg of moist air), given in<br>Psychrometric chart                        | v(20,0.5,101325) = 0.834                            |
| rho(dbt,RH,P)                 | density (kg/m^3 moist air), given in<br>Psychrometric chart                           | rho(20, 0.5, 101325) = 1.199                        |
| hg(T)                         | Enthalpy (kJ/kg) of water vapor   | $h_g(25) = 2.5464 \times 10^3$                      |
| h <sub>dryair</sub> (T)       | Enthalpy (kJ/kg) of dry air   | h <sub>dryair</sub> (25) = 25.125                   |
| h <sub>moist</sub> (dbt,RH,P) | Enthalpy (kJ/kg) of moist air   | h <sub>moist</sub> (20, 0.5, 101325) = 38.527       |
| phi(DBT, WBT)                 | RH when dbt and wbt are known   | phi(20,15.7) = 0.647                                |
| pw(dbt,wbt,P)                 | Carrier's eqn for partial pressure of water (Pa), from dbt and wbt                    | $pw(20, 15.7, 101325) = 1.5 \times 10^3$            |
| RH(dbt,wbt,P)                 | RH when dbt and wbt are known, P is<br>atm. pr in Pa                                  | RH(20,15.7,101325) = 0.641                          |
| W1(dbt,wbt,P)                 | Sp. humidity (kg H2O/kg dry air) when<br>dbt and wbt are known, P is atm. pr<br>in Pa | $W1(20, 15, 101325) = 8.558 \times 10^{-3}$         |
| ω1(DBT,RH,P)                  | Sp. humidity (kg H2O/kg dry air) when<br>dbt and RH are known, P is atm. pr in<br>Pa  | $\omega 1(20, 0.64, 101325) = 9.326 \times 10^{-3}$ |
| WBT(DBT, phi, P)              | WBT (C) when DBT (C) and RH are known, P is atm. pressure in Pa                       | WBT(25.4, 0.6, 101325) = 19.832                     |
| $p_{W}(w, P)$                 | Pw (Pa) from w (kgH2O/kg dry air) and,<br>P (Pa)                                      | $p_{\rm W}(0.0152, 101325) = 2.417 \times 10^3$     |
| P_w(DBT,RH,P)                 | Pw (Pa) from DBT (C), RH and P(Pa)  | $P_w(25, 0.75, 100000) = 2.377 \times 10^3$         |

**Prob.7.2.2** The sling psychrometer in a laboratory test recorded following readings: dbt = 35 C; wbt = 25 C. Calculate the following: (i) sp. humidity (ii) relative humidity (iii) Vapor density in air (iv) dew point temp (v) enthalpy of mixture/kg of dry air. Take total atmospheric pressure as 1.0132 bar.[M.U.]

#### Mathcad Solution:

Data:

dbt := 35 C wbt := 25 C P := 101325 Pa

Calculations:

Recollect that we have: Humidity from DBT and WBT:

 $W1(dbt, wbt, P) := RH(dbt, wbt, P) \cdot \frac{0.622 \cdot psatt(dbt)}{P - psatt(dbt) \cdot RH(dbt, wbt, P)}$ 

- (i) Sp. humidity: W1(dbt,wbt,P) = 0.016 kg vap/ kg dry air .... Ans.
- (ii) Rel. humidity: RH(dbt,wbt,P) = 0.446 = 44.6 %....Ans.
- (iii) density of moist air: rho(dbt,RH(dbt,wbt,P),P) = 1.135 kg moist air /m^3 ...Ans.

#### For density of vapor in mixture:

Vap. pressure: pw := pw(dbt, wbt, P)  $pw = 2.513 \times 10^3$  Pa Therefore: pa := P - pw  $pa = 9.881 \times 10^4$  Pa .... partial pressure of dry air

And, density of dry air in mixture:  $rho_a := \frac{pa}{287 \cdot (dbt + 273)}$ 

\_\_\_\_\_\_

i.e.  $rho_a = 1.118$  kg dry air/m^3 dry air

And, density of vapor air in mixture:  $rho_w := rho_a \cdot W1(dbt, wbt, P)$ 

i.e. thow = 0.018 kg. vap/kg. dry air ... Ans.

\_\_\_\_\_

- (iv) Dew point temp: dewpt(dbt,RH(dbt,wbt,P)) = 21.029 deg. C....Ans.
- (v) Enth. of mixture:  $h_{moist}(dbt, RH(dbt, wbt, P), P) = 75.737$  kJ/kg..... Ans.

**Prob. 7.2.3** Temp of air on a certain day is 30C and the RH is 70%. What is the sp. humidity and dew point temp? If the air is cooled at const. pressure to 10C, what mass of water vapor would condense? [M.U.]

#### Mathcad Solution:

#### Data:

dbt := 30 C phi := 0.70 P := 101325 Pa

#### Calculations:

wbt := 20 trial value

Then: root(RH(dbt,wbt,P) - phi,wbt) = 25.509 ....applying the root function

Therefore: wbt := 25.509 deg. C.... wet bulb temp.

And:

W1(dbt,wbt,P) = 0.0188 kg vap/kg dry air..sp. humidity.... Ans.



dewpt(dbt,RH(dbt,wbt,P)) = 23.821 deg. C..Dew point...Ans.

 $W1(10,10,P) = 7.63073 \times 10^{-3}$  kg vap/kg dry air....sp. hum. at sat temp of 10C... since on sat. line dbt = wbt

Verify: at 10 C, sp. humidity is:

 $\frac{0.622 \cdot psatt(10)}{P - psatt(10)} = 7.631 \times 10^{-3}$  kg.vap/kg. dry air .... verified.

Therefore, water condensed:

W1(dbt,wbt,P) - W1(10,10,P) = 0.01116 kg vap/ kg dry air...Ans

\_\_\_\_\_\_

**Prob. 7.2.4** Atmospheric air at 101.325 kPa has 30 C DBT and 15 C DPT. Without using the Psychrometric chart, using property values from tables, calculate: (i) partial pressures of air and water vapor, (ii) sp. humidity, (iii) RH, (iv) vapor density, and (v) enthalpy of moist air. [VTU]

#### **Mathcad Solution:**

Data:

dbt := 30 C .... dry bulb temp P := 101325 Pa ..... atm. pressure dpt := 15 C ... dew point temp

#### Calculations:

Recollect the following Mathcad Function we wrote earlier:

Dew point temp, deg.C: ... between 0 and 70 C:

 $dpt(pw) := \begin{bmatrix} -35.957 - 1.8726 \cdot ln(pw) + 1.1689 \cdot (ln(pw))^2 \end{bmatrix} \quad \dots deg. \ C, \quad pw \ in \ Pa$ 

Now, we shall use this Function to find partial pressure of water, pw as follows:

Using the Solve block to find partial pressure of water, pw::

Given dpt(pw) = 15 pw := Find(pw)

i.e. pw = 1.723 × 10<sup>3</sup> Pa.... partial pressure of water vapor .... Ans.

#### Therefore, partial pressure of dry air:

pa := P - pw

i.e. pa = 9.96 × 10<sup>4</sup> Pa.... partial pressure of dry air.... Ans.

#### To find RH:

Agin, recollect the following Mathcad Function we wrote earlier:

#### Dew point temp, deg.C: ... between 0 and 70 C: ... in terms of DBT and RH:

dewpt(dbt, RH) = dpt(pw(dbt, RH)) C.

#### Using the Solve block to find RH::

rh := 0.5 ...rel. humidity.... trial value dbt := 30 C

Given

dewpt(dbt, rh) = 15

Find(rh) = 0.406

i.e. RH := 0.406 = 40.6% ..... Ans.

#### Sp. humidity:

We have: w1 := w(P, pw)

i.e. w1 = 0.011 kg. vapor/kg dry air .... Ans.

Applied Thermodynamics: Software Solutions: Part-IV (Psychrometrics, Reactive systems)

**Psychrometrics** 

#### Density of vapor in mixture:

Density of dry air in mixture:  $rho_a := \frac{pa}{287 \cdot (dbt + 273)}$ i.e.  $rho_a = 1.145$  kg dry air/m^3 dry air And, density of vapor air in mixture:  $rho_w := rho_a \cdot w1$ i.e.  $rho_w = 0.012$  kg. vap/m^3 dry air ... Ans.

#### Enthalpy of moist air:

Recollect that enthalpy of moist air is the sum of enthalpies of dry air and associated water vapor.:

 $h := 1.005 \cdot dbt + w1 \cdot (2500.9 + 1.82 \cdot dbt)$ 

i.e. h = 57.652 kJ/kg ..... Ans.

**Prob.** 7.2.5 A room  $6m \times 4m \times 4m$  contains air at 25 C and 1 atm at a RH = 80%.Determine: (i) partial pressures of air and water vapor, (ii) sp. humidity, (iii) enthalpy of moist air per unit mass of dry air (iv) masses of dry air and water vapor in the room. [VTU]

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#### Mathcad Solution:

#### Data:

dbt := 25 C .... dry bulb temp P := 101325 Pa ..... atm. pressure RH := 0.8 ... relative humidity

#### **Calculations:**

Sat. vap. pressure of water:

 $pw_s := psatt(dbt)$  i.e.  $pw_s = 3.169 \times 10^3$  Pa

#### Therefore, vapor pressure at 25 C:

 $pw := RH \cdot pw_s$ 

i.e. pw = 2.535 × 10<sup>3</sup> Pa....partial pressure of water ... Ans.

Therefore, partial pressure of air at 25 C:

$$pa := P - pw$$

i.e. pa = 9.879 × 10<sup>4</sup> Pa....partial pressure of air ... Ans.

#### Specific humidity:

w1 := 
$$\frac{0.622 \cdot pw}{P - pw}$$

i.e. w1 = 0.016 kg H2O/kg dry air ... Ans.

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#### Enthalpy per unit mass of dry air:

Recollect:

$$h_{moist}(dbt, RH, P) = 1.005 \cdot dbt + W(dbt, RH, P) \cdot (2500.9 + 1.82 \cdot dbt)$$
 kJ/kg

h<sub>moist</sub>(dbt,RH,P) = 65.774 kJ/kg....Ans.

#### Masses of dry air and water vapor in the room:

Both dry air and vapor fill the entire room, i.e. volume occupied by air and vapor is the same = 6 x 4 x 4 = 96 m^3.

V := 96 m^3

Apply Ideal Gas Law to determine the masses of dry air and vapor:

R<sub>a</sub> := 287 J/kg.K ... Gas const. for air T := dbt + 273.15 K

$$R_{w} := \frac{8314}{18}$$
 i.e.  $R_{w} = 461.889$  J/kg.K ... Gas const. for water vapor

Therefore:

$$\begin{split} m_{a} &\coloneqq \frac{p a \cdot V}{R_{a} \cdot T} & \text{i.e.} & m_{a} = 110.832 \quad \text{kg....mass of dry air .... Ans.} \\ m_{w} &\coloneqq \frac{p w \cdot V}{R_{w} \cdot T} & \text{i.e.} & m_{w} = 1.767 \quad \text{kg....mass of water vapor .... Ans.} \end{split}$$

**Prob. 7.2.6** In a room, a sling psychrometer reads a dry bulb temp of 25 C and wet bulb temp of 15 C. Determine: (i) sp. humidity (ii) relative humidity, and (iii) enthalpy of air.

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#### Mathcad Solution:

Data:

DBT := 25 C WBT := 15 C P := 101325 Pa

#### Calculations:

Sp. humidity and Relative humidity can be determined with the Mathcad Functions written earlier:

#### For sp. humidity:

 $W1(dbt, wbt, P) = RH(dbt, wbt, P) \cdot \frac{0.622 \cdot psatt(dbt)}{P - psatt(dbt) \cdot RH(dbt, wbt, P)}$ 

For relative humidity:

 $phi(DBT, WBT) := \frac{[psatt(WBT) - (DBT - WBT) \cdot 63]}{psatt(DBT)}$ 

#### Therefore:

#### Sp. humidity:

w1 := W1(DBT, WBT, P)

i.e.  $w1 = 6.48 \times 10^{-3}$  kg H2O/kg dry air ..... Ans.

#### **Relative humidity:**

RH := phi(DBT, WBT)

i.e. RH = 0.339 = 33.9% .... Ans.

#### Enthalpy of air:

 $h := h_{moist}(DBT, RH, P)$ 

i.e. h = 42.116 kJ/kg .... enthalpy of moist air ... Ans.

**Note:** Refer to the section under **Adiabatic saturation**. For air at 1 atm, adiabatic saturation temp (T2) can be taken as Wet bulb temp, and we can apply the equations given for w2 and w1 in that section:

We have:

$$w2 = \frac{0.622 \cdot pws2}{P - pws2}$$
  $w1 = \frac{cp \cdot (T2 - T1) + w2 \cdot h_{fg2}}{hg1 - hf2}$ 

Therefore:

$$w2 := \frac{0.622 \cdot psatt(T2)}{P - psatt(T2)}$$

i.e. w2 = 0.011 kg H2O/kg dry air



51



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And:

w1 := 
$$\frac{\text{cp} \cdot (\text{T2} - \text{T1}) + \text{w2} \cdot \text{HFGSATT(T2)}}{\text{HGSATT(T1)} - \text{HFSATT(T2)}}$$

i.e.  $w1 = 6.524 \times 10^{-3}$  kg H2O/kg dry air

- Therefore: RH1 =  $\frac{w1 \cdot P}{(0.622 + w1) \cdot P_{g1}}$
- i.e. RH1 :=  $\frac{w1 \cdot P}{(0.622 + w1) \cdot psatt(T1)}$ 
  - i.e. RH1 = 0.332 = 33.2 % ..... verified.

**Prob.7.2.7** For a hall to be air conditioned, following conditions are given:

Outdoor condition: 40 C DBT, 20 C WBT Required comfort condition: 20 C DBT, 60% RH Seating capacity of hall = 1500; Amount of outdoor air supplied = 0.3 m^3/person If the required condition is achieved first by adiabatic humidification and then by cooling, estimate:

(i) capacity of cooling coil in Tons of Refrigeration (ii) capacity of humidifier (iii) condition of air after adiabatic humidification. [VTU]

#### Mathcad Solution:

Here, starting from state 1, first humidification is done adiabatically to state 2, and then cooling is done to final state 3. Note that process 2=3 occurs at const. sp. humidity. See the schematic Psychrometric chart below:



#### Data:

DBT1 := 40 C WBT1 := 20 C DBT3 := 20 C RH3 := 0.6 V := 450 m^3/min P := 101325 Pa R<sub>a</sub> := 287 J/kg.C

#### Calculations:

Recollect the Mathcad Function we wrote earlier for pw as function of dbt and wbt:

 $pw(dbt,wbt,P) := \left[ \begin{array}{c} psatt(wbt) - \frac{(P-psatt(wbt)) \cdot (dbt-wbt)}{1527.4 - 1.3 \cdot wbt} \end{array} \right] \quad ...Pa$ 

Then:  $p_{w1} := pw(DBT1, WBT1, P)$ 

i.e.  $p_{w1} = 1.02 \times 10^3$  Pa...partial pressure of water at state 1

#### Therefore, partial pressure of air:

$$p_a := P - p_{w1}$$
 i.e.  $p_a = 1.003 \times 10^3$  Pa....partial pressure of air

Therefore, mass flow rate of air:

$$m_a := \frac{p_a \cdot V}{R_a \cdot (DBT1 + 273)}$$
 i.e.  $m_a = 502.467$  kg/min

Sp. humidity at 1:

w1 := 
$$\frac{0.622 \cdot p_{w1}}{P - p_{w1}}$$
 i.e. w1 =  $6.326 \times 10^{-3}$  kg H2O/kg dry air

#### Moist air enthalpy at 1:

Recollect the Mathcad Function we wrote earlier for pw as function of dbt and pw:

$$\phi(pw, dbt) := \frac{pw}{psatt(dbt)}$$



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54

Therefore:

RH1 :=  $\phi(p_{w1}, DBT1)$  i.e. RH1 = 0.138 = 13.8% .... RH at 1 h1 :=  $h_{moist}(DBT1, RH1, P)$  i.e. h1 = 56.482 kJ/kg dry air

#### Condition of air immediately after adiabatic humidification, i.e. state 2:

Sp. humidity at 2 is equal to sp. humidity at 3, since in cooling from 2 to 3, sp. humidity remains constant.

 $\omega 1(DBT,RH,P) := RH \cdot \frac{0.622 \cdot psatt(DBT)}{P - psatt(DBT) \cdot RH}$  ...Function for sp. hum. written earlier

Therefore:

w3 :=  $\omega1(DBT3,RH3,P)$  i.e. w3 =  $8.735 \times 10^{-3}$  kg H2O/kg dry air

And,

w2 := w3 i.e. 
$$w2 = 8.735 \times 10^{-3}$$
 kg H2O/kg dry air .... sp. humidity at 2, after humidification

To find DBT at state 2:

We have: h1 = 56.482 kJ/kg dry air

And, h2 := h1 ...since 1-2 is adiabatic humidification

i.e. h2 = 1.005·DBT2 + w2·(2500.9 + 1.82·DBT2)

Therefore: DBT2 :=  $\frac{(h2 - w2 \cdot 2500.9)}{1.005 + w2 \cdot 1.82}$ 

i.e. DBT2 = 33.927 C .... dry bulb temp at state 2, after humidifying

i.e. Temp of air at state 2, immediately after adiabatic humidification is: 33.927 C.

Wet bulb temp at 2: this is equal to WBT1 = 20 C, since constant enthalpy lines in a Psychrometric chart run parallel to constant wet bulb temp. lines.

i.e. WBT2 := WBT1

#### To find RH at state 2:

Recollect the Mathcad Function written earlier: RH := phi(DBT, WBT)

Therefore:

RH2 := phi(DBT2, WBT2)

i.e. RH2 = 0.276 = 27.6 % ... relative humidity at state 2, after humidification.

Thus, conditions at state 2 are:

DBT2 = 33.927 C, WBT2 = 20 C, RH2 = 27.6 % , w2 = w3 = 0.008735 kg H2O/kg dry air, h2 = h1 = 56.482 kJ/kg of dry air ... Ans.

Then: Amount of H2O added in humidifier:

 $m_{w} := w2 - w1$  i.e.  $m_{w} = 2.409 \times 10^{-3}$  kg H2O/kg dry air

Actual amount of water added:

 $M_w := m_w \cdot m_a$  i.e.  $M_w = 1.21$  kg H2O per min .... Ans.

Capacity of cooling coils:

 $Q = m_a \cdot (h2 - h3)$  kJ/min

Moist air enthalpy at 3:

 $h3 := h_{moist}(DBT3, RH3, P)$  i.e. h3 = 42.264 kJ/kg dry air

Therefore, total cooling required, Q:

 $Q := m_{a} \cdot (h2 - h3)$  i.e.  $Q = 7.144 \times 10^{3}$  kJ/min

And, cooling capacity in tons:

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 $Q_{ton} := \frac{Q}{211}$  ...since 1 ton = 211 kJ/min

i.e. Q<sub>ton</sub> = 33.859 tons of refrigeration ... Ans.

**Prob.7.2.8** We have one stream, 30 m<sup>3</sup>/min of air at 15 C DBT and 13 C WBT mixed with 12 m<sup>3</sup>/min of air at 25 C DBT and 18 C WBT. Calculate DBT, sp. humidity of mixture. Take atm pressure as 101.325 kPa. [VTU]



Fig.Prob.7.2.8 Adiabatic mixing of two streams

#### Mathcad Solution:

Data:

DBT1 := 15 C WBT1 := 13 C DBT2 := 25 C WBT2 := 18 C V1 := 30 m^3/min V2 := 12 m^3/min

P := 101325 Pa R<sub>a</sub> := 287 J/kg.C

#### Calculations:

#### For stream 1:

Recollect the Mathcad Function we wrote earlier for pw as function of dbt and wbt:

 $pw(dbt,wbt,P) := \left[ psatt(wbt) - \frac{(P - psatt(wbt)) \cdot (dbt - wbt)}{1527.4 - 1.3 \cdot wbt} \right] \dots Pa$ 

Then:  $p_{w1} := pw(DBT1, WBT1, P)$ 

i.e.  $p_{w1} = 1.366 \times 10^3$  Pa...partial pressure of water at state 1

#### Therefore, partial pressure of air:

$$p_{a1} := P - p_{w1}$$
 i.e.  $p_{a1} = 9.996 \times 10^4$  Pa....partial pressure of air

#### And, mass flow rate of air:

$$m_{a1} := \frac{p_{a1} \cdot V1}{R_a \cdot (DBT1 + 273)}$$
 i.e.  $m_{a1} = 36.28$  kg/min

Sp. humidity at 1:

$${\rm w1} := \frac{0.622 \cdot p_{w1}}{P - p_{w1}} \qquad \mbox{ i.e. } {\rm w1} = 8.498 \times 10^{-3} \qquad \mbox{kg H2O/kg dry air}$$

#### Moist air enthalpy at 1:

Recollect the Mathcad Function we wrote earlier for pw as function of dbt and pw:

$$\phi(pw, dbt) := \frac{pw}{psatt(dbt)}$$

Therefore:

RH1 := 
$$\phi(p_{w1}, DBT1)$$
 i.e. RH1 = 0.801 = 80.1 % .... RH at 1

 $h1 := h_{moist}(DBT1,RH1,P) \qquad i.e. \qquad h1 = 36.559 \qquad kJ/kg \; dry \; air$ 

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#### Similarly, for stream 2:

Partial pressure of water for stream 2:

$$p_{w2} := pw(DBT2, WBT2, P)$$

i.e.  $p_{w2} = 1.602 \times 10^3$  Pa...partial pressure of water at state 2

Therefore, partial pressure of air:

 $p_{a2} := P - p_{w2}$  i.e.  $p_{a2} = 9.972 \times 10^4$  Pa....partial pressure of air

And, mass flow rate of air:

$$m_{a2} := \frac{p_{a2} \cdot V2}{R_a \cdot (DBT2 + 273)}$$
 i.e.  $m_{a2} = 13.992$  kg/min

Sp. humidity at 2:

w2 := 
$$\frac{0.622 \cdot p_{w2}}{P - p_{w2}}$$
 i.e. w2 = 9.994 × 10<sup>-3</sup> kg H2O/kg dry air

#### Moist air enthalpy at 2:

Recollect the Mathcad Function we wrote earlier for pw as function of dbt and pw:

$$\phi(pw, dbt) := \frac{pw}{psatt(dbt)}$$

Therefore:

RH2 := 
$$\phi(p_{w2}, DBT2)$$
 i.e. RH2 = 0.506 = 50.6 % .... RH at 2  
h2 :=  $h_{moist}(DBT2, RH2, P)$  i.e. h2 = 50.574 kJ/kg dry air... at state 2

Now, for adiabatic mixing of two streams, we have:

Dry air mass balance:  $m_{a1} + m_{a2} = m_{a3}$ 

Water mass balance:  $m_{a1} \cdot w_1 + m_{a2} \cdot w_2 = m_{a3} \cdot w_3$ 

Energy balance:  $m_{a1} \cdot h_1 + m_{a2} \cdot h_2 = m_{a3} \cdot h_3$ 

Applied Thermodynamics: Software Solutions: Part-IV (Psychrometrics, Reactive systems)

Then, we get:

$$\frac{\mathbf{m}_{a1}}{\mathbf{m}_{a2}} = \frac{\mathbf{w}_2 - \mathbf{w}_3}{\mathbf{w}_3 - \mathbf{w}_1} = \frac{\mathbf{h}_2 - \mathbf{h}_3}{\mathbf{h}_3 - \mathbf{h}_1}$$

Therefore:

 $m_{a1} \cdot w1 + m_{a2} \cdot w2$ 

i.e. 
$$w_3 = 8.914 \times 10^{-3}$$
 kg/kg... sp. humidity of mixture....Ans.

And, enthalpy of mixture is given by::

w3

h3 := 
$$\frac{m_{a1} \cdot h1 + m_{a2} \cdot h2}{m_{a1} + m_{a2}}$$

i.e. h3 = 40.46 kJ/kg dry air .... enthalpy of mixture ... Ans.

#### To find T3, the DBT of the mixture stream:

We have:  $p_w3 := p_w(w3, P)$  ...partial pressure of vapor at 3

i.e. 
$$pw3 = 1.432 \times 10^3$$
 Pa





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**Psychrometrics** 

#### Now, enthalpy of mixture is also given by:

h3 = 1.005·T3 + w3·(2500.9 + 1.82·T3) kJ/kg dry air

Therefore:

$$T3 := \frac{h3 - 2600.9 \cdot w3}{1.005 + w3 \cdot 1.82}$$

i.e. T3 = 16.916 C... DBT of mixture .... Ans.

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#### 7.3 Problems solved with Psychrometric chart:

Prob.7.3.1 Solve the above problem (i.e. problem 7.2.7) with Psychrometric chart:

#### Following are the steps:

1. We use the simplified Psychrometric chart published by Ureili [Ref: 14], shown below:



- 2. Locate state 1, i.e. DBT = 40 C, WBT = 20 C. Also, locate State 3, with DBT = 20 C, and RH = 60%.
- 3. Proces 1-2 is adiabatic humidification. And 2-3 is cooling with constant sp. humidity. So, from State 1, proceed along const. enthalpy line to State 2 to intersect const. sp. humidity line from State 3, and the point of intersection is State 2. These processes are shown below:



4. From the chart, we read that:

RH1 = 14%, h1 = 57 kJ/kg dry air, v1 = 0.9 m3/kg, w1 = 6.5 g/kg dry air

Therefore, mass flow rate of air =  $m_a = 450/0.9 = 500$  kg/min.

RH2 = 26%, h2 = h1, and w2 = w3 = 9 g/kg dry air

RH3 = 60%, h3 = 42 kJ/kg dry air

Note that these values from chart match very well with the calculated values obtained earlier. Further, using the chart is very convenient.

Then, capacity of cooling coil, capacity of humidifier etc are calculated as earlier, i.e.

Cooling capacity =  $m_a * (h2 - h3) = 500 * (57 - 42)/211 = 35.545$  Tons of Refrigeration ... Ans.

Capacity of humidifier = ma \* (w2 - w1) = 500 \* (0.009 - 0.0065) = 1.25 kg H2O/min.... Ans.

**Prob.7.3.2** The dry and wet bulb temps of air at 1 atm are measured with a sling psychrometer and determined to be 25 C and 15 C respectively. Find: (i) sp. humidity, (ii) relative humidity, (iii) enthalpy, and (iv) sp. volume of air [VTU]

#### Solution:

#### Following are the steps:

- 1. We use the simplified Psychrometric chart published by Ureili [Ref: 14], shown above.
- 2. Locate state 1, i.e. DBT = 25 C, WBT = 15 C:



#### 3. Read from the chart:

Sp. humidity = w1 = 6.5 g/kg dry air .. Ans.

RH = 34% ... Ans.

Enthalpy = 41 kJ/kg dry air ... Ans.

Sp. volume =  $0.852 \text{ m}^{3}/\text{kg}$  ... Ans.

Prob.7.3.3 An air conditioning system is designed under following conditions:

Outdoor conditions: 30 C DBT, 75% RH

Required Indoor conditions: 22 C DBT, 70% RH

Amount of free air circulated: 3.33 m^3/s

Coil dew point temp: 14 C



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The required condition is achieved first by cooling and dehumidification and then by heating. Estimate: (i) capacity of cooling coil in Tons of refrigeration (ii) capacity of heating coil in kW (iii) amount of water vapor removed in kg/h. [VTU]

#### Solution:

#### This problem is solved very conveniently with Psychrometric chart:

#### Following are the steps:

1. We use the simplified Psychrometric chart published by Ureili [Ref: 14], shown below:



2. Locate state 1, i.e. DBT = 30 C, 75% RH. Also, locate State 2, with DPT = 14 C. And state 3 is the required indoor condition with DBT = 22 C, 70% RH

3. Connect proces 1-2 Draw the constant sp. humidity line through point 3 to cut the line 1-2 at point 4. So, 1-4 represents the cooling with dehumidification, and 4-3 is the heating process. These processes are shown below:



#### 4. From the chart, we read that:

h1 = 80 kJ/kg dry air, v1 = 0.887 m3/kg, w1 = 20 g/kg dry air Therefore, mass flow rate of air =  $m_a = 3.33/0.887 = 3.754$  kg/s h4 = 44 kJ/kg , and w4 = w3 = 12 g/kg dry air, h3 = 50 kJ/kg dry air

5. Therefore:

Capacity of cooling coils = ma \* (h1 – h4) = 8109 kJ/min = 38.431 TOR ... Ans. Capacity of heating coils = ma \* (h3 – h4) = 22.524 kW ... Ans. Amount of water vapor removed = ma \* (w1 – w4) = 108.115 kg/h .. Ans.

**Prob.7.3.4** A mixture of air and water vapor enters an adiabatic saturator at 35 C and leaves at 25 C at 1 atm pressure. Determine: (i) sp. humidity (ii) RH, and (iii) dew point of the entering air. [VTU]

#### Solution:

#### Remember that in an adiabatic saturation process, air at the exit is saturated, i.e at exit RH = 100%.

#### Following are the steps:

- 1. We use the simplified Psychrometric chart published by Ureili [Ref: 14], shown above.
- Locate exit state of adiabatic saturator first, i.e. DBT = 25 C, 100% RH, i.e. on the saturation line. Proceed on the const. enthalpy line (i.e. parallel to const. wet bulb temp line) to meet the vertical line at DBT = 35 C. This is State 1.



3. Read from the chart:

Sp. humidity = w1 = 16 g/kg dry air ... Ans.

RH = 42% .... Ans.

Dew point temp = DPT = 21.5 C ... Ans.

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Prob.7.3.5 Sat.air leaving the cooling section of an air conditioning system at 14 C DBT at a rate of 50 m<sup>3</sup>/min is mixed adiabatically with the outside air at 32 C DBT and 60% RH at a rate of 20 m<sup>3</sup>/min. Assuming that mixing process is adiabatic at a pressure of 1 atm, determine the sp. humidity, RH, DBT and volume flow rate of mixture. [VTU]

#### Solution:

#### We shall solve this problem with Psychrometric chart.

#### Following are the steps:

- 1. We use the simplified Psychrometric chart published by Ureili [Ref: 14], shown above.
- 2. Locate the State 1, i.e. state of saturated air first, i.e. DBT = 14 C, 100% RH, i.e. on the saturation line. Then locate State 2, i.e. the state at DBT = 32 C, RH = 60%. Connect States 1 and 2. Final State 3, will be located on this line 1-2. To find State 3, proceed as follows:



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#### From the chart:

w1 = 10.5 g H2O/kg dry air, h1 = 41.5 kJ/kg, v1 = 0.83 m^3/kg

Therefore,  $m_{a1} = 50/0.83 = 60.241 \text{ kg/min}$ 

w2 = 17.5 g/kg dry air, h2 = 76.5 kJ/kg, v2 = 0.887 m^3/kg

Therefore,  $m_{a2} = 20/0.887 = 22.548 \text{ kg/min}$ 



And,  $m_{a3} = m_{a1} + m_{a2} = 82.789$  kg/min .... Total mass flow rate of mixture

#### Now, for adiabatic mixing, we have:

$$\frac{m_{a1}}{m_{a2}} = \frac{w_2 - w_3}{w_3 - w_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

Solving, w3 = 12.406 kg H2O/kg dry air, h3 = 51.032 kJ/kg

Note that w3 and h3 fix the State 3, on the line joining State 1 and State 2.

#### Then, from the Psychrometric chart, we read:

RH = 89% ... Ans.

DBT = 20 C .... Ans.

w3 = 12.406 kg H2O/kg dry air ... Ans.

v3 = 0.846 m^3/kg

Therefore, volume flow rate of mixture =  $m_{a3} * v3 = 82.789 * 0.846 = 70.039 m^3/min ... Ans.$ 

**Prob.7.3.6** Air enters at 32 C and RH of 70% in a summer air conditioning system where the air is cooled and then dehumidified. The air leaving the cooling coil is saturated at the coil temp. It is then heated to comfort condition of 24 C and 50% RH. Sketch the flow diagram of the system and represent the various processes in the Psychrometric chart. Determine: (i) temp of cooling coil, (ii) amount of moisture removed per kg of dry air in the cooling coil, (iii) heat removed per kg dry air in the cooling coil, (iii) heat added per kg dry air in the heating coils. [VTU]

#### Solution:

#### We shall solve this problem with Psychrometric chart.

#### Following are the steps:

- 1. We use the simplified Psychrometric chart published by Ureili [Ref: 14], shown above.
- 2. Locate the State 1, i.e. state of entering air, i.e. DBT = 32 C, 70% RH. It is cooled (with const. sp. humidity) till it reaches the sat. state 2, and then cooling proceeds along the sat. line to state 3, which is decided as follows:
- 3. To fix State 3, first locate State 4, i.e. the final state with DBT = 24 C and RH = 50%. Since heating is with const. sp. humidity, proceed horizontally to left, and cut the sat. line at point 3.
- 4. States 1, 2, 3 and 4 are shown in the Psychrometric chart below:



#### From the chart, we read:

w1 = 21.5 g H2O/kg dry air, h1 = 85 kJ/kg, v1 = 0.89 m^3/kg

w2 = w1, h2 = 80 kJ/kg

w3 = 9.5 g H2O/kg dry air, h3 = 37 kJ/kg, T3 = 13.5 C

w4 = w3 = 9.5 5 kg H2O/kg dry air, h4 = 47 kJ/kg

#### Therefore:

Temp. of cooling coil =  $T3 = 13.5 C \dots Ans$ .

Amount of moisture removed in cooling coil = (w1 - w3) = 12 g/kg dry air ... Ans.

Amount of heat removed in cooling coil per kg dry air =  $(h1 - h3) = 48 \text{ kJ/kg dry air } \dots$  Ans.

Amount of heat added per kg dry air = (h4 - h3) = 10 kJ/kg dry air. Ans.

71

### 7.4 Problems solved with EES:

**Note 1:** EES has built-in Functions for Psychrometric properties. *This makes it very convenient to make Psychrometric calculations with EES.* 

To access the psychrometric Functions, choose AirH2O as the substance in EES. To do this:

1. In EES, go to Options - Function Info:



2. Clicking on Function Info gives following window. Here you choose Fluid Properties and AirH2O radio buttons as shown:

|  | 0.550.0   |
|--|---|
| Math and string functions  | s EES library routines                                    |
| Fluid properties   | C External routines                                       |
| Solid/liquid properties  |   |
| 🔿 Heat Transfer  |   |
| C Mechanical Design  |   |
| C User-defined   |   |
| <b>?</b> Function Info   | l fluids 💿 AirH2O 🔿 Brines 🍸 Fluid Info<br>I gases 🖓 NASA |
| CompressibilityFactor  | AirH20  |
| Conductivity [\/m-K]   |   |
| Cv [kJ/kg-K]   |   |
| Density [kg/m3]  |   |
| JewPoint [L]<br>Inthaloy [k,1/kg]  |   |
| Turnalpy Inving]   |   |
| ntropy [kJ/kg-K]   |   |
| Entropy [kJ/kg-K]<br>HumRat [kg/kg]  |   |
| Intropy [kJ/kg-K]<br>TumRat [kg/kg]<br>Independent Properties  |   |
| Intropy [kJ/kg-K]<br>IumRat [kg/kg]<br>Independent Properties<br>Temperature [C]                             | Dewpoint [C]  |
| ntropy [kJ/kg-K]<br>lumRat [kg/kg]<br>Independent Properties<br>Temperature [C]<br>x: omega[1]=HumRat(AirH2) | Dewpoint [C] T  |
Now, all Psychrometric Functions are available for use in calculations.

Note 2: Pssychrometric chart is easily drawn in EES. To do this:

Go to Plots Menu and choose 'Property Plots':

| File Edit Search Options Calculate Tables | Plots Windows Help Ex      | kamples |
|---|----------------------------|---------|
| 요 🕒 😫 🦛 🕸 🛣 🖬 🗐                           | New Plot Window ►          |         |
| Equations Window                          | Modify Plot<br>Modify Axes |         |
| Į.  | Show Tool Bar              |         |
|   | Delete Plot Window         |         |
|   | Property Plot<br>Curve Fit |         |
|   |                            |         |



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# Clicking on Property Plot brings up the following window. Choose AirH2O as shown:

| <b>?</b> Fluid Info<br>Acetone<br>Air<br>Air ha        | Pressure<br>101.3  | e<br>[kPa]                            |             | 🗸 ОК        |
|--|--------------------|---------------------------------------|-------------|-------------|
| AirH2O<br>Ammonia_mh<br>Ar<br>Argon<br>Benzene<br>C2H2 | From 0.0<br>to 40. | ature<br>[*C]<br>.0 [*C]<br>er format |             | 🗙 Cancel    |
| [X] Include lines                                      | of                 | [X] Incl                              | ude lines o | f           |
| <b>₩b=</b> 10  | [*C]               | V=                                    | 0.8         | <br>[m3/kg] |
| <b>₩b=</b> 15  | ['C]               | V=                                    | 0.825       | [m3/kg]     |
| ₩b=20  | ['C]               | V=                                    | 0.85        | [m3/kg]     |
| ₩b=25  | [*C]               | <b>▼ v</b> =                          | 0.875       | <br>[m3/kg] |
| ₩b=30  | ['C]               | <b>▼ v</b> =                          | 0.9         | <br>[m3/kg] |
| 17 mb-35   | [10]               | V v=                                  | 0.925       | <br>[m3/kg] |

We can include the lines of const. wet bulb and const. sp. volume, as we choose. Accept the default at the moment. Click OK. We get:



We can draw the Psychrometric processes on this chart, as shown later while solving problems.

"**Prob.7.4.1** Atm. air at 101.325 kPa has 30 C DBT and 15 C DPT. Calculate: (i) partial pressures of air and water vapor, (ii) sp. humidity, (iii) RH, (iv) vapor density, and (v) enthalpy of moist air [VTU]"

**EES Solution:** 

# "Data:"

P = 101.325 **"kPa"** 

DBT = 30 **"C"** 

DPT = 15 **"C"** 

"Calculations:"

"To find partial pressure of H2O at DBT = 30 C, first find the sp. humidity, omega:"

"sp. humidity, omega:"

omega=HumRat(AirH2O,T=DBT,D=DPT,P=P) "kg H2O/kg dry air"

"partial pressure of water vapor in air, p\_w"

omega = 0.622 \* p\_w / (P - p\_w) "....finds the partial pressure of water vapor in air, kPa"

"partial pressure of air, p\_a:"

p\_a = P – p\_w "...partial pressure of air, kPa"

# "Relative humidity:"

rh=RelHum(AirH2O,T=DBT,D=DPT,P=P)"...finds rel. humidity"

"Vapor density, rho\_w"

R\_w = 8.314/18 "kJ/kg.K ..... Gas constant for water vapor"

 $rho_w = p_w / (R_w * (DBT + 273)) "kg/m^3 .... vapor density"$ 

# "Enthalpy of moist air"

h = Enthalpy(AirH2O,T=DBT,D=DPT,P=P)"kJ/kg"

# **Results:**

# Unit Settings: SI C kPa kJ mass deg

| DBT = 30 [C]                      |
|-----------------------------------|
| ω = 0.01065 [kg/kg]               |
| p <sub>w</sub> = 1.705 [kPa]      |
| R <sub>w</sub> = 0.4619 [kJ/kq-K] |

| DPT = 15 [C]    |
|-----------------|
| P = 101.3 [kPa] |
| rh = 0.4017 [-] |

| h = 57.42 [kJ/kg]              |   |
|--------------------------------|---|
| p <sub>a</sub> =99.62 [kPa]    |   |
| ρ <sub>w</sub> = 0.01219 [kg/m | ì |

Thus:

Partial pressure of air =  $p_a$  = 99.62 kPa ... Ans.

Partial pressure of water vapor = p\_w = 1.705 kPa .... Ans.

Sp. humidity = omega = 0.01065 kg H2O/kg dry air ... Ans.

RH = 0.4017 = 40.17% .... Ans.

Vapor density =  $rho_w = 0.01219 \text{ kg/m}^3 \dots \text{Ans.}$ 

Enthalpy of moist air = h = 57.42 kJ/kg .... Ans.



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**Psychrometrics** 

**Psychrometrics** 

# \$UnitSystem SI kg kPa C

"**Prob.7.4.2** A room measures  $5m \ge 5m \ge 3m$ . It contains atm air at 100 kPa, DBT = 30 C and RH = 30%. Find the masses of dry air and the associated water vapor.[VTU]"

# **EES Solution:**

# "Data:"

Vol = 75"m^3"

P = 100 "kPa"

DBT = 30**"C"** 

RH = 0.3

R\_a = 0.287 "kJ/kg.K ... gas constant for air"

R\_w = 8.314/18"kJ/kg.K....gas constant for water vapor"

# "Calculations:"

"We have to first, find out the partial pressures of water vapor and air"

"So, we find the sp. humidity from built-in function of EES:"

omega =HumRat(AirH2O,T=DBT,r=RH,P=P)"kgH2O/kg dry air"

# "Then, partial pressure of water vapor:"

omega = 0.622 \* p\_w /(P - p\_w) "...finds p\_w, kPa"

p\_a = P - p\_w "...partial pressure of dry air ....KPa"

# "Mass of water vapor:"

 $m_w = p_w * Vol / (R_w * (DBT + 273))$ "kg"

# "Mass of dry air:"

```
m_a = p_a * Vol / (R_a * (DBT + 273))"kg"
```

# **Results:**

# Unit Settings: SI C kPa kJ mass deg

| DBT = 30 [C]                      | m <sub>a</sub> = 85.15 [kg] | m <sub>w</sub> = 0.6826 [kg]     |
|-----------------------------------|-----------------------------|----------------------------------|
| ω = 0.008025 [kg/kg]              | P = 100 [kPa]               | p <sub>a</sub> = 98.73 [kPa]     |
| p <sub>w</sub> = 1.274 [kPa]      | RH = 0.3 [-]                | R <sub>a</sub> = 0.287 [kJ/kg-K] |
| R <sub>w</sub> = 0.4619 [kJ/kq-K] | Vol = 75 [m <sup>3</sup> ]  |                                  |

Thus:

Mass of water vapor =  $m_w = 0.6826$  kg .... Ans.

Mass of dry air = m\_a = 85.15 kg ... Ans.

"**Prob.7.4.3** A summer air conditioning system for hot and humid weather (DBT = 32 C, RH = 30%) consists in passing the atmospheric air over a cooling coil where air is cooled and dehumidified. The air leaving the coil is saturated at the coil temp. It is then sensibly heated to the required comfort condition of 24 C and 50% RH by passing it over an electric heater and then delivered to the room. Sketch the processes on a psychrometric chart and determine: (i) temp of cooling coil, (ii) amount of moisture removed per kg of dry air in the cooling coil, (iii) heat removed per kg of dry air in cooling coil, (iii) heat removed per kg of dry air in cooling coil, (iv) heat added per kg dry air in heating coil. [VTU]"

### **EES Solution:**

This problem is the same as Prob.7.3.6 which was solved with Psychrometric chart.

### But, now we shall solve it with EES:

Let the ambient condition be State 1, condition at exit of cooling coils be State 2, and final condition be State 3.

Heating from State 2 to State 3 occurs at const. sp. humidity.i,e. w2 = w3.

### "Data:"

P[1] = 101.325 "kPa"

P[2] = P[1]

**Psychrometrics** 

P[3] = P[1]

T[1] = 32**"C"** 

RH[1] = 0.7

RH[2] = 1 "...since saturated"

T[3] = 24**"C"** 

RH[3] = 0.5

# "Calculations:"

omega[1]=HumRat(AirH2O,T=T[1],r=RH[1],P=P[1])"sp. humidity ... kg H2O/kg dry air"

omega[3]=HumRat(AirH2O,T=T[3],r=RH[3],P=P[3])"sp. humidity ... kg H2O/kg dry air"

omega[2] = omega[3]"sp. humidity ... kg H2O/kg dry air"



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T[2] =DewPoint(AirH2O,r=RH[2],w=omega[2],P=P[2])"C .... since the air is saturated while leaving the coils"

h[1]=Enthalpy(AirH2O,T=T[1],w=omega[1],P=P[1]) "kJ/kg dry air"

h[2]=Enthalpy(AirH2O,T=T[2],w=omega[2],P=P[2]) "kJ/kg dry air"

h[3]=Enthalpy(AirH2O,T=T[3],w=omega[3],P=P[3]) "kJ/kg dry air"

moisture\_removed = omega[1] - omega[2] "kg H2O/kg dry air"

 $q_{coolingcoil} = h[1] - h[2]$  "kJ/kg dry air"

 $q_{heatingcoil} = h[3] - h[2] "kJ/kg dry air"$ 

# **Results:**

Unit Settings: SI C kPa kJ mass deg moisture<sub>removed</sub> = 0.01184 [kg/kg] 9<sub>heatingcoil</sub> = 11.32 [kJ/kg]

q<sub>coolingcoil</sub> = 49.83 [kJ/kg]

Thus:

Moisture removed in cooling coils = 0.01184 kg/kg dry air .... Ans.

Heat removed in cooling coils = 49.83 kJ/kg dry air .... Ans.

Heat supplied in heating coils = 11.32 kJ/kg dry air ... Ans.

Draw the Psychrometric chart by selecting 'Plots - Property plots' for AirH2O.

**Psychrometrics** 



# On that chart, overlay the (omega vs T) graph, to get the process lines 1-2 and 2-3:

Note that this chart does not show constant enthalpy lines.

**Prob.7.4.4** It is required to design an air conditioning plant for an office room with the following conditions: Outdoor conditions: 14 C DBT, 10 C WBT; required conditions: 20 C DBT, 60% RH. Amount of air circulation: 0.3 m^3/min/person. Seating capacity of office: 60. The required condition is achieved first by heating and then by adiabatic humidifying. Determine: (i) heating capacity of coil in kW and the surface temp required if the bypass factor of coil is 0.4, (ii) capacity of humidifier. [VTU]



Fig.Prob.7.4.4. Heating and humidifying

# **EES Solution:**

# "Data:"

P1 = 101.325"kPa"

T[1] = 14 "C"

- wb[1] = 10"C....wet bulb temp"
- T[3] = 20**"C"**

rh[3] = 0.6

- Vol = 18 "m^3/min .... air circulation rate"
- BF = 0.4 "Bypass Factor of heating coils"





# "Calculations:"

```
omega[1]=HumRat(AirH2O,T=T[1],B=wb[1],P=P1)"kg H2O/kg dry air"
```

omega[2] = omega[1]"....since heating is at const. sp. humidity"

```
omega[3] = HumRat(AirH2O,T=T[3],r=rh[3],P=P1)"kg H2O/kg dry air"
```

wb[3]=WetBulb(AirH2O,T=T[3],r=rh[3],P=P1)"C....wet bulb temp at state 3"

wb[2] = wb[3]"...since heating from state 2 to state 3 is adiabatic"

```
rh[1]=RelHum(AirH2O,T=T[1],B=wb[1],P=P1)
```

# "Therefore:"

h[1]=Enthalpy(AirH2O,T=T[1],B=wb[1],P=P1)"kJ/kg .... enthalpy at State 1"

h[3]=Enthalpy(AirH2O,T=T[3],r=rh[3],P=P1)"kJ/kg .... enthalpy at State 3"

h[2] = h[3]

T[2]=Temperature(AirH2O,h=h[2],w=omega[2],P=P1)

v[1]=Volume(AirH2O,T=T[1],r=rh[1],P=P1)"m^3/kg .... sp. vol. of air at state 1"

m\_a = Vol/v[1]"kg/min of dry air"

# "Heating capacity of coil:"

Q\_heating =  $(m_a/60) * (h[2] - h[1])$  "kW"

# "Capacity of humidifier:"

m\_w\_humidifier = m\_a \* 60 \* (omega[3] - omega[2]) "kg / min"

"Temp of Heating coil:"

**"By definition:** 

Bypass Factor = (Temp of coil – exit temp of air from heater) / (Temp of coil – inlet temp of air to heater)"

 $BF = (T_heater - T[2]) / (T_heater - T[1]) "...finds T_heater"$ 

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# **Results:**

# Unit Settings: SI C kPa kJ mass deg

| BF  | = 0.4                  |
|-----|------------------------|
| P1  | = 101.3 [kPa]          |
| Vol | = 18 [m <sup>3</sup> ] |

m<sub>a</sub> = 21.92 [kg] Q<sub>heating</sub> = 4.778 [kW]

| m <sub>w,humidifier</sub> = 3.613 | 3 [kg/h] |
|-----------------------------------|----------|
| T <sub>heater</sub> = 35.42 [C]   |          |

Thus:

Heating capacity of heater coils = Q\_heating = 4.778 kW .... Ans.

Temp of cooling coils, when Bypass Factor is 0.4 = T\_heater = 35.42 C .... Ans.

Humidifier capacity = m\_w,humidifier = 3.613 kg/h ... Ans.

Draw the Psychrometric chart by selecting 'Plots – Property plots' for AirH2O.

On that chart, overlay the (omega vs T) graph, to get the process lines 1-2 and 2-3:



**Psychrometrics** 

"**Prob.7.4.5** Sat. air at 2 C is required to be supplied to a room where the temp must be held at 20 C and RH of 50%. The air is heated and then water at 10 C is sprayed in to give the required humidity. Determine the temp to which the air must be heated and the mass of spray water required per m<sup>3</sup> of air at room conditions. Assume that the total pressure is 1.013 bar. [VTU]"

# **EES Solution:**



Fig.Prob.7.4.5 Heating and humidification

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# "Data:"

P1 = 101.325"kPa"

T[1] = 2**"C"** 

rh[1] = 1 "...since saturated"

T[3] = 20**"C"** 

rh[3] = 0.5

# "Calculations:"

h[3]=Enthalpy(AirH2O,T=T[3],r=rh[3],P=P1)"kJ/kg dry air"

omega[1]=HumRat(AirH2O,T=T[1],r=rh[1],P=P1)"kg H2O/kg dry air"

h[1]=Enthalpy(AirH2O,T=T[1],r=rh[1],P=P1)"kJ/kg dry air"

v[3]=Volume(AirH2O,T=T[3],r=rh[3],P=P1)"m^3/kg dry air ... sp. vol. of air at room conditions of State 1"

omega[2] = omega[1]"....since heating is at const. sp. humidity"

h[2] + (omega[3] - omega[2]) \* Enthalpy(Water, T=10, x=0) = h[3] "..energy balance for humidification"

T[2]=Temperature(AirH2O,h=h[2],w=omega[2],P=P1)"..finds DBT at State 2"

omega[3]=HumRat(AirH2O,T=T[3],r=rh[3],P=P1)"kg H2O/kg dry air"

rh[2]=RelHum(AirH2O,T=T[2],w=omega[2],P=P1)"...RH at State 2"

# "Mass of spray water, m\_w:"

 $m_w = (\text{omega}[3] - \text{omega}[2]) / v[3]$  "kg per m^3 of air at room conditions"

### **Results:**

Unit Settings: SI C kPa kJ mass deg mw = 0.003455 [kg/m<sup>3.</sup>ofroom·air]

P1 = 101.3 [kPa]

# And:

| Es Arrays | Table    |                   |                         |                           |                           |
|-----------|----------|-------------------|-------------------------|---------------------------|---------------------------|
| Main      |          |                   |                         |                           |                           |
| Sort      | 1        | rh <sub>i</sub> 3 | T <sub>i</sub> ▲<br>[C] | h <sub>i</sub><br>[kJ/kg] | v <sub>i</sub><br>[m³/kg] |
| [1]       | 0.004359 | 1                 | 2                       | 12.94                     |                           |
| [2]       | 0.004359 | 0.1961            | 27.14                   | 38.44                     |                           |
| [3]       | 0.007262 | 0.5               | 20                      | 38.56                     | 0.8401                    |

# Thus:

Temp to which air is heated =  $T[2] = 27.14 \text{ C} \dots \text{ Ans.}$ 

Mass of air condensed per m<sup>3</sup> of room air =  $m_w = 0.003455 \text{ kg/m}^3$  of room air .... Ans.

Note: Above calculation to determine T[2] would involve tedious trial and error calculations, if you do it by hand using property tables. But, with EES it is solved effortlessly.



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# Processes of heating and humidifying are shown on the Psychrometric chart as follows:

"**Prob.7.4.6** A stream consisting of 145 m $^3$ /min of moist air at a temp of 5 C and humidity ratio of 0.002 kg H2O/kg dry air is mixed adiabatically with a second stream consisting of 420 m $^3$ /min of moist air at 24 C and 50% RH. The pressure is constant throughout at 1.01325 bar. Determine: (i) humidity ratio of mixture (ii) temp of mixture. [Ref: 3]"



Fig.Prob.7.4.6 Adiabatic mixing of two air streams

# **EES Solution:**

# "Data:"

P1 = 101.325 "kPa"

Vol[1] = 145 "m^3/min"

Vol[2] = 420 "m^3/min"

T[1] = 5 **"C"** 

omega[1] = 0.002 "kg H2O/kg dry air for stream 1"

T[2] = 24 "C"

rh[2] = 0.5

# "Calculations:"

h[1]=Enthalpy(AirH2O,T=T[1],w=omega[1],P=P1)"kJ/kg dry air ... for stream 1"

h[2]=Enthalpy(AirH2O,T=T[2],r=rh[2],P=P1)"kJ/kg dry air .... for stream 2"

v[1]=Volume(AirH2O,T=T[1],w=omega[1],P=P1)"...sp. vol. of moist air/kg dry air ... for stream 1"

m\_a1 = Vol[1]/v[1] "...kg / min .... stream 1"

```
v[2]=Volume(AirH2O,T=T[2],r=rh[2],P=P1)<sup>"</sup>...sp. vol. of moist air/kg dry air ... for stream 2"
```

m\_a2 = Vol[2]/v[2] "...kg / min .... stream 2"

omega[2]=HumRat(AirH2O,T=T[2],r=rh[2],P=P1)"kg H2O/kg dry air for stream 2"

# "Mass balance for dry air:"

m\_a1 + m\_a2 = m\_a3"..finds mass of dry air in mixture stream"

# "Mass balance for water vapor:"

 $m_{a1} m_{a2} m_{a2} m_{a3} m_{a3}$ 

# "Enegy balance:"

 $m_{a1} * h[1] + m_{a2} * h[2] = m_{a3} * h[3]$  "...finds h[3], the enthalpy of mixture stream"

h[3]=Enthalpy(AirH2O,T=T[3],w=omega[3],P=P1)"...finds the temp T[3] of mixture stream"

# Solution:

| Uni             | t Settings: SI C kPa | kJ mass deg                      |                                |                  |
|-----------------|----------------------|----------------------------------|--------------------------------|------------------|
| m <sub>a1</sub> | = 183.4 [kg/min]     | m <sub>a2</sub> = 491.6 [kg/min] | m <sub>a3</sub> = 675 [kg/min] | P1 = 101.3 [kPa] |

And:

| 🔤 Arrays | Table    |                   |                         |                              |                           |
|----------|----------|-------------------|-------------------------|------------------------------|---------------------------|
| Main     |          |                   |                         |                              |                           |
| Sort     | 1        | rh <sub>i</sub> 3 | T <sub>i</sub> ▲<br>[C] | h <sub>i</sub> ■₅<br>[kJ/kg] | v <sub>i</sub><br>[m³/kg] |
| [1]      | 0.002    |                   | 5                       | 10.05                        | 0.7905                    |
| [2]      | 0.009299 | 0.5               | 24                      | 47.83                        | 0.8543                    |
| [3]      | 0.007316 |                   | 18.89                   | 37.56                        |                           |

Thus:

Humidity ratio of mixture stream = omega[3] = 0.007316 kg H2O/kg dry air .... Ans.

Temp of mixture stream = T[3] = 18.89 C ... Ans.



# Process of mixing is shown on the Psychrometric chart as follows:

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# (b) Plot the exit temp T[3] vs volume flow rate of stream 2, ranging from 0 to 1400 m^3/min:

# First, compute the Parametric Table:

| 115    | <sup>1</sup> Vol <sub>2</sub><br>[m³/min] | ² ▼<br>T <sub>3</sub><br>[C] |
|--------|---|------------------------------|
| Run 1  | 0   | 5                            |
| Run 2  | 100                                       | 12.46                        |
| Run 3  | 200                                       | 15.72                        |
| Run 4  | 300                                       | 17.54                        |
| Run 5  | 400                                       | 18.7                         |
| Run 6  | 500                                       | 19.51                        |
| Run 7  | 600                                       | 20.11                        |
| Run 8  | 700                                       | 20.56                        |
| Run 9  | 800                                       | 20.92                        |
| Run 10 | 900                                       | 21.21                        |
| Run 11 | 1000                                      | 21.46                        |
| Run 12 | 1100                                      | 21.66                        |
| Run 13 | 1200                                      | 21.83                        |
| Run 14 | 1300                                      | 21.98                        |
| Run 15 | 1400                                      | 22.11                        |

Now, plot the Results:



\_\_\_\_\_

**Psychrometrics** 

"**Prob.7.4.7** A wet cooling tower is to cool 40 kg/s of water from 40 to 30 C. Atm. air enters the tower at 1 atm with dry and wet bulb temps of 22 and 16 C respectively, and leaves at 32 C and 95% RH. Determine: (i) the volume flow rate of air in to the cooling tower, and (ii) mass flow rate of required make-up water. [Ref: 1]"



Make up water

Fig.Prob.7.4.7 Wet cooling tower

#### **EES Solution:**

# "Data:"

P1 = 101.325 "kPa"

DBT1 = 22 "C"

WBT1 = 16 "C"

DBT2 = 32 **"C"** 

RH2 = 0.95

mw\_3 = 40"kg/s .... amount of water entering the tower"

T3 = 40 "C ... temp of hot water inlet to tower"

"Let mw\_4 be the amount of water leaving"

T4 = 30 °C ... temp of cooled water leaving the tower"

"Calculations:"

v1=Volume(AirH2O,T=DBT1,B=WBT1,P=P1)"m^3/kg dry air"

"Let: mass of dry air entering = ma\_1.

Then mass of dry air leaving remains the same, i.e. ma\_2 = ma\_1 = ma, say."

omega1=HumRat(AirH2O,T=DBT1,B=WBT1,P=P1)"kgH2O/kg dry air....sp. humidity of entering air"

omega2=HumRat(AirH2O,T=DBT2,r=RH2,P=P1)"kgH2O/kg dry air..... sp. humidity of exiting air"

"Water mass balance:"

 $mw_3 + ma * omega1 = mw_4 + ma * omega2$ 

# "Energy balance:"

ma \* h1 + mw\_3 \* h3 = ma \* h2 + mw\_4 \* h4 "Energy going in to the tower = energy going out"

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# "Enthalpies:"

h1=Enthalpy(AirH2O,T=DBT1,B=WBT1,P=P1)

h2=Enthalpy(AirH2O,T=DBT2,r=RH2,P=P1)

h3 = Enthalpy(Water,T= T3,x=0)

h4 = Enthalpy(Water,T= T4,x=0)

#### "Make up water:"

 $mw_makeup = mw_3 - mw_4 "kg/s"$ 

# "Volume flow rate of air in to the cooling tower:"

Vol1\_air = ma \* v1"m3/s"

# **Results:**

# Unit Settings: SI C kPa kJ mass deg

| DBT1 = 22 [C]                        | DBT2 = 32 [C]                   | h1 = 44.7 [kJ/kg]                               |
|--------------------------------------|---------------------------------|---|
| h2 = 106.6 [kJ/kg]                   | h3 = 167.5 [kJ/kg]              | h4 = 125.7 [kJ/kg]                              |
| ma = 28.2 [kg/s]                     | mw <sub>3</sub> = 40 [kg/s]     | mw <sub>4</sub> = 39.43 [kg/s]                  |
| mw <sub>makeup</sub> = 0.5687 [kg/s] | omega1 = 0.008875 [kg/kg]       | omega2 = 0.02905 [kg/kg]                        |
| P1 = 101.3 [kPa]                     | RH2 = 0.95                      | T3 = 40 [C]                                     |
| T4 = 30 [C]                          | ∨1 = 0.848 [m <sup>3</sup> /kg] | Vol1 <sub>air</sub> = 23.91 [m <sup>3</sup> /s] |
| WBT1 = 16 [C]                        |                                 |   |

# Thus:

Mass flow rate of make-up water = 0.5687 kg/s ... Ans.

Volume flow rate of air in to the tower = Vol1\_air =  $23.91 \text{ m}^3/\text{s} \dots \text{Ans}$ .

# 7.5 Problems solved with TEST:

# Note: It is extremely easy and convenient to solve Psychrometric problems in TEST.

**Prob. 7.5.1** Atmospheric air at 101.325 kPa has 30 C DBT and 15 C DPT. Calculate: (i) Partial pressure of air and water vapor, (ii) sp. humidity, (iii) RH (iv) Vapor density, and (enthalpy of moist air. [VTU]

# **TEST Solution:**

# Following are the steps:

1. After logging in to TEST (<u>www.thermofluids.net</u>), go to the 'TESTCalcs tree', and choose the **System Analysis-Closed-Psychrometry** as shown below:



2. Hovering the mouse pointer over 'Psychrometry' brings up the explanatory pop up:



3. Clicking on Psychrometry, we go to the following screen, where pressure p1 and material: moist air are selected by default. Here, enter the parameters for the State, viz.T1 = 30 C for dry bulb temp, and T\_dp1 = 15 C for dew point temp. Hit Enter (or, click on Calculate). All calculations are done immediately, and we get:

| Move mouse over a variable to display its value with more |                                       |                                       |
|---|---------------------------------------|---------------------------------------|
| • Mixed C SI C English < Case-0                           | ► ► ► ► ► ► ► ► ► ► ► ► ► ► ► ► ► ► ► | Super-Calculate Load Super-Initialize |
| State Panel   | Process Panel                         | I/O Panel                             |
|   |                                       |                                       |
| < ©State-1 V > Calculate                                  | No-Plots 👻 Initialize MA mode         | I: Dry Air+H2O MoistAir 🗸             |
| 🖌 p1 🖌 T1   | xt                                    | yt vt                                 |
| 101.325 kPa 💉 30.0 deg-(                                  | fraction                              | fraction 💙 0.87339 m^3/kg 💙           |
| u1 h1   | ✓ Vel1 ✓                              | z1 e1                                 |
| -29.59251 kJ/kg 🌱 57.41154 kJ/kg                          | ✓ 0.0 m/s ✓ 0.0                       | m ↔ <mark>-29.59251 kJ/kg ↔</mark>    |
| jt mt   | Vol1                                  | p_v1 p_a1                             |
| 57.41154 kJ/kg 🖌 kg                                       | ✓ m^3 ✓ 1.707                         | 198 kPa 🗸 99.61702 kPa 🗸              |
| p_g1 RH1  | omega1                                | T_dp1 T_wb1                           |
| 4.246 kPa ❤ 40.22555 %                                    | ✓ 0.01066 kg-H2O/kg-d.a. ✓ 15.0       | deg-C 💙 20.00213 deg-C 💙              |
| m_t1 m_v1   | m_g1                                  |                                       |
| kg 💙 kg   | ✓ kg ✓                                |                                       |

### Thus:

Partial pressure of air = p\_a1 = 99.61702 kPa ... Ans.

Partial pressure of water vapor = p\_v1 = 1.70798 kPa ... Ans.

Sp. humidity = omega1 = 0.01066 kg H2O/kg dry air ... Ans.

Enthalpy of moist air =  $h1 = 57.41154 \text{ kJ/kg} \dots$  Ans.

Vapor density: This is calculated from Ideal Gas Law as follows:

Partial pressure of vapor = 1.70798 kPa

Gas Constant for water vapor = R\_w = 8.314/18 = 0.46189 kJ/kg.K

Therefore: rho\_vap =  $p_v1 / (R_w * (30 + 273)) = 0.0122 \text{ kg/m^3} \dots \text{Ans.}$ 

#

# 4. Clicking on SuperCalc gives TEST code etc:

#~~~~~OUTPUT OF SUPER-CALCULATE

| #      | TESTcalc Path: Systems>Closed>Process>Specific>HVAC; v-10.ce01;                          |
|--------|--|
| #      | Start of TEST-code   |
| States | {  |
|        | State-1: MoistAir;   |
|        | Given: { p1= 101.325 kPa; T1= 30.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; T_dp1= 15.0 deg-C; } |
|        | }  |
| #      | End of TEST-code   |

<image><image>

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98

**Psychrometrics** 

| #F    | Property spreads | heet starts: |       |                 |      |            |               |
|-------|------------------|--------------|-------|-----------------|------|------------|---------------|
| State | DBT(K)           | WBT(K)       | DPT(K | ) v(m3/kg-d.a.) | R.H. | h(kJ/kg) C | )mega(kg-H2O/ |
|       |                  |              |       |                 |      | k          | g-d.a.)       |
| # 1   | 303.2            | 293.2        | 288.2 | 0.8734          | 0.4  | 57.4       | 0.0107        |
|       |                  |              |       |                 |      |            |               |

**Prob. 7.5.2** A sling psychrometer reads 40 C DBT and 28 C WBT. Find the following: (i) sp. humidity, (ii) RH, (iii) Dew point temp,and (iv) Vapor density. [VTU]

**TEST Solution:** 

Following are the steps:

Steps 1, 2 and 3 are the same as for previous problem.

Fill up the given parameters i.e. DBT = 40 C and WBT = 28 C in the following screen and hit Enter. We get:

| Mixed C SI C English < Case-0  | ✓ > ✓ Help Messages On | Super-Iterate Super-Calculate | Load Super-Initialize          |
|--------------------------------|------------------------|-------------------------------|--------------------------------|
| State Panel                    | Process Panel          |                               | I/O Panel                      |
|                                |                        |                               |                                |
| < ©State-1 v > Calculate       | No-Plots V Initialize  | MA model: Dry Air+H2O         | MoistAir 🔽                     |
| 🖌 p1 🖌 T1                      | ×1                     | y1                            | V1                             |
| 101.325 kPa 🕥 40.0 deg-        | fraction               | Y fraction                    | ✓ 0.91451 m <sup>3</sup> /kg ✓ |
| u1 h1                          | Vel1                   | 🖌 zt                          | et                             |
| 0.01217 kJ/kg 😪 89.88622 kJ/kg | ✓ 0.0 m/s              | ✓ 0.0 m                       | ✓ 0.01217 kJ/kg ✓              |
| j1 m1                          | Vol1                   | p_v1                          | p_a1                           |
| 89.88622 kJ/kg 🖌 kg            | ✓ m^3                  | ✓ 3.04953 kPa                 | ✓ 98.27547 kPa ✓               |
| p_g1 RH1                       | omega1                 | T_dp1                         | T_wb1                          |
| 7.38722 kPa 💉 41.2812 %        | V 0.0193 kg-H2O/kg-d.  | a. 💉 24.333 deg-C             | ✓ 28.0 deg-C ✓                 |
| m_t1 m_v1                      | m_g1                   |                               |                                |
| kg 💌 kg                        | ₩ kg                   | ¥                             |                                |

Thus:

Sp. humidity = omega1 = 0.01066 kg H2O/kg dry air ... Ans.

RH1 = 41.2812% .... Ans.

Dew Point Temp = T\_dp1 = 24.333 C ... Ans.

Vapor density: This is calculated from Ideal Gas Law as follows:

**Psychrometrics** 

# Partial pressure of vapor = 3.04953 kPa

Gas Constant for water vapor = R\_w = 8.314/18 = 0.46189 kJ/kg.K

Therefore:  $rho_vap = p_v1 / (R_w * (40 + 273)) = 0.0211 \text{ kg/m}^3 \dots \text{ Ans.}$ 

Click on SuperCalculate and get TEST code etc in the I/O panel:

#~~~~~OUTPUT OF SUPER-CALCULATE

# TESTcalc Path: Systems>Closed>Process>Specific>HVAC; v-10.ce01;

#-----Start of TEST-code -----

States {

State-1: MoistAir;

Given: { p1= 101.325 kPa; T1= 40.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; T\_wb1= 28.0 deg-C; }

}

#-----End of TEST-code -----

#\*\*\*\*\*DETAILED OUTPUT: All the computed properties and variables are displayed on this block.\*\*\*\*\*\*\*\*\*\*

# Evaluated States:

| # | State-1: MoistAir > MA-Model;                                       |
|---|---|
| # | Given: p1= 101.325 kPa; T1= 40.0 deg-C; Vel1= 0.0 m/s;              |
| # | z1= 0.0 m; T_wb1= 28.0 deg-C;                                       |
| # | Calculated: v1= 0.9145 m^3/kg; u1= 0.0122 kJ/kg; h1= 89.8862 kJ/kg; |
| # | e1= 0.0122 kJ/kg; j1= 89.8862 kJ/kg; p_v1= 3.0495 kPa;              |
| # | p_a1= 98.2755 kPa; p_g1= 7.3872 kPa; RH1= 41.2812 %;                |
| # | omega1= 0.0193 kg-H2O/kg-d.a.; T_dp1= 24.333 deg-C;                 |

**Psychrometrics** 

| #     | Property spread | sheet sta | rts:    |                |          |          |                           |
|-------|-----------------|-----------|---------|----------------|----------|----------|---------------------------|
| State | DBT(K)          | WBT(      | K) DPT( | K) v(m3/kg-d.a | ı.) R.H. | h(kJ/kg) | Omega(kg-H2O/kg-<br>d.a.) |
| # 1   | 313.2           | 301.2     | 297.5   | 0.9145         | 0.41     | 89.9     | 0.0193                    |

**Prob.7.5.3** A room measures  $5m \times 5m \times 3m$ . It contains atmospheric air at 100 kPa, DBT = 30 C, RH = 30%. Find the mass of dry air and the mass of associated water vapor in the room. [VTU]

**TEST Solution:** 

Following are the steps:

Steps 1, 2 and 3 are the same as for previous problem.



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\* Figures taken from London Business School's Masters in Management 2010 employment report



Fill up the given parameters i.e. p = 100 kPa, DBT = 30 C and RH1 = 30%, and Vol1 = 75 m^3, in the following screen and hit Enter. We get:

| Mixed C SI C Eng            | glish < Case-0 | ▼ > F Help Mess | ages On Super-Ite | erate Super-Calculate | Load        | uper-Initialize |  |  |
|-----------------------------|----------------|-----------------|-------------------|-----------------------|-------------|-----------------|--|--|
| State Pan                   | el             | Pro             | icess Panel       |                       | I/O Panel   |                 |  |  |
|                             |                |                 |                   |                       |             |                 |  |  |
| < <mark>©State-1 v</mark> > | Calculate      | No-Plots        | Initialize MA     | model: Dry Air+H2O    | MoistAir    | ×               |  |  |
| ✓ p1                        | ✓ T1           | ×1              |                   | y1                    | V1          |                 |  |  |
| 100.0 kPa 👻                 | 30.0 deg-(     | c 🖌 🗸           | fraction 💉        | fraction              | √ 0.88127   | m^3/kg 💉        |  |  |
| u1                          | h1             | ✓ Vel1          |                   | ✓ z1                  | e1          |                 |  |  |
| -36.33908 kJ/kg 🗡           | 50.66497 kJ/kg | ✓ 0.0           | m/s 🗸             | 0.0 m                 | ✓ -36.33908 | kJ/kg 💉         |  |  |
| j1                          | m1             | Vol1            |                   | p_v1                  | p_a1        |                 |  |  |
| 50.66497 kJ/kg 🗸            | 85.10483 kg    | ✓ 75.0          | m^3 🗸             | 1.2738 kPa *          | ♥ 98.7262   | kPa 💙           |  |  |
| p_g1                        | ✓ RH1          | omega1          |                   | T_dp1                 | T_wb1       |                 |  |  |
| 4.246 kPa ❤                 | 30.0 %         | ✓ 0.00803       | kg-H2O/kg-d.a. 💉  | 10.53393 deg-C        | ₩ 17.78852  | deg-C 💉         |  |  |
| m_t1                        | m_v1           | m_g1            |                   |                       |             |                 |  |  |
| 85.78782 kg 🛩               | 0.68299 kg     | ✓ 2.27663       | kg 💉              |                       |             |                 |  |  |

Thus:

Mass of dry air in the room = m1 = 85.10483 kg .... Ans.

Mass of water vapor =  $m_v 1 = 0.68299 \text{ kg} \dots \text{ Ans.}$ 

Also, total mass = m\_t1 = 85.78782 kg ... Ans.

5. From the Plots widget, choose Psychro Plot and we get a schematic pf a psychrometric plot with the State point at 30 C DBT and Sp. humidity omega1 = 0.008, shown therein:



# #\*\*\*\*\*DETAILED OUTPUT:

## # Evaluated States:

| # | State-1: MoistAir > MA-Model;   |
|---|---|
| # | Given: p1= 100.0 kPa; T1= 30.0 deg-C; Vel1= 0.0 m/s;                      |
| # | z1= 0.0 m; Vol1= 75.0 m^3; RH1= 30.0 %;                                   |
| # | Calculated: v1= 0.8813 m^3/kg; u1= -36.3391 kJ/kg; h1= 50.665 kJ/kg;      |
| # | e1= -36.3391 kJ/kg; j1= 50.665 kJ/kg; m1= 85.1048 kg;                     |
| # | p_v1= 1.2738 kPa; p_a1= 98.7262 kPa; p_g1= 4.246 kPa;                     |
| # | omega1= 0.008 kg-H2O/kg-d.a.; T_dp1= 10.5339 deg-C; T_wb1= 17.7885 deg-C; |
| # | m_t1= 85.7878 kg; m_v1= 0.683 kg; m_g1= 2.2766 kg;                        |
| # | Property spreadsheet starts:  |
|   |   |

| State | DBT(F | K) WBT(K) | DPT(K | (m3/kg-d.a.) | ) R.H. | h(kJ/kg) Omega(kg-H2O/kg-d.a.) |       |  |
|-------|-------|-----------|-------|--------------|--------|--------------------------------|-------|--|
| # 1   | 303.2 | 290.9     | 283.7 | 0.8813       | 0.3    | 50.7                           | 0.008 |  |

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**Prob.7.5.4** As a result of adiabatic saturation of moist air in a steady flow device at a constant pressure of 96 N/m<sup>2</sup>, the temp of moist air at initial condition from 32 C is reduced to 22 C at sat. condition. Calculate the RH of moist air at the initial condition.[VTU]

# **TEST Solution:**

# Following are the steps:

# Steps 1, and 2 are the same as for problem 7.5.1.

3. Fill up the given parameters i.e. p = 0.096 kPa, DBT = 32 C and Wet bulb temp,T\_wb1 = T\_wb2 (yet to be determined) in the following screen and hit Enter. We get:

| • Mixed C  | SI CI | Engl | lish | < Cas          | e-0 🗸 | >     | •   | Help Mess | ages On       | Super-Iter | ate       | Super-Calcula | te | Lo    | ad     | Super-Initial | ize |
|------------|-------|------|------|----------------|-------|-------|-----|-----------|---------------|------------|-----------|---------------|----|-------|--------|---------------|-----|
|            | State | Pane | ł    |                |       |       |     | Pro       | cess Panel    |            |           |               |    | I/O F | anel   |               |     |
|            |       |      |      |                |       |       |     |           |               |            |           |               |    |       |        |               |     |
| < ©State-1 | ¥ >   |      | Cal  | <b>iculate</b> | No-   | Plots | 3   | ~         | Initialize    | MA n       | nodel: Dr | y Air+H2O     |    | Мо    | istAir | ×             |     |
| 🖌 p1       |       |      | -    | T1             |       |       |     | x1        |               |            | y1        |               |    |       | V1     |               |     |
| 0.096      | kPa   | ~    | 32.0 |                | deg-C | ~     |     |           | fraction      | <b>∽</b> [ |           | fraction      | ~  |       |        | m^3/kg        | ~   |
| u1         |       |      | 1    | h1             |       |       | -   | Vel1      |               |            | < z1      |               |    |       | e1     |               |     |
|            | kJ/kg | ~    |      | 1              | kJ/kg | ~     | 0.0 |           | m/s           | × (        | ).0       | m             | ~  |       |        | kJ/kg         | ~   |
| j†         |       |      | 1    | m1             |       |       |     | Vol1      |               |            | P_1       | 11            |    |       | p_a1   |               |     |
|            | kJ/kg | ~    |      |                | kg    | ~     |     |           | <i>m</i> ^3   | <b>~</b> [ |           | kPa           | ~  |       |        | kPa           | ~   |
| p_g1       |       |      | 1    | RH1            |       |       |     | omega1    |               |            | T_0       | dp1           |    | 1     | T_wb1  | r .           |     |
| 4.75807    | kPa   | *    |      | 9              | %     | ~     |     |           | kg-H2O/kg-d.a | e. 💌 🗸     |           | deg-C         | ~  | =T_\  | vb2    | deg-C         | ~   |
| m_t1       |       |      | 1    | m_v1           |       |       |     | m_g1      |               |            |           |               |    |       |        |               |     |
|            | kg    | *    |      |                | kg    | ~     |     |           | kg            | *          |           |               |    |       |        |               |     |

4. Go to State 2: Enter p2 = p1, T2 = 22 C, RH2 = 100 % (since saturated) and hit Enter. We get:

| Move mouse over a variable to display its value with more precision. |                  |                         |                              |                                  |  |  |  |  |
|--|------------------|-------------------------|------------------------------|----------------------------------|--|--|--|--|
| Mixed O SI O Eng   | glish < Case-0 v | > Field Messages On     | Super-Iterate Super-Calculat | te Load Super-Initialize         |  |  |  |  |
| State Pan  | nel              | Process Panel           |                              | I/O Panel                        |  |  |  |  |
|  |                  |                         |                              |                                  |  |  |  |  |
| < <mark>©State-2 V</mark> >  | Calculate No-    | Plots 🗸 Initialize      | MA model: Dry Air+H2O        | MoistAir 🗸 🗸                     |  |  |  |  |
| ✓ p2   | ✓ T2             | x2                      | y2                           | v2                               |  |  |  |  |
| =p1 kPa 👻  | 22.0 deg-C       | fraction                | ✓ fraction                   | ✓ -33.23818 m <sup>3</sup> /kg ✓ |  |  |  |  |
| u2   | h2               | ✓ Vel2                  | ✓ z2                         | e2                               |  |  |  |  |
| -1703.12 kJ/kg 💙   | -1618.412 kJ/kg  | ▶ 0.0 m/s               | ✓ 0.0 m                      | ✓ -1703.12 kJ/kg ✓               |  |  |  |  |
| j2   | m2               | Vol2                    | p_v2                         | p_a2                             |  |  |  |  |
| -1618.412 kJ/kg 💙  | kg               | ✓ m^3                   | ✓ 2.64452 kPa                | ✓ -2.54852 kPa ✓                 |  |  |  |  |
| p_g2   | ✓ RH2            | omega2                  | T_dp2                        | T_wb2                            |  |  |  |  |
| 2.64452 kPa ♥  | 100.0 %          | ✓ -0.64543 kg-H2O/kg-d. | a. 🗙 21.99999 deg-C          | ✓ 21.99937 deg-C ✓               |  |  |  |  |
| m_t2   | v2               | m_g2                    |                              |                                  |  |  |  |  |
| kg 💙   | kg               | ✓ kg                    | × .                          |                                  |  |  |  |  |

5. Click on SuperCalculate. All calculations are now up-dated and the value of T\_wb2 is posted back to State 1, and RH1 is also calculated. Go back to State 1 and read the value of RH1:

| Move mouse over a variable to display its value with more precision. |                        |                              |                                   |  |  |  |  |  |  |  |
|--|------------------------|------------------------------|-----------------------------------|--|--|--|--|--|--|--|
| • Mixed • SI • English < ©Cas  | e-0 ▼ >                | Super-Iterate Super-Calculat | Load Super-Initialize             |  |  |  |  |  |  |  |
| State Panel  | Process Panel          |                              | I/O Panel                         |  |  |  |  |  |  |  |
|  |                        |                              |                                   |  |  |  |  |  |  |  |
| < State-1 > Calculate  | No-Plots 🗸 Initialize  | MA model: Dry Air+H2O        | MoistAir 🗸 🗸                      |  |  |  |  |  |  |  |
| 🖌 p1 🖌 T1  | x1                     | y1                           | vt                                |  |  |  |  |  |  |  |
| 0.096 kPa 💙 32.0 d   | ig-C 💙 fraction        | ✓ fraction                   | ✓ -33.41192 m <sup>*</sup> 3/kg ✓ |  |  |  |  |  |  |  |
| ut ht  | ✓ Vel1                 | 🖌 z1                         | e1                                |  |  |  |  |  |  |  |
| -1705.9922 kJ/kg ❤ -1618.4142 kJ                                     | kg 🕑 0.0 m/s           | 🗙 0.0 m                      | ✓ -1705.9922 kJ/kg ✓              |  |  |  |  |  |  |  |
| j1 m1  | Vol1                   | p_v1                         | p_81                              |  |  |  |  |  |  |  |
| -1618.4142 kJ/kg ❤   | ŋ ♥ m^3                | ✓ 2.71716 kPa                | ✓ -2.62116 kPa ✓                  |  |  |  |  |  |  |  |
| p_g1 RH1   | omega1                 | T_dp1                        | ✓ T_wb1                           |  |  |  |  |  |  |  |
| 4.75807 kPa ♥ 57.10634 %   | ✓ -0.64478 kg-H2O/kg-d | .a. 💙 22.42672 deg-C         | ✓ =T_wb2 deg-C ✓                  |  |  |  |  |  |  |  |
| m_t1m_v1   | m_g1                   |                              |                                   |  |  |  |  |  |  |  |
| kg 🗸 k   | 7 👻 kg                 | ~                            |                                   |  |  |  |  |  |  |  |

We get: RH1 = 57.11% ... Ans.

6. Go to I/O panel to get the TEST code etc:

#~~~~OUTPUT OF SUPER-

# # TESTcalc Path: Systems>Closed>Process>Specific>HVAC; v-10.ce02;

#-----Start of TEST-code -----

States {

State-1: MoistAir;

Given: { p1= 0.096 kPa; T1= 32.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; T\_wb1= "T\_wb2" deg-C; }

State-2: MoistAir;

Given: { p2= "p1" kPa; T2= 22.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; RH2= 100.0 %; }

}

#-----End of TEST-code -----

#----Property spreadsheet starts: The following property table can be copied onto a spreadsheet (such as Excel) for further analysis or plots. ------

| State | DBT(K) | WBT(K) | DPT(K | ) v(m3/kg-d.a.) | R.H. | h(kJ/kg) | Omega(kg-H2O/kg-d.a.) |
|-------|--------|--------|-------|-----------------|------|----------|-----------------------|
| # 1   | 305.2  | 295.1  | 295.6 | -33.4119        | 0.57 | -1618.4  | -0.6448               |
| # 2   | 295.2  | 295.1  | 295.1 | -33.2382        | 1.0  | -1618.4  | -0.6454               |

Note that for the above problem, pressure was not atmospheric, but 96 Pa.

\_\_\_\_\_

**Prob.7.5.5** Moist air enters a humidifier-heater unit at 26 C and 80% RH. It is to leave at 26 C and 50% RH. For a flow rate of 0.47 m^3/s, find the refrigeration in tons and the heating required in kW. [VTU]

# **TEST Solution:**

First, the air is cooled at const. sp. humidity to reduce the RH to 50% (process 1-3), and then heated at const. sp. humidity to 26 C.(process 3-2)





# Following are the steps:



1. From the TESTCalcs tree, choose Open System-Psychrometry:

2. Hovering the mouse pointer over Psychrometry gives following explanatory pop-up:


Click on Psychrometry, and we get the following window with moist air as default material.
 Fill up the data for state 1, i.e. T1 = 26 C, Voldot1 = 0.47 m<sup>3</sup>/s, RH1 = 80%, and hit Enter.
 We get:

| Move mouse over a variable to di | splay its value with more | precision.               |                 |                       |             |                  |
|----------------------------------|---------------------------|--------------------------|-----------------|-----------------------|-------------|------------------|
| Mixed O SI O Eng                 | glish < ©Case-0           | ▼ > F Help N             | lessages On Sup | super-Calculate       | Load        | Super-Initialize |
| State Par                        | nel                       |                          | Device Panel    |                       | I/O Panel   |                  |
|                                  |                           |                          |                 |                       |             |                  |
|                                  |                           |                          |                 |                       |             |                  |
| < OState-1 V >                   | Calculate                 | No-Plots                 | Initialize      | MA model: Dry Air+H2O | MoistAir    | ~                |
| 🖌 p1                             | 🖌 T1                      | xt                       |                 | y1                    | V1          |                  |
| 101.325 kPa 🛩                    | 26.0 deg-C                |                          | fraction 💙      | fraction              | ✓ 0.87051   | m^3/kg 💙         |
| u1                               | ht                        | ✓ Vel1                   |                 | 21                    | e1          |                  |
| -16.35266 kJ/kg ↔                | 69.50339 kJ/kg            | ▶ 0.0                    | m/s 💉 🚺         | .0 m                  | ✓ -16.35266 | kJ/kg 💉          |
| jf                               | mdot1                     | <ul> <li>Vold</li> </ul> | ot1             | A1                    | p_v1        |                  |
| 69.50339 kJ/kg 💙                 | 32.39468 kg/min           | n 💙 0.47                 | m^3/s 🛛 🖌       | 7000.0 m^2            | ✓ 2.69807   | kPa 💙            |
| p_a1                             | p_g1                      | ✓ RH1                    | 1               | omega1                | T_dp1       |                  |
| 98.62693 kPa 🛩                   | 3.37259 kPa               | ₩ 80.0                   | % 🖌 🛛           | .01702 kg-H20/kg-d.a. | ✓ 22.31454  | deg-C 💙          |
| T_wb1                            | mdot_t1                   | mdot                     | _v1             | mdot_g1               |             |                  |
| 23.30707 deg-C ♥                 | 32.9459 kg/min            | n 🛛 🖌 0.55122            | kg/min 🛛 🖌 🛛    | .68902 kg/min         | ~           |                  |

4. Go to State 2, i.e. final state. Fill up T2 = T1, mdot2 = mdot1(since dry air mass rate does not change), and RH2 = 50%. Hit Enter. We get:

| Move mouse over a variable to disp | play its value with more pr | recision.  |                    |                     |             |                  |
|------------------------------------|-----------------------------|------------|--------------------|---------------------|-------------|------------------|
| • Mixed C SI C Engl                | ish < ©Case-0 >             | ▼ >        | ages On Super-Iter | ate Super-Calculate | Load        | Super-Initialize |
| State Pane                         | H                           | D          | evice Panel        |                     | I/O Panel   |                  |
|                                    |                             |            |                    |                     |             |                  |
|                                    |                             |            |                    |                     |             |                  |
| < ©State-2 🗸 >                     | Calculate N                 | lo-Plots 🔽 | Initialize MA n    | nodel: Dry Air+H2O  | MoistAir    | <b>~</b>         |
| ✓ p2                               | ✓ T2                        | x2         | y                  | 2                   | v2          |                  |
| 101.325 kPa 💉                      | 26.0 deg-C                  | ✓          | fraction 💉         | fraction            | ✓ 0.86167   | m^3/kg 💉         |
| u2                                 | h2                          | ✓ Vel2     | 1                  | z2                  | e2          |                  |
| -32.89295 kJ/kg 💉                  | 52.9631 kJ/kg               | 0.0        | m/s 💉 0.0          | m                   | ✓ -32.89295 | kJ/kg 💉          |
| j2                                 | ✓ mdot2                     | Voldot2    | A                  | 12                  | p_v2        |                  |
| 52.9631 kJ/kg 💙                    | =mdot1 kg/min               | ✓ 27.91364 | m^3/min ₩ 46522.7  | 742 m^2             | ✓ 1.68629   | kPa 🗸            |
| p_a2                               | p_g2                        | 🖌 RH2      | c                  | omega2              | T_dp2       | 18.1             |
| 99.63871 kPa 🛩                     | 3.37259 kPa                 | ❤ 50.0     | % 💙 0.01053        | kg-H2O/kg-d.a.      | ✓ 14.80291  | deg-C 💙          |
| T_wb2                              | mdot_t2                     | mdot_v2    | n                  | ndot_g2             |             |                  |
| 18.64234 deg-C ❤                   | 32.73569 kg/min             | ♥ 0.34101  | kg/min 💉 0.68202   | 2 kg/min            | *           |                  |

5. Go to State 3, i.e. state after cooling. Fill up omega3 = omega2 (since the sp. humidity, omega remains const. during heating), mdot3 = mdot1, RH3 = 100%, since condensation has occurred. Hit Enter, and we get:

| Move mouse over a variable to dis | splay its value with more       | precision.      |                   |                       |           |                  |
|-----------------------------------|---------------------------------|-----------------|-------------------|-----------------------|-----------|------------------|
| Mixed C SI C Eng                  | glish <mark>&lt;</mark> ©Case-0 | ✓ > ✓ Help Mess | ages On Super-Ite | erate Super-Calculate | Load      | Super-Initialize |
| State Pan                         | nel                             | De              | evice Panel       |                       | I/O Panel |                  |
|                                   |                                 |                 |                   |                       |           |                  |
| < ©State-3 💙 >                    | Calculate                       | No-Plots        | Initialize MA     | model: Dry Air+H2O    | MoistAir  | <b>~</b>         |
| ✓ p3                              | T3                              | x3              |                   | у3                    | v3        |                  |
| 101.325 kPa 😽                     | 14.80291 deg-0                  | . 🖌             | fraction 💙        | fraction              | 0.82942   | m^3/kg 💉         |
| u3                                | h3                              | ✓ Vel3          | ×                 | z3                    | e3        |                  |
| -41.14771 kJ/kg 🗸                 | 41.49477 kJ/kg                  | ✓ 0.0           | m/s 💉 0.0         | m 💌                   | -41.14771 | kJ/kg 💉          |
| j3                                | 🖌 mdot3                         | Voldot3         |                   | A3                    | p_v3      |                  |
| 41.49477 kJ/kg 🗸                  | =mdot1 kg/mir                   | 26.86884        | m^3/min ❤ 44781   | .41 m^2 💉             | 1.68629   | kPa 🗸            |
| p_a3                              | p_g3                            | 🖌 RH3           | ×                 | omega3                | T_dp3     |                  |
| 99.63871 kPa 💉                    | 1.68629 kPa                     | ✓ 100.0         | % 💉 =omeg         | ga2 kg-H2O/kg-d.a. 🗸  | 14.80291  | deg-C 💉          |
| T_wb3                             | mdot_t3                         | mdot_v3         |                   | mdot_g3               |           |                  |
| 14.80291 deg-C 🗸                  | 32.73569 kg/min                 | 0.34101         | kg/min 🛛 💙 0.3410 | )1 kg/min 😽           |           |                  |

Note that T3 = 14.8 C, i.e. air is cooled to 14.8 C in the refrigeration unit.... Ans.

Amount of water vapor removed = (mdot\_v1 - mdot\_v3) = 0.21021 kg/min. ... Ans.



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6. Go to Device panel. For Device A (i.e. cooling unit), fill up State 1 and State 3 for i-1 state and e1-state, Wdot\_ext = 0. Hit Enter. We get:



Note that refrigeration (negative since heat is going out of system) is chosen in tons and is equal to -15.122 kW = 4.3 tons, (since 1 ton of refrogeration = 211 kJ/min) ... Ans.

7. Go to Device B (i.e. heating unit). Fill up State 3 and State 2 for i-1 state and e1-state, Wdot\_ext = 0. Hit Enter. We get:

| Move mouse over a variable to display its v | value with more precision. |                        |                 |                       |
|---|----------------------------|------------------------|-----------------|-----------------------|
| • Mixed C SI C English                      | < ©Case-0 v >              | ✓ Help Messages On Sup | Super-Calculate | Load Super-Initialize |
| State Panel                                 |                            | Device Panel           |                 | I/O Panel             |
| Device-B [3-2]                              | Calculate                  | Initialize             | Generic Device  | e Cooling Tower       |
| i1-State: State-3 💌                         | i2-State: State-Null       | e1-State: Stat         | te-2 💌 e2-Sta   | te: State-Null 🐱      |
| Qdot  |                            | ✓ Wdot_e               | ext             |                       |
| 6.19188                                     | kW                         | ▶ 0.0                  | kW              | *                     |

We get: heat supplied in heater unit = Qdot = 6.192 kW .... Ans.



#### 8. Choosing Psychro Plots from Plots widget, gives the State points on the psychrometric chart;

9. Click on SupeCalculate and get the TEST code etc from the I/O panel:

#~~~~~OUTPUT OF SUPER-CALCULATE

# TESTcalc Path: Systems>Open>SteadyState>Specific>HVAC; v-10.ce02;

#-----Start of TEST-code -----

States {

State-1: MoistAir;

Given: { p1= 101.325 kPa; T1= 26.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; Voldot1= 0.47 m^3/s; RH1= 80.0 %; }

State-2: MoistAir;

Given: { p2= 101.325 kPa; T2= 26.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= "mdot1" kg/min; RH2= 50.0 %; }

State-3: MoistAir;

Given: { p3= 101.325 kPa; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= "mdot1" kg/min; RH3= 100.0 %; omega3= "omega2" kg-H2O/kg-d.a.; }

**Psychrometrics** 

}

Analysis

Device-A: i-State = State-1; e-State = State-3; CoolingTower: false;

Given: { Wdot\_ext= 0.0 kW; }

{

Device-B: i-State = State-3; e-State = State-2; CoolingTower: false;

Given: { Wdot\_ext= 0.0 kW; }

}

#-----End of TEST-code

| State | DBT(K) | WBT(k | K) DPT(K) | v(m3/kg-d.a.) | R.H. | h(kJ/kg) | Omega(kg-H2O/kg-d.a.) |
|-------|--------|-------|-----------|---------------|------|----------|-----------------------|
| # 1   | 299.2  | 296.5 | 295.5     | 0.8705        | 0.8  | 69.5     | 0.017                 |
| # 2   | 299.2  | 291.8 | 288.0     | 0.8617        | 0.5  | 53.0     | 0.0105                |
| # 3   | 288.0  | 288.0 | 288.0     | 0.8294        | 1.0  | 41.5     | 0.0105                |



#### #Analysis

| # | Device-A: i-State = State-1; e-State = State-3; CoolingTower: false; |
|---|--|
| # | Given: Wdot_ext= 0.0 kW;   |
| # | Calculated: Qdot= -15.122171 kW;                                     |
| # | Device-B: i-State = State-3; e-State = State-2; CoolingTower: false; |
| # | Given: Wdot_ext= 0.0 kW;   |
| # | Calculated: <b>Qdot= 6.1918793 kW</b> ;                              |
|   |  |

\_\_\_\_\_

Prob.7.5.6 For a hall to be air conditioned, following conditions are given:

Outdoor condition: 40 C DBT, 20 C WBT

Required comfort condition: 20 C DBT, 60% RH

Seating capacity of hall = 1500; Amount of outdoor air supplied =  $0.3 \text{ m}^3/\text{person}$ 

If the required condition is achieved first by adiabatic humidification and then by cooling, estimate:

- a) capacity of cooling coil in Tons of Refrigeration
- b) capacity of humidifier
- c) condition of air after adiabatic humidification. [VTU]

Note: This is the same as prob. 7.2.7 solved with Mathcad.



Fig.Prob.7.5.6 Adiabatic humidification and heating

#### **TEST Solution:**

#### Following are the steps:



1. From the TESTCalcs tree, choose Open System-Psychrometry:

2. Hovering the mouse pointer over Psychrometry gives following explanatory pop-up:



 Click on Psychrometry, and we get the following window with moist air as default material.
 Fill up the data for state 1, i.e. T1 = 40 C, T\_wb1 = 20 C, Voldot1 = 450 m^3/min, and hit Enter. We get:

| z1 = 0.0 m [Elevation above a datum] |                            |                               |                       |
|--------------------------------------|----------------------------|-------------------------------|-----------------------|
|                                      | e-0 ∨ > ✓ Help Messages On | Super-Iterate Super-Calculate | Load Super-Initialize |
| State Panel                          | Device Panel               |                               | I/O Panel             |
|                                      |                            |                               |                       |
|                                      |                            |                               |                       |
| < ©State-1 > Calculate               | No-Plots 💌 Initialize      | MA model: Dry Air+H2O         | MoistAir 💌            |
| 🖌 p1 🖌 T1                            | x1                         | y/1                           | vi                    |
| 101.325 kPa 💙 40.0                   | seg-C V fraction           | fraction                      | ✓ 0.89652 m^3/kg ✓    |
| ut ht                                | Vel1                       | ✓ z1                          | e1                    |
| -32.47001 kJ/kg ❤ 57.40404 k         | J/kg 🖌 0.0 m/s             | ✓ 0.0 m                       | ✓ -32.47001 kJ/kg ✓   |
| j1 mdot1                             | Voldot1                    | A1                            | p_v1                  |
| 57.40404 kJ/kg 🌱 501.94193 I         | g/min 🖌 450.0 m^3/min      | ✓ 750000.06 m <sup>2</sup>    | ✓ 1.0771 kPa ✓        |
| p_a1p_g1                             | RH1                        | omega1                        | T_dp1                 |
| 100.2479 kPa 💉 7.38722               | kPa 💉 14.58065 %           | ✓ 0.00668 kg-H2O/kg-d.a.      | ✓ 8.06582 deg-C ✓     |
| T_wb1 mdot_t1                        | mdot_v1                    | mdot_g1                       |                       |
| 20.0 deg-C → 505.29642 I             | ig/min 💙 3.35449 kg/min    | ✓ 23.00645 kg/min             | *                     |

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116

4. Go to State 2, i.e. final state. Fill up T2 = 20 C, mdot2 = mdot1(since dry air mass rate does not change), and RH2 = 60%. Hit Enter. We get:

| Move mouse over a variable to display its value with more | precision.                           |  |
|---|--------------------------------------|--|
| • Mixed C SI C English Case-0                             | ✓ > ✓ Help Messages On Supe          | er-Iterate Super-Calculate Load Super-Initialize |
| State Panel   | Device Panel                         | I/O Panel  |
|   |                                      |  |
| < ©State-2 V > Calculate                                  | No-Plots V Initialize                | MA model: Dry Air+H2O MoistAir 🔽                 |
| ✔ p2 ✔ T2   | x2                                   | y2 v2  |
| 101.325 kPa 💙 20.0 deg-0                                  | raction                              | fraction V 0.842 m <sup>A</sup> 3/kg V           |
| u2 h2   | Vel2                                 | z2 e2  |
| -41.8612 kJ/kg 🌱 42.27285 kJ/kg                           | ✓ 0.0 m/s ✓ 0.0                      | 0 m 💙 -41.8612 kJ/kg 💙                           |
| j2 🖌 mdot2  | Voldot2                              | A2 p_v2  |
| 42.27285 kJ/kg 💉 =mdot1 kg/mir                            | ✓ 422.6354 m <sup>*</sup> 3/min ✓ 70 | )4392.4 m <sup>4</sup> 2 Y 1.4034 kPa Y          |
| p_a2 p_g2   | ✓ RH2                                | omega2 T_dp2                                     |
| 99.9216 kPa 👻 2.339 kPa                                   | ↔ 60.0 % ↔ 0.0                       | 00874 kg-H2O/kg-d.a. 💙 12.01431 deg-C 💙          |
| T_wb2 mdot_t2   | mdot_v2                              | mdot_g2  |
| 15.08166 deg-C ❤ 506.32687 kg/mir                         | ✓ 4.38497 kg/min ✓ 7.3               | 30828 kg/min 🗸                                   |

Go to State 3, i.e. state after adiabatic humidification. Fill up omega3 = omega2 (since the sp. humidity, omega remains const. during cooling), mdot3 = mdot1, h3 = h1 (for adiabatic process 1-3). Hit Enter, and we get:

| Move mouse over a variable to di | splay its value with more prec | cision.        |                 |                       |                                 |
|----------------------------------|--------------------------------|----------------|-----------------|-----------------------|---------------------------------|
| Mixed C SI C Eng                 | glish < ©Case-0 v              | > 🔽 Help Messa | ges On Super-It | erate Super-Calculate | Load Super-Initialize           |
| State Par                        | nel                            | Dev            | vice Panel      |                       | I/O Panel                       |
|                                  |                                |                |                 |                       |                                 |
| < <mark>©State-3 v</mark> >      | Calculate No-                  | -Plots 💌       | Initialize MA   | model: Dry Air+H2O    | MoistAir 🗸 🗸                    |
| ✓ p3                             | T3                             | x3             |                 | y3                    | v3                              |
| 101.325 kPa 🛩                    | 34.82221 deg-C                 |                | fraction 🖌      | fraction              | ✓ 0.88457 m <sup>*</sup> 3/kg ✓ |
| u3                               | 🖌 h3                           | Vel3           | ×               | z3                    | e3                              |
| -30.98403 kJ/kg 🗸                | =h1 kJ/kg                      | ♥ 0.0          | m/s 💉 0.0       | m                     | ✓ -30.98403 kJ/kg ✓             |
| <i>j</i> 3                       | ✓ mdot3                        | Voldot3        |                 | A3                    | p_v3                            |
| 57.40404 kJ/kg 💙                 | =mdot1 kg/min                  | ✓ 444.00464    | m^3/min 💉 74000 | 07.8 m^2 *            | ✓ 1.4034 kPa ✓                  |
| p_a3                             | p_g3                           | RH3            | ×               | omega3                | T_dp3                           |
| 99.9216 kPa 🛩                    | 5.57985 kPa                    | ✓ 25.15125     | % 💉 😑           | ga2 kg-H2O/kg-d.a.    | ✓ 12.01431 deg-C ✓              |
| T_wb3                            | mdot_t3                        | mdot_v3        |                 | mdot_g3               |                                 |
| 20.0 deg-C 🗸                     | 506.32687 kg/min               | ✓ 4.38497      | kg/min 💉 17.43  | 439 kg/min 🕚          | ¥                               |

Note that RH3 = 25.15 %, T3 = 34.82 C, i.e. temp of air before it is cooled to 20 C in the refrigeration unit.... Ans.

6. Go to Device panel. For Device A (i.e. humidifying unit), fill up State 1 and State 3 for i-1 state and e1-state, Wdot\_ext = 0, h = 0. Hit Enter. We get:



7. Go to Device B (i.e. cooling unit). Fill up State 3 and State 2 for i-1 state and e1-state, Wdot\_ext = 0. Hit Enter. We get:

| Move mouse over a variable to display its value with more precision. |                         |                     |                 |                       |  |  |
|--|-------------------------|---------------------|-----------------|-----------------------|--|--|
| • Mixed C SI C English   | < Case-0 > F Help Messa | super-Iterate       | Super-Calculate | Load Super-Initialize |  |  |
| State Panel  | De                      | vice Panel          | L D             | O Panel               |  |  |
| Device-B [3-2]   | Calculate Initialize    |                     | Generic Device  | C Cooling Tower       |  |  |
| i1-State: State-3 💌  | i2-State: State-Null 🔽  | e1-State: State-2 💌 | e2-State:       | State-Null 💌          |  |  |
| Qdot   |                         | ✓ Wdot_ext          |                 |                       |  |  |
| -126.58298   | kW                      | • 0.0               | kW              | *                     |  |  |

i.e. Heat removed in cooling unit = Qdot = 126.58 kW (negative, since heat is removed).

OR: we can get in Tons also in TEST:

| Qdot = -126582.98 W [Net heat transfer rate] |                        |                           |                      |                  |  |  |  |
|--|------------------------|---------------------------|----------------------|------------------|--|--|--|
| Mixed C SI C English                         | < ©Case-0 v > V Help N | lessages On Super-Iterate | Super-Calculate Load | Super-Initialize |  |  |  |
| State Panel                                  |                        | Device Panel              | I/O Pan              | el               |  |  |  |
| Device-B [3-2]                               | Calculate Initia       | alize                     | Generic Device       | C Cooling Tower  |  |  |  |
| i1-State: State-3 🗸                          | i2-State: State-Null 💌 | e1-State: State-2 💌       | e2-State: State-N    | ull 💌            |  |  |  |
| Qdot   |                        | ✓ Wdot_ext                |                      |                  |  |  |  |
| -35.99516                                    | ton(refrig)            | 0.0                       | kW                   | *                |  |  |  |

#### i.e. Heat removed in cooling unit = Qdot = 35.995 tons of refrign. (negative, since heat is removed).

- 8. Choosing Psychro Plots from Plots widget, gives the State points on the psychrometric chart;





#### 9. Click on SupeCalculate and get the TEST code etc from the I/O panel:

#~~~~~OUTPUT OF SUPER-CALCULATE

#### # TESTcalc Path: Systems>Open>SteadyState>Specific>HVAC; v-10.ce02;

#-----Start of TEST-code -----

States {

State-1: MoistAir;

Given: { p1= 101.325 kPa; T1= 40.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; Voldot1= 450.0 m^3/min; T\_wb1= 20.0 deg-C; }

State-2: MoistAir;

Given: { p2= 101.325 kPa; T2= 20.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= "mdot1" kg/min; RH2= 60.0 %; }

State-3: MoistAir;

{

Given: { p3= 101.325 kPa; h3= "h1" kJ/kg; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= "mdot1" kg/min; omega3= "omega2" kg-H2O/kg-d.a.; }

#### }

Analysis

Device-A: i-State = State-1; e-State = State-3; CoolingTower: false;

Given: { Qdot= 0.0 kW; Wdot\_ext= 0.0 kW; }

Device-B: i-State = State-3; e-State = State-2; CoolingTower: false;

Given: { Wdot\_ext= 0.0 kW; }

}

#-----End of TEST-code -----

#### #----Property spreadsheet starts:

| State   | DBT(K)   | WBT(K)                | DPT(K)           | v(m3/kg-d.a.)    | R.H.    | h(kJ/kg)    | Omega(kg-H2O/kg-d.a.) |  |
|---------|--|-----------------------|------------------|------------------|---------|-------------|-----------------------|--|
| # 1     | 313.2  | 293.2                 | 281.2            | 0.8965           | 0.15    | 57.4        | 0.0067                |  |
| # 2     | 293.2  | 288.2                 | 285.2            | 0.842            | 0.6     | 42.3        | 0.0087                |  |
| # 3     | 308.0  | 293.2                 | 285.2            | 0.8846           | 0.25    | 57.4        | 0.0087                |  |
|         |  |                       |                  |                  |         |             |                       |  |
| # Analy | ysis   |                       |                  |                  |         |             |                       |  |
| #       |  |                       |                  |                  |         |             |                       |  |
| #       | Device-  | A: i-State = State    | e-1; e-Sta       | te = State-3; Co | olingTo | wer: false; |                       |  |
| #       |  | Given: <b>Qdot=</b> 0 | <b>.0 kW</b> ; V | Vdot_ext= 0.0 k  | W;      |             |                       |  |
| #       |  | Calculated:           |                  |                  |         |             |                       |  |
| #       | Device-B: i-State = State-3; e-State = State-2; CoolingTower: false; |                       |                  |                  |         |             |                       |  |
| #       | Given: Wdot_ext= 0.0 kW;   |                       |                  |                  |         |             |                       |  |
| #       |  | Calculated: Qd        | ot= -126.        | 582985 kW;       |         |             |                       |  |
|         |  |                       |                  |                  |         |             |                       |  |

**Prob.7.5.7** One kg of air (dry basis) at 35 C DBT and 60% RH is mixed with 2 kgof air (dry basis) at 20 C DBT and 13 C DPT. Calculate the sp. humidity and DBT of mixture.

\_\_\_\_\_

#### **TEST Solution:**

#### Here, we use Closed System-Psychrometry daemon (as in Prob.7.5.1):

1. Enter data for State1: m1 = 1 kg, T1 = 35 C DBT, RH1 = 60%. P1 = 101.325 by default. Hit Enter. We get:

| Move mouse over a variable to display its value with more precision. |                                  |                                       |  |  |  |  |  |  |  |  |  |
|--|----------------------------------|---------------------------------------|--|--|--|--|--|--|--|--|--|
| • Mixed C SI C English Case-0  | ► Help Messages On Super-Iterate | Super-Calculate Load Super-Initialize |  |  |  |  |  |  |  |  |  |
| State Panel  | Process Panel                    | I/O Panel                             |  |  |  |  |  |  |  |  |  |
|  |                                  |                                       |  |  |  |  |  |  |  |  |  |
| < State-1 > Calculate  | No-Plots 🗸 Initialize MA mo      | del: Dry Air+H2O MoistAir 🗸 🗸         |  |  |  |  |  |  |  |  |  |
| ✓ p1 ✓ T1  | x1                               | ty t                                  |  |  |  |  |  |  |  |  |  |
| 101.325 kPa 💉 35.0 deg-  | c V fraction V                   | fraction V 0.90296 m*3/kg V           |  |  |  |  |  |  |  |  |  |
| u1 h1  | ✓ Vel1 ✓                         | zi ei                                 |  |  |  |  |  |  |  |  |  |
| 1.81792 kJ/kg ❤ 90.25697 kJ/kg                                       | ✓ 0.0 m/s ✓ 0.0                  | m 💙 1.81792 kJ/kg 🌱                   |  |  |  |  |  |  |  |  |  |
| jt 🖌 mt  | Vol1                             | p_v1p_a1                              |  |  |  |  |  |  |  |  |  |
| 90.25697 kJ/kg 💙 1.0 kg  | ✓ 0.90296 m <sup>3</sup> ✓ 3.381 | 1 kPa 💙 97.9439 kPa 💙                 |  |  |  |  |  |  |  |  |  |
| p_g1 ✓ RH1   | omega1                           | T_dp1T_wb1                            |  |  |  |  |  |  |  |  |  |
| 5.63517 kPa 💉 60.0 %   | ✓ 0.02147 kg-H2O/kg-d.a. ✓ 26.04 | 1394 deg-C 💉 28.07594 deg-C 💉         |  |  |  |  |  |  |  |  |  |
| m_t1m_v1   | m_g1                             |                                       |  |  |  |  |  |  |  |  |  |
| 1.02147 kg ❤ 0.02147 kg  | ✓ 0.03579 kg ✓                   |                                       |  |  |  |  |  |  |  |  |  |

2. For State 2: m2 = 2 kg, T2 = 20 C, T\_dp2 = 13 C. Hit Enter. We get:

| Move mouse over a variable to dis | splay its value with more | precision.      |                     |                    |             |                  |
|-----------------------------------|---------------------------|-----------------|---------------------|--------------------|-------------|------------------|
| Mixed C SI C Eng                  | jlish < Case-0            | ▼ > ▼ Help Mess | ages On Super-Itera | te Super-Calculate | Load        | Super-Initialize |
| State Pane                        | el                        | Pro             | cess Panel          |                    | I/O Panel   |                  |
|                                   |                           |                 |                     |                    |             |                  |
| < ©State-2 V >                    | Calculate                 | No-Plots 💌      | Initialize MA       | model: Dry Air+H2O | MoistAir    | <b>v</b>         |
| ✓ p2                              | ✓ T2                      | x2              |                     | y2                 | v2          |                  |
| 101.325 kPa 🗸                     | 20.0 deg-                 | c 🖌             | fraction 💌          | fraction           | ♥ 0.84282   | m^3/kg 💌         |
| u2                                | h2                        | ✓ Vel2          |                     | z2                 | e2          |                  |
| -40.31245 kJ/kg 💙                 | 43.8216 kJ/kg             | ✓ 0.0           | m/s 💉 0.            | .0 m               | ✓ -40.31245 | kJ/kg 💌          |
| j2                                | 🖌 m2                      | Vol2            |                     | p_v2               | p_a2        | 2                |
| 43.8216 kJ/kg ₩                   | 2.0 kg                    | ▶ 1.68563       | m^3 🔰 1             | 49998 kPa          | ♥ 99.82502  | kPa 🗸            |
| p_g2                              | RH2                       | omega2          |                     | T_dp2              | T_wi        | b2               |
| 2.339 kPa 🗸                       | 64.12889 %                | ✓ 0.00935       | kg-H2O/kg-d.a. 💽 1  | 3.0 deg-C          | ✓ 15.63624  | deg-C 💌          |
| t2                                | v2                        | m_g2            |                     |                    |             |                  |
| 2.01869 kg 💙                      | 0.01869 kg                | ✓ 0.02915       | kg 🗸                |                    |             |                  |

3. For State 3, enter known data: m3 = m1+m2, and hit Enter. We get:

| Mixed C SI C Eng            | glish < Case-0 v | > 🔽 Help Messages On | Super-Iterate Super-Ca | culate Load S   | uper-Initialize |  |  |  |  |  |  |
|-----------------------------|------------------|----------------------|------------------------|---|-----------------|--|--|--|--|--|--|
| State Pan                   | el               | Process Panel        |                        | I/O Panel   |                 |  |  |  |  |  |  |
|                             |                  |                      |                        |   |                 |  |  |  |  |  |  |
| < <mark>©State-3 v</mark> > | Calculate        | No-Plots 🔽 Initializ | e MA model: Dry Air+H2 | D MoistAir  | ~               |  |  |  |  |  |  |
| ✓ p3                        | 73               | x3                   | y3                     | V3  |                 |  |  |  |  |  |  |
| 101.325 kPa 🗸               | deg-C            | fraction             | Y fra                  | tion 💙  | m^3/kg 💉        |  |  |  |  |  |  |
| иЗ                          | h3               | ✓ Vel3               | 🖌 z3                   | e3  |                 |  |  |  |  |  |  |
| kJ/kg 💙                     | kJ/kg            | ✓ 0.0 m/s            | ✓ 0.0 n                | <ul> <li>Image: A state of the state of</li></ul> | kJ/kg 💙         |  |  |  |  |  |  |
| <i>j</i> 3                  | 🖌 m3             | Vol3                 | p_v3                   | p_a3  |                 |  |  |  |  |  |  |
| kJ/kg 💙                     | =m1+m2 kg        | ✓ m^3                | × ki                   | 28 💙  | kPa 💉           |  |  |  |  |  |  |
| p_g3                        | RH3              | omega3               | T_dp3                  | T_wb3   |                 |  |  |  |  |  |  |
| kPa 🗸                       | %                | kg-H2O/kg-d.         | a. 💙 de                | g-C 🗸   | deg-C 💙         |  |  |  |  |  |  |
| m_t3                        | m_v3             | m_g3                 |                        |   |                 |  |  |  |  |  |  |
| kg 💙                        | kg               | ▶ kg                 | *                      |   |                 |  |  |  |  |  |  |

Note that above data was not enough. However, results will be up-dated after we go to Process panel.

4. In the Process panel, foe bA and bB States, enter State 1 and State 2. For, fA state enter State 3. And, for fB state, leave it as Null State, since there is only one final state. Also, W\_ext = 0, Q = 0. Hit Enter. And click on SuperCalculate.







5. Now, all calculations are updated. Go to State 3, and see the results:

| Move mouse over a variable to display its value with mo | re precision.                          |  |
|---|--|--|
| Mixed C SI C English                                    | e-0 v > V Help Messages On Super-Itera | te Super-Calculate Load Super-Initialize |
| State Panel   | Process Panel                          | I/O Panel                                |
|   |  |  |
| < State-3 V > Calculate                                 | No-Plots 💌 Initialize MA               | model: Dry Air+H2O MoistAir 🗸            |
| ✓ p3 T3   | x3                                     | y3 v3                                    |
| 101.325 kPa ❤ 25.09819 de                               | g-C 💌 fraction 💌                       | fraction 💙 0.86296 m^3/kg 👻              |
| u3 h3   | Vel3                                   | ′ z3 ✓ e3                                |
| -26.269 kJ/kg 🌱 59.32849 kJ/                            | kg 💉 0.0 m/s 💌 0.                      | 0 m 💙 -26.268997 kJ/kg 💙                 |
| j3 🖌 🖌 m3   | Vol3                                   | p_v3p_a3                                 |
| 59.32849 kJ/kg ❤ =m1+m2 kg                              | ✓ 2.58889 m <sup>4</sup> 3 ✓ 2.        | 135 kPa 💙 99.19 kPa 💙                    |
| p_g3 RH3  | ✓ omega3                               | T_dp3T_wb3                               |
| 3.19783 kPa ❤ 66.76397 %                                | ✓ 0.013388114 kg-H20/kg-d.a. ✓ 18      | 1.51687 deg-C 💙 20.54536 deg-C 🗸         |
| m_t3 🖌 m_v3   | m_g3                                   |  |
| 3.04016 kg ❤ 0.04016434 kg                              | ✓ 0.06016 kg ✓                         |  |

Thus, for State 3, i.e. for the mixture: T3 = 25.1 C, sp. humidity, omega3 = 0.013388 kg H2O/kg dry air, and RH3 = 66.77% .... Ans..

6. We get from the Plots widget:



#### 7. I/O panel gives the TEST code etc:

| #~~~~~~       | ~~~~~~OUTPUT OF SUPER-CALCULATE  |  |  |  |  |  |  |  |  |  |  |  |
|---------------|--|--|--|--|--|--|--|--|--|--|--|--|
| # TEST        | Ccalc Path: Systems>Closed>Process>Specific>HVAC; v-10.ce02;                           |  |  |  |  |  |  |  |  |  |  |  |
| #             | #Start of TEST-code  |  |  |  |  |  |  |  |  |  |  |  |
| States        | 3 {  |  |  |  |  |  |  |  |  |  |  |  |
|               | State-1: MoistAir;   |  |  |  |  |  |  |  |  |  |  |  |
| 60.0 %; }     | Given: { p1= 101.325 kPa; T1= 35.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 1.0 kg; RH1=   |  |  |  |  |  |  |  |  |  |  |  |
|               | State-2: MoistAir;   |  |  |  |  |  |  |  |  |  |  |  |
| 13.0 deg-C; } | Given: { p2= 101.325 kPa; T2= 20.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; m2= 2.0 kg; T_dp2= |  |  |  |  |  |  |  |  |  |  |  |
|               | State-3: MoistAir;   |  |  |  |  |  |  |  |  |  |  |  |
|               | Given: { p3= 101.325 kPa; Vel3= 0.0 m/s; z3= 0.0 m; m3= "m1+m2" kg; }                  |  |  |  |  |  |  |  |  |  |  |  |
|               | }  |  |  |  |  |  |  |  |  |  |  |  |
| Analy         | vsis {   |  |  |  |  |  |  |  |  |  |  |  |
|               | Process-A: b-State = State-1, State-2; f-State = State-3;                              |  |  |  |  |  |  |  |  |  |  |  |
|               | Given: { Q= 0.0 kJ; W_ext= 0.0 kJ; }   |  |  |  |  |  |  |  |  |  |  |  |
|               | }  |  |  |  |  |  |  |  |  |  |  |  |
| #             | End of TEST-code   |  |  |  |  |  |  |  |  |  |  |  |

**Psychrometrics** 

#### #\*\*\*\*\*DETAILED OUTPUT:

#### # Evaluated States:

| # | State-1: MoistAir > MA-Model;  |
|---|--|
| # | Given: p1= 101.325 kPa; T1= 35.0 deg-C; Vel1= 0.0 m/s;                     |
| # | z1= 0.0 m; m1= 1.0 kg; RH1= 60.0 %;  |
| # | Calculated: v1= 0.903 m^3/kg; u1= 1.8179 kJ/kg; h1= 90.257 kJ/kg;          |
| # | e1= 1.8179 kJ/kg; j1= 90.257 kJ/kg; Vol1= 0.903 m^3;                       |
| # | p_v1= 3.3811 kPa; p_a1= 97.9439 kPa; p_g1= 5.6352 kPa;                     |
| # | omega1= 0.0215 kg-H2O/kg-d.a.; T_dp1= 26.0439 deg-C; T_wb1= 28.0759 deg-C; |
| # | m_t1= 1.0215 kg; m_v1= 0.0215 kg; m_g1= 0.0358 kg;                         |
| # | State-2: MoistAir > MA-Model;  |
| # | Given: p2= 101.325 kPa; T2= 20.0 deg-C; Vel2= 0.0 m/s;                     |
| # | z2= 0.0 m; m2= 2.0 kg; T_dp2= 13.0 deg-C;                                  |
| # | Calculated: v2= 0.8428 m^3/kg; u2= -40.3124 kJ/kg; h2= 43.8216 kJ/kg;      |
| # | e2= -40.3124 kJ/kg; j2= 43.8216 kJ/kg; Vol2= 1.6856 m^3;                   |
| # | p_v2= 1.5 kPa; p_a2= 99.825 kPa; p_g2= 2.339 kPa;                          |
| # | RH2= 64.1289 %; omega2= 0.0094 kg-H2O/kg-d.a.; T_wb2= 15.6362 deg-C;       |
| # | m_t2= 2.0187 kg; m_v2= 0.0187 kg; m_g2= 0.0292 kg;                         |

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126

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| #  | State-3: MoistAir > MA-Model;                                       |
|----|---|
| #  | Given: p3= 101.325 kPa; Vel3= 0.0 m/s; z3= 0.0 m;                   |
| #  | m3= "m1+m2" kg;   |
| #  | Calculated: T3= 25.0982 deg-C; v3= 0.863 m^3/kg; u3= -26.269 kJ/kg; |
| #  | h3= 59.3285 kJ/kg; e3= -26.269 kJ/kg; j3= 59.3285 kJ/kg;            |
| #  | Vol3= 2.5889 m^3; p_v3= 2.135 kPa; p_a3= 99.19 kPa;                 |
| #  | p_g3= 3.1978 kPa; RH3= 66.764 %; omega3= 0.0134 kg-H2O/kg-d.a.;     |
| #  | T_dp3= 18.5169 deg-C; T_wb3= 20.5454 deg-C; m_t3= 3.0402 kg;        |
| #  | m_v3= 0.0402 kg; m_g3= 0.0602 kg;                                   |
| "D |   |

**#Property Spreadsheet:** 

| State | DBT(K | ) WBT(K) | DPT(K) | v(m3/kg-d.a.) | R.H. | h(kJ/kg) | Omega(kg-H2O/kg-d.a.) |
|-------|-------|----------|--------|---------------|------|----------|-----------------------|
| # 1   | 308.2 | 301.2    | 299.2  | 0.903         | 0.6  | 90.3     | 0.0215                |
| # 2   | 293.2 | 288.8    | 286.2  | 0.8428        | 0.64 | 43.8     | 0.0093                |
| # 3   | 298.2 | 293.7    | 291.7  | 0.863         | 0.67 | 59.3     | 0.0134                |

#### # Analysis

#

- # Process-A: b-State = State-1, State-2; f-State = State-3;
  - Given: Q= 0.0 kJ; W\_ext= 0.0 kJ;

**Prob.7.5.8**. Two air streams are mixed adiabatically. The first stream enters at 32 C, 40% RH at a rate of 20 m^3/min. The second stream enters at 12 C, 90% RH and at a rate of 25 m^3/min. Mixing process occurs at a pressure of 1 atm. Find the sp. humidity, RH, DBT and volume flow rate of the mixture. [Ref:1]



#### Fig.Prob.7.5.8 Adiabatic mixing of two air streams

#### **TEST Solution:**

#### Here, since there is flow, we use the Open-System-Psychrometry daemon (as in Prob.7.5.5)

1. For stream 1, fill in parameters for State 1: i.e. T1 = 32 C, RH1 = 40%, Voldot1 = 20 m^3/ min. Hit Enter. We get:

| z1 = 0.0 m [Elevation above a datum] |                 |                 |                       |                    |           |                  |  |  |  |  |  |
|--------------------------------------|-----------------|-----------------|-----------------------|--------------------|-----------|------------------|--|--|--|--|--|
| Mixed O SI O Eng                     | glish < Case-0  | ▼ > F Help Mess | ages On Super-Iterate | Super-Calculate    | Load      | Super-Initialize |  |  |  |  |  |
| State Par                            | nel             | De              | evice Panel           |                    | I/O Panel |                  |  |  |  |  |  |
|                                      |                 |                 |                       |                    |           |                  |  |  |  |  |  |
|                                      |                 |                 |                       | Dev Alex 1900      |           |                  |  |  |  |  |  |
| < OState-1 V >                       | Calculate       | No-Plots 💌      | Initialize MA model:  | Dry Air+H20        | MoistAir  | ×                |  |  |  |  |  |
| 🖌 p1                                 | 🖌 T1            | X1              | y1                    |                    | V1        |                  |  |  |  |  |  |
| 101.325 kPa 🗸                        | 32.0 deg-C      | ×               | fraction 💙            | fraction           | 0.88087   | m^3/kg 💉         |  |  |  |  |  |
| U1                                   | ht              | ✓ Vel1          | 🖌 z1                  |                    | e1        |                  |  |  |  |  |  |
| -24.93748 kJ/kg 💙                    | 62.64057 kJ/kg  | ▶ 0.0           | m/s 💉 0.0             | m 🗸                | -24.93748 | kJ/kg 💉          |  |  |  |  |  |
| jt                                   | mdot1           | ✓ Voldot1       | A1                    |                    | p_v1      |                  |  |  |  |  |  |
| 62.64057 kJ/kg 💙                     | 22.70472 kg/min | ✓ 20.0          | m^3/min 💉 33333.336   | m^2 🔹              | 1.90323   | kPa 🗸            |  |  |  |  |  |
| p_a1                                 | p_g1            | ✓ RH1           | omega                 | 1                  | T_dp      | 1                |  |  |  |  |  |
| 99.42177 kPa 🗸                       | 4.75807 kPa     | ✓ 40.0          | % 🗸 0.01191           | kg-H2O/kg-d.a. 🛛 👻 | 16.6932   | deg-C 💙          |  |  |  |  |  |
| T_wb1                                | mdot_t1         | mdot_v1         | mdot_g                | 1                  |           |                  |  |  |  |  |  |
| 21.48195 deg-C ♥                     | 22.97507 kg/min | ✓ 0.27034       | kg/min 💉 0.67586      | kg/min 💊           | *         |                  |  |  |  |  |  |

 Similarly, for State 2, i.e. for stream 2: T1 = 12 C, RH2 = 90%, Voldot2 = 25 m^3/min. Hit Enter. We get:

| T2 = 12.0 deg-C [Absolute temperature] |  |                                       |  |  |  |  |  |  |  |  |  |
|--|--|---------------------------------------|--|--|--|--|--|--|--|--|--|
| • Mixed C SI C English < Case-0        | ✓         >         ✓ Help Messages On         Super-Iterate | Super-Calculate Load Super-Initialize |  |  |  |  |  |  |  |  |  |
| State Panel                            | Device Panel   | I/O Panel                             |  |  |  |  |  |  |  |  |  |
|  |  |                                       |  |  |  |  |  |  |  |  |  |
|  |  |                                       |  |  |  |  |  |  |  |  |  |
| < ©State-2 V > Calculate               | No-Plots V Initialize MA model                               | : Dry Air+H2O MoistAir 😪              |  |  |  |  |  |  |  |  |  |
| ✓ p2 ✓ T2                              | x2 y2  | v2                                    |  |  |  |  |  |  |  |  |  |
| 101.325 kPa 💉 12.0 deg                 | c 🔹 🔽 fraction 👻   | fraction V 0.81786 m^3/kg V           |  |  |  |  |  |  |  |  |  |
| u2 h2                                  | ✓ Ve/2 ✓ Z2  | e2                                    |  |  |  |  |  |  |  |  |  |
| -49.98593 kJ/kg ❤ 31.85212 kJ/kg       | ✓ 0.0 m/s ✓ 0.0  | m ✓ <mark>-49.98593 kJ/kg ✓</mark>    |  |  |  |  |  |  |  |  |  |
| j2 mdot2                               | ✓ Voldot2 A2   | p_v2                                  |  |  |  |  |  |  |  |  |  |
| 31.85212 kJ/kg ❤ 30.56744 kg/m         | n 💙 25.0 m^3/min 👻 41666.668                                 | m^2 🗸 1.2618 kPa 🗸                    |  |  |  |  |  |  |  |  |  |
| p_a2 p_g2                              | ✓ RH2 omeg   | a2 T_dp2                              |  |  |  |  |  |  |  |  |  |
| 100.0632 kPa 💉 1.402 kPa               | ✓ 90.0 % ✓ 0.00784   | kg-H2O/kg-d.a. 💙 10.39669 deg-C 💙     |  |  |  |  |  |  |  |  |  |
| T_wb2 mdot_t2                          | mdot_v2 mdot_  | g2                                    |  |  |  |  |  |  |  |  |  |
| 11.07536 deg-C 💉 30.8072 kg/m          | n 🕶 0.23975 kg/min 👻 0.26639                                 | kg/min 🗸                              |  |  |  |  |  |  |  |  |  |

3. For mixture, i.e. State 3, enter known values. i.e. p3 is selected as 101.325 by default, mass of dry air, mdot3 = (mdot1 + mdot2), and hit Enter. We get the following:

| nouse ov   | house over a variable to display its value with more precision. |         |      |                     |         |       |     |           |             |   |               |             |                 |             |   |       |         |              |     |
|------------|---|---------|------|---------------------|---------|-------|-----|-----------|-------------|---|---------------|-------------|-----------------|-------------|---|-------|---------|--------------|-----|
| Mixed      | C SI  | C En    | glis | h < <mark>Ca</mark> | ise-0 🗸 | >     | V   | Help Mess | ages On     |   | Super-Iterate |             | Super-Calculate |             |   | Load  |         | uper-Initial | ize |
|            | S   | tate Pa | nel  |                     |         |       |     | D         | evice Panel |   |               |             |                 |             |   | I/O F | Panel   |              |     |
|            |   |         |      |                     |         |       |     |           |             |   |               |             |                 |             |   |       |         |              |     |
| < ©Stat    | ie-3 🗸  | >       |      | Calculate           | No      | -Plot | s   | ~         | Initialize  |   | Ī             | IA model: E | Dry Air+        | +H20        |   | Mo    | oistAir | ×            | 2   |
| p3         | 112   |         |      | Т3                  |         |       |     | х3        |             |   |               | у3          |                 |             |   |       | v3      |              |     |
| 325        | kPa   | *       |      | al                  | deg-C   | *     |     |           | fraction    | ~ |               |             |                 | fraction    | ~ |       |         | m^3/kg       | *   |
| иЗ         |   |         |      | h3                  |         |       | 1   | Vel3      |             |   | 1             | z3          |                 |             |   |       | e3      |              |     |
|            | kJ/kg   | ~       |      |                     | kJ/kg   | ~     | 0.0 |           | m/s         | ~ | 0.0           |             |                 | m           | ~ |       |         | kJ/kg        | ~   |
| <i>j</i> 3 |   |         | 1    | mdot3               |         |       |     | Voldot3   |             |   |               | A3          |                 |             |   |       | p_v3    |              |     |
|            | kJ/kg   | *       | =n   | ndot1+mdot2         | kg/min  | *     |     |           | m^3/min     | * |               |             |                 | m^2         | ~ |       |         | kPa          | ~   |
| p_a3       |   |         |      | p_g3                |         |       |     | RH3       |             |   |               | omega3      |                 |             |   |       | T_dp3   |              |     |
|            | kPa   | ~       |      |                     | kPa     | ~     |     |           | %           | * |               |             | kg-H            | H2O/kg-d.a. | ~ |       |         | deg-C        | ~   |
| T_wb3      |   |         |      | mdot_t3             |         |       |     | mdot_v3   |             |   |               | mdot_g3     | 3               |             |   |       |         |              |     |
|            | deg-C   | • •     |      |                     | kg/min  | ~     |     |           | kg/min      | ~ |               |             |                 | kg/min      | ~ |       |         |              |     |

Note that data is not enough to calculate all parameters. They will be calculated and posted back when we fill in data in the Device Panel.



4. Go to Device panel. Fill in State 1 and State 2 for i1-state and i-2 state, and State 3 for e1-state, and keep e2-state as Null state, since there is only one exit stream. Further, Wdot\_ext = 0 and Qdot = 0. Hit Enter. WE get:



5. Now, click on SuperCalculate. All calculations are up-dated, and properties for State 3 are posted back there. Go to State 3:

| Move mouse over a variable to display its value with more precision. |              |             |             |               |                  |           |                  |  |  |  |  |
|--|--------------|-------------|-------------|---------------|------------------|-----------|------------------|--|--|--|--|
| • Mixed C SI C English <   | ©Case-0 🗸 >  | 🔽 Help Mess | ages On 🔡   | Super-Iterate | Super-Calculate  | Load      | Super-Initialize |  |  |  |  |
| State Panel  |              | D           | evice Panel |               | 1                | I/O Panel |                  |  |  |  |  |
|  |              |             |             |               |                  |           |                  |  |  |  |  |
| < Calculate  | No-Plo       | ts 💌        | Initialize  | MA model: Dr  | y Air+H2O        | MoistAir  | <b>~</b>         |  |  |  |  |
| 🖌 p3 T3  |              | x3          |             | у3            |                  | V3        | 200              |  |  |  |  |
| 101.325 kPa 💙 20.55852   | deg-C 💙      |             | fraction 💉  |               | fraction 💌       | 0.84473   | m^3/kg 💉         |  |  |  |  |
| u3 h3  |              | ✓ Vel3      |             | 🖌 z3          |                  | e3        |                  |  |  |  |  |
| -39.32018 kJ/kg 💙 44.97423   | kJ/kg 💙      | 0.0         | m/s 💙       | 0.0           | m 🗸              | -39.32018 | kJ/kg 💉          |  |  |  |  |
| 🖌 j3 🖌 mdoi  | 3            | Voldot3     |             | A3            |                  | p_v.      | 3                |  |  |  |  |
| 44.97423 kJ/kg 💙 =mdot1+md   | ot2 kg/min 🔽 | 45.00046    | m^3/min 💉   | 75000.77      | m^2 🗸            | 1.53619   | kPa 🗸            |  |  |  |  |
| p_a3 p_g3  |              | RH3         |             | ✓ omega3      |                  | T_d       | 03               |  |  |  |  |
| 99.78881 kPa 🛩 2.42432   | kPa 🗸        | 63.36568    | % 🗸         | 0.009575309   | kg-H2O/kg-d.a. 🗸 | 13.36959  | deg-C 💙          |  |  |  |  |
| T_wb3 mdot_t3  |              | ✓ mdot_v3   |             | mdot_g3       |                  |           |                  |  |  |  |  |
| 16.04465 deg-C 💉 53.78227  | kg/min 💉     | 0.5100975   | kg/min 💌    | 0.80501       | kg/min 👻         |           |                  |  |  |  |  |

Thus:

Sp. humidity of mixture = omega3 = 0.009575 jgH2O/kg dry air ... Ans.

RH of mixture = RH3 = 63.36% ... Ans.

Dry bulb temp = T3 = 20.56 C ... Ans.

Vol. flow rate of mixture = Voldot3 =  $45 \text{ m}^3/\text{min} \dots \text{Ans.}$ 





7. I/O panel gives TEST code etc:

#~~~~~OUTPUT OF SUPER-CALCULATE

# TESTcalc Path: Systems>Open>SteadyState>Specific>HVAC; v-10.ce02;

#-----Start of TEST-code -----

States {

State-1: MoistAir;

Given: { p1= 101.325 kPa; T1= 32.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; Voldot1= 20.0 m^3/min; RH1= 40.0 %; }

State-2: MoistAir;

Given: { p2= 101.325 kPa; T2= 12.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; Voldot2= 25.0 m^3/min; RH2= 90.0 %; }

Applied Thermodynamics: Software Solutions: Part-IV (Psychrometrics, Reactive systems)

**Psychrometrics** 

#### State-3: MoistAir;

#### #\*\*\*\*\*DETAILED OUTPUT:



132

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#### # Evaluated States:

| #  | State-1: MoistAir > MA-Model;  |
|----|--|
| #  | Given: p1= 101.325 kPa; T1= 32.0 deg-C; Vel1= 0.0 m/s;                     |
| #  | z1= 0.0 m; Voldot1= 20.0 m^3/min; RH1= 40.0 %;                             |
| #  | Calculated: v1= 0.8809 m^3/kg; u1= -24.9375 kJ/kg; h1= 62.6406 kJ/kg;      |
| #  | e1= -24.9375 kJ/kg; j1= 62.6406 kJ/kg; mdot1= 22.7047 kg/min;              |
| #  | A1= 33333.336 m^2; p_v1= 1.9032 kPa; p_a1= 99.4218 kPa;                    |
| #  | p_g1= 4.7581 kPa; omega1= 0.0119 kg-H2O/kg-d.a.; T_dp1= 16.6932 deg-C;     |
| #  | T_wb1= 21.482 deg-C; mdot_t1= 22.9751 kg/min; mdot_v1= 0.2703 kg/min;      |
| #  | mdot_g1= 0.6759 kg/min;  |
| #  | State-2: MoistAir > MA-Model;  |
| #  | Given: p2= 101.325 kPa; T2= 12.0 deg-C; Vel2= 0.0 m/s;                     |
| #  | z2= 0.0 m; Voldot2= 25.0 m^3/min; RH2= 90.0 %;                             |
| #  | Calculated: v2= 0.8179 m^3/kg; u2= -49.9859 kJ/kg; h2= 31.8521 kJ/kg;      |
| #  | e2= -49.9859 kJ/kg; j2= 31.8521 kJ/kg; mdot2= 30.5674 kg/min;              |
| #  | A2= 41666.668 m^2; p_v2= 1.2618 kPa; p_a2= 100.0632 kPa;                   |
| #  | p_g2= 1.402 kPa; omega2= 0.0078 kg-H2O/kg-d.a.; T_dp2= 10.3967 deg-C;      |
| #  | T_wb2= 11.0754 deg-C; mdot_t2= 30.8072 kg/min; mdot_v2= 0.2398 kg/min;     |
| #  | mdot_g2= 0.2664 kg/min;  |
| #  | State-3: MoistAir > MA-Model;  |
| #  | Given: p3= 101.325 kPa; Vel3= 0.0 m/s; z3= 0.0 m;                          |
| #  | mdot3= "mdot1+mdot2" kg/min;   |
| #  | Calculated: T3= 20.5585 deg-C; v3= 0.8447 m^3/kg; u3= -39.3202 kJ/kg;      |
| #  | h3= 44.9742 kJ/kg; e3= -39.3202 kJ/kg; j3= 44.9742 kJ/kg;                  |
| #  | Voldot3= 45.0005 m^3/min; A3= 75000.77 m^2; p_v3= 1.5362 kPa;              |
| #  | p_a3= 99.7888 kPa; p_g3= 2.4243 kPa; RH3= 63.3657 %;                       |
| #  | omega3= 0.0096 kg-H2O/kg-d.a.; T_dp3= 13.3696 deg-C; T_wb3= 16.0446 deg-C; |
| #  | mdot_t3= 53.7823 kg/min; mdot_v3= 0.5101 kg/min; mdot_g3= 0.805 kg/min;    |
| #P | Property spreadsheet starts: #   |

| State | DBT(K) | ) WBT(ŀ | K) DPT(K) | v(m3/kg-d.a.) | R.H. | h(kJ/kg) | Omega(kg-H2O/kg-d.a.) |
|-------|--------|---------|-----------|---------------|------|----------|-----------------------|
| # 1   | 305.2  | 294.6   | 289.8     | 0.8809        | 0.4  | 62.6     | 0.0119                |
| # 2   | 285.2  | 284.2   | 283.5     | 0.8179        | 0.9  | 31.9     | 0.0078                |
| # 3   | 293.7  | 289.2   | 286.5     | 0.8447        | 0.63 | 45.0     | 0.0096                |

#### # Analysis

#

# Device-A: i-State = State-1, State-2; e-State = State-3; CoolingTower: false;

Given: Qdot= 0.0 kW; Wdot\_ext= 0.0 kW;

\_\_\_\_\_\_

**Prob.7.5.9** A wet cooling tower is to cool 25 kg/s of water from 40 C to 30 C at a location where the atm. pressure is 96 kPa. Atm. air enters the tower at 20 C and 70% RH and leaves saturated at 35 C. Neglecting the power input to the fan, determine: (a) volume flow rate of air in to the tower, and (b) mass flow rate of required make up water. [Ref: 1]

#### **TEST Solution:**

#### Here, we use the Open-System-Psychrometry daemon (as in Prob.7.5.5)

1. Choose H2O as the working substance, fill in the data for State 1, i.e. water entering the tower: Enter p1 = 96 kPa, T1 = 40 C, mdot1 = 25 kg/s. Hit Enter. We get:

| Nove mouse over a variable to display its value with more precision. |                 |                |              |                |                 |             |                |  |  |
|--|-----------------|----------------|--------------|----------------|-----------------|-------------|----------------|--|--|
| Mixed C SI C Eng   | glish < ©Case-0 | ✓ > ✓ Help Mes | sages On     | Super-Iterate  | Super-Calculate | Load St     | per-Initialize |  |  |
| State Par  | nel             | l l            | Device Panel |                |                 | I/O Panel   |                |  |  |
|  |                 |                |              |                |                 |             |                |  |  |
| < OState-1 V >   | Calculate       | No-Plots 💌     | Initialize   | Subcooled Liqu | uid             | H20         | <b>v</b>       |  |  |
| ✓ p1   | ✓ T1            | x1             |              | y1             |                 | v1          |                |  |  |
| 96.0 kPa 💙   | 40.0 deg-C      | ✓              | fraction 💉   |                | fraction        | ✓ 0.00101   | m^3/kg 💉       |  |  |
| U1   | h1              | ✓ Vel1         |              | 🖌 z1           |                 | e1          |                |  |  |
| 167.56152 kJ/kg 🗸  | 167.65825 kJ/kg | ✓ 0.0          | m/s 🗸        | 0.0            | m               | ✓ 167.56152 | kJ/kg 💉        |  |  |
| jt   | 🖌 mdot1         | Voldot1        |              | A1             |                 | p_v1        |                |  |  |
| 167.65825 kJ/kg 🗸  | 25.0 kg/s       | ✓ 1.51135      | m^3/min 💉    | 2518.9243      | m^2             | <b>~</b>    | kPa 💙          |  |  |
| p_a1   | p_g1            | RH1            |              | omega1         |                 | T_dp1       |                |  |  |
| kPa 🗸  | kPa             | ¥              | %            | K              | g-H2O/kg-d.a.   | ¥           | deg-C 💙        |  |  |
| T_wb1  | mdot_t1         | mdot_v1        |              | mdot_g1        |                 |             |                |  |  |
| deg-C 💙  | kg/min          | ×              | kg/min 💙     |                | kg/min          | ~           |                |  |  |

2. For State 2, i.e. water leaving the tower: Enter  $p_2 = p_1$ ,  $T_2 = 30$  C, hit Enter. We get:

| x2 = | x2 = fraction [Quality]                                      |       |        |           |       |            |        |           |     |           |                |   |           |          |   |
|------|--|-------|--------|-----------|-------|------------|--------|-----------|-----|-----------|----------------|---|-----------|----------|---|
| ¢    | Image: Mixed         C SI         C English         < Case-0 |       |        |           |       |            |        |           |     |           |                |   |           |          |   |
|      |  | Stat  | te Pan | el        |       |            |        | Device Pa | nel |           |                |   | I/O Panel |          |   |
|      |  |       |        |           |       |            |        |           |     |           |                |   |           |          |   |
|      | < @State-  | 2 × > |        | Calcula   | ite   | No-Plots   | ×      | Initiali  | 7e  | Subcoole  | d Liquid       |   | H20       |          |   |
| 1    |  |       | 1      | <u> </u>  |       | THO I TOLO |        |           |     |           |                |   |           |          |   |
| =01  | ρ2   | kPa   | *      | 30.0      | deg-C | v 1        | ×2     | fraction  | ×   | y2        | fraction       | ~ | 0.001     | m^3/kg   | ~ |
|      |  |       |        | 60.0      |       |            | < 1 V/ | 10        |     | · · · · · | 1              |   |           | Los anda |   |
| 125  | .78574   | kJ/kg | ~      | 125.88212 | kJ/kg | ~          | 0.0    | m/s       | *   | 0.0       | m              | ~ | 125.78574 | kJ/kg    | ~ |
|      | i2   |       |        | mdo       | t2    |            | Vo     | dot2      |     | A2        |                |   | D V2      | <u></u>  |   |
| 125  | .88212   | kJ/kg | *      |           | kg/s  | ~          |        | m^3/mir   | , 🗸 |           | <i>m</i> ^2    | ~ |           | kPa      | ~ |
|      | p_a2   |       |        | p_g       | 2     | ĺ          | RH     | 2         |     | omeg      | a2             |   | T_dp      | 2        |   |
|      |  | kPa   | ~      |           | kPa   | ×          |        | %         | ~   |           | kg-H2O/kg-d.a. | ~ |           | deg-C    | ~ |
|      | T_wb2  |       |        | mdot_t2   |       |            | ma     | lot_v2    |     | mdot_     | g2             |   |           |          |   |
|      |  | deg-C | *      |           | kg/mi | 7 🖌        |        | kg/min    | *   |           | kg/min         | * |           |          |   |

3. For State 3, i.e. air entering the tower: Now, change the substance to moist air, enter p3 = 96 kpa, T3 = 20 C, RH3 = 90%, hit Enter. We get:





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135

4. For State 4, i.e. air leaving the tower: enter p4 = p3, T4 = 35 C, RH4 = 100% (since saturated), and mdot4 = mdot3 (since amount of dry air does not change), hit Enter. We get:

| love mouse over a variable to display its value with more precision. |                                   |  |  |  |  |  |  |  |  |
|--|-----------------------------------|--|--|--|--|--|--|--|--|
| Case-0   | ▼ > F Help Messages On Super-Iter | rate Super-Calculate Load Super-Initialize |  |  |  |  |  |  |  |
| State Panel  | Device Panel                      | I/O Panel                                  |  |  |  |  |  |  |  |
|  |                                   |  |  |  |  |  |  |  |  |
|  |                                   |  |  |  |  |  |  |  |  |
| < <mark>©State-4 ∨ &gt; Calculate</mark>                             | No-Plots 💌 Initialize MA r        | nodel: Dry Air+H2O MoistAir 🗸              |  |  |  |  |  |  |  |
| 🖌 p4 🖌 T4  | x4 3                              | v4 v4                                      |  |  |  |  |  |  |  |
| =p3 kPa ❤ 35.0 deg-C   | fraction                          | fraction 💙 0.97869 m^3/kg 💙                |  |  |  |  |  |  |  |
| u4 h4  | ✓ Vel4 ✓                          | z4 e4                                      |  |  |  |  |  |  |  |
| 46.23894 kJ/kg ❤ 134.678 kJ/kg                                       | ✓ 0.0 m/s ✓ 0.0                   | m 🗸 46.23894 kJ/kg 🗸                       |  |  |  |  |  |  |  |
| j4 ✔ mdot4   | Voldot4                           | 14 p_v4                                    |  |  |  |  |  |  |  |
| 134.678 kJ/kg ❤ =mdot3 kg/s  | ▼ m^3/min ▼                       | m^2 ❤ 5.63517 kPa ❤                        |  |  |  |  |  |  |  |
| p_a4 p_g4  | ✓ RH4 0                           | mega4 T_dp4                                |  |  |  |  |  |  |  |
| 90.36483 kPa 💙 5.63517 kPa   | ✓ 100.0 % ✓ 0.0387                | 9 kg-H2O/kg-d.a. 💙 34.99996 deg-C 💙        |  |  |  |  |  |  |  |
| T_wb4 mdot_t4  | mdot_v4 r                         | ndot_g4                                    |  |  |  |  |  |  |  |
| 34.99999 deg-C ✓ kg/min  | kg/min 🗸                          | kg/min 🗸                                   |  |  |  |  |  |  |  |

Amount of mdot4 will be automatically posted later, after we complete the Device panel and SuperCalculate.

5. Now, go to Device panel. **Important: change the radio button to Cooling Tower.** Looking at the schematic of cooling tower given there, fill in i1-State, i2-state e1-state and e2-state carefully. See below. Also, Wdot\_ext = 0 and Qdot = 0. Click Enter. We get:



6. Click on SuperCalculate. Now, all calculations are up-dated and relevant parameters are posted to respective State panels. Go to State 2, and see the following:

| love mouse over a variable to display its value with more precision. |                  |                    |               |                 |             |                |  |  |  |
|--|------------------|--------------------|---------------|-----------------|-------------|----------------|--|--|--|
| • Mixed C SI C English   | < ©Case-0 💙 >    | 🔽 Help Messages On | Super-Iterate | Super-Calculate | Load        | per-Initialize |  |  |  |
| State Panel  |                  | Device Pan         | el            |                 | I/O Panel   |                |  |  |  |
|  |                  |                    |               |                 |             |                |  |  |  |
| < OState-2 V > Cal   | Iculate No-Plots | ✓ Initialize       | Subcooled Lie | quid            | H20         | ~              |  |  |  |
| ✓ p2 ✓   | T2               | x2                 | y2            |                 | v2          |                |  |  |  |
| =p1 kPa 💙 30.0   | deg-C 💌          | fraction           |               | fraction        | ✓ 0.001     | m^3/kg 💉       |  |  |  |
| u2 /   | h2               | Ve/2               | 🖌 z2          |                 | e2          |                |  |  |  |
| 125.78574 kJ/kg 💙 125.88   | 212 kJ/kg 🛛 🗸    | 0.0 m/s            | ✓ 0.0         | m               | ✓ 125.78574 | kJ/kg 🗸 🗸      |  |  |  |
| j2 🖌   | mdot2            | Voldot2            | A2            |                 | p_v2        |                |  |  |  |
| 125.88212 kJ/kg 🝸 1479.0   | 1306 kg/min 💉 🚺  | .48495 m^3/min     | ✓ 2474.9114   | m^2             | • <u> </u>  | kPa 💙          |  |  |  |
| p_a2 /   | p_g2             | RH2                | omega2        |                 | T_dp2       |                |  |  |  |
| kPa 🗸  | kPa 💙            | %                  | ×             | kg-H2O/kg-d.a.  | <b>~</b>    | deg-C 💙        |  |  |  |
| T_wb2 mdo  | ot_t2            | mdot_v2            | mdot_g2       |                 |             |                |  |  |  |
| deg-C 🗸  | kg/min 💙         | kg/min             | ×             | kg/min          | *           |                |  |  |  |

Note that the quantity of water leaving the tower = mdot2 = 1479 kg/min.

7. State 3 shows:

| Nove mouse over a variable to display its value with more precision. |            |                    |               |                  |           |                  |  |  |  |
|--|------------|--------------------|---------------|------------------|-----------|------------------|--|--|--|
| ି Mixed ମ ସା ମି English < <mark>୭୦</mark> :                          | ase-0 💙 >  | 🔽 Help Messages On | Super-Iterate | Super-Calculate  | Load      | Super-Initialize |  |  |  |
| State Panel  |            | Device Panel       |               |                  | I/O Panel |                  |  |  |  |
|  |            |                    |               |                  |           |                  |  |  |  |
| < ©State-3 V > Calculate   | No-Plots   | ✓ Initialize       | MA model: D   | ry Air+H2O       | MoistAir  | ~                |  |  |  |
| 🖌 р3 🖌 Т3  |            | x3                 | y3            |                  | V3        |                  |  |  |  |
| 96.0 kPa 🕑 20.0  | deg-C 💌 🔽  | fraction           | <b>~</b>      | fraction 🗸       | 0.8916    | m^3/kg 💉         |  |  |  |
| u3 h3  |            | Vel3               | 🖌 z3          |                  | e3        |                  |  |  |  |
| -36.64183 kJ/kg 🛛 47.49222   | kJ/kg 🔽 🚺  | ).0 m/s *          | ✓ 0.0         | m 🗸              | -36.64183 | kJ/kg 🛛 👻        |  |  |  |
| j3 🖌 mdot3   |            | Voldot3            | A3            |                  | p_v3      | 3                |  |  |  |
| 47.49222 kJ/kg 💙 749.01965   | kg/min 💉 🧧 | 667.828 m^3/min    | 1113046.8     | m^2 🗸            | 1.6373    | kPa 🗸            |  |  |  |
| p_a3 p_g3  |            | RH3                | omega3        |                  | T_dp      | 03               |  |  |  |
| 94.3627 kPa 💉 2.339  | kPa 💉 🔽    | 70.0 %             | ✓ 0.01079     | kg-H2O/kg-d.a. 💙 | 14.35763  | deg-C 💙          |  |  |  |
| T_wb3 mdot_t3  |            | mdot_v3            | mdot_g3       |                  |           |                  |  |  |  |
| 16.3286 deg-C ❤ 757.10333  | kg/min 🔽 8 | 3.083729 kg/min    | 11.54818      | kg/min 🗸         |           |                  |  |  |  |

Note that Volume of air entering the tower = Voldot  $3 = 667.8 \text{ m}^3/\text{min} = 11.13 \text{ m}^3/\text{s} \dots$  Ans.

#### 8. And, State 4 shows:

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I.All

| Move mouse over a variable to display its value with more precision. |   |   |  |  |  |  |  |  |
|--|---|---|--|--|--|--|--|--|
| Mixed C SI C English Case-0  | ► > F Help Messages On Super-Ite              | arate Super-Calculate Load Super-Initialize |  |  |  |  |  |  |
| State Panel  | Device Panel                                  | I/O Panel                                   |  |  |  |  |  |  |
|  |   |   |  |  |  |  |  |  |
| < ©State-4 V > Calculate   | No-Plots 🗸 Initialize MA                      | model: Dry Air+H2O MoistAir 🗸               |  |  |  |  |  |  |
| ✓ p4 ✓ T4  | x4  | v4 v4                                       |  |  |  |  |  |  |
| =p3 kPa ✓ 35.0 deg-C   | raction                                       | fraction V 0.97869 m^3/kg V                 |  |  |  |  |  |  |
| u4 h4  | ✓ Vel4 ✓                                      | z4 e4                                       |  |  |  |  |  |  |
| 46.23894 kJ/kg ❤ 134.678 kJ/kg                                       | ✓ 0.0 m/s ✓ 0.0                               | m ↔ 46.23894 kJ/kg ↔                        |  |  |  |  |  |  |
| j4 🖌 mdot4   | Voldot4                                       | 44p_v4                                      |  |  |  |  |  |  |
| 134.678 kJ/kg 💙 =mdot3 kg/s  | ✓ 733.0571 m <sup>A</sup> 3/min      ✓ 122176 | 2.0 m⁴2 ❤ 5.63517 kPa ❤                     |  |  |  |  |  |  |
| p_a4 p_g4  | ✓ RH4   | pmega4T_dp4                                 |  |  |  |  |  |  |
| 90.36483 kPa 🛩 5.63517 kPa   | ✓ 100.0 % ✓ 0.0387                            | 9 kg-H2O/kg-d.a. 💙 34.99996 deg-C 💙         |  |  |  |  |  |  |
| T_wb4 mdot_t4  | ✓ mdot_v4                                     | mdot_g4                                     |  |  |  |  |  |  |
| 34.99999 deg-C 🗸 778.07263 kg/min                                    | ✓ 29.05301 kg/min ✓ 29.053                    | 01 kg/min 🗸                                 |  |  |  |  |  |  |

Therefore, make up water required = (mdot4 – mdot3) = 20.97 kg/min = 0.35 kg/s ... Ans.

# Day one and you're ready

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#### 9. I/O panel gives TEST code etc:

#### #~~~~~OUTPUT OF SUPER-CALCULATE

#### # TESTcalc Path: Systems>Open>SteadyState>Specific>HVAC; v-10.ce02;

#-----Start of TEST-code -----

States {

State-1: H2O;

Given: { p1= 96.0 kPa; T1= 40.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 25.0 kg/s; }

State-2: H2O;

Given: { p2= "p1" kPa; T2= 30.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; }

State-3: MoistAir;

Given: { p3= 96.0 kPa; T3= 20.0 deg-C; Vel3= 0.0 m/s; z3= 0.0 m; RH3= 70.0 %; }

State-4: MoistAir;

Given: { p4= "p3" kPa; T4= 35.0 deg-C; Vel4= 0.0 m/s; z4= 0.0 m; mdot4= "mdot3" kg/s; RH4= 100.0 %; }

}

Analysis {

```
Device-A: i-State = State-3, State-1; e-State = State-4, State-2; CoolingTower: true;
```

Given: { Qdot= 0.0 kW; Wdot\_ext= 0.0 kW; }

}

#-----End of TEST-code -----

#### #\*\*\*\*\*DETAILED OUTPUT:

#### **# Evaluated States:**

| # | State-1: H2O > MA-Model;  |
|---|---|
| # | Given: p1= 96.0 kPa; T1= 40.0 deg-C; Vel1= 0.0 m/s;                   |
| # | z1= 0.0 m; mdot1= 25.0 kg/s;  |
| # | Calculated: v1= 0.001 m^3/kg; u1= 167.5615 kJ/kg; h1= 167.6582 kJ/kg; |
| # | e1= 167.5615 kJ/kg; j1= 167.6582 kJ/kg; Voldot1= 1.5114 m^3/min;      |
| # | A1= 2518.9243 m^2;  |
| # | State-2: H2O > MA-Model;  |
| # | Given: p2= "p1" kPa; T2= 30.0 deg-C; Vel2= 0.0 m/s;                   |
| # | z2= 0.0 m;  |
| # | Calculated: v2= 0.001 m^3/kg; u2= 125.7857 kJ/kg; h2= 125.8821 kJ/kg; |
| # | e2= 125.7857 kJ/kg; j2= 125.8821 kJ/kg; mdot2= 1479.0306 kg/min;      |
| # | Voldot2= 1.485 m^3/min; A2= 2474.9114 m^2;                            |
| # | State-3: MoistAir > MA-Model;   |
| # | Given: p3= 96.0 kPa; T3= 20.0 deg-C; Vel3= 0.0 m/s;                   |
| # | z3= 0.0 m; RH3= 70.0 %;   |
| # | Calculated: v3= 0.8916 m^3/kg; u3= -36.6418 kJ/kg; h3= 47.4922 kJ/kg; |
| # | e3= -36.6418 kJ/kg; j3= 47.4922 kJ/kg; mdot3= 749.0196 kg/min;        |



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| #  | Voldot3= 667.828 m^3/min; A3= 1113046.8 m^2; p_v3= 1.6373 kPa;        |
|----|---|
| #  | p_a3= 94.3627 kPa; p_g3= 2.339 kPa; omega3= 0.0108 kg-H2O/kg-d.a.;    |
| #  | T_dp3= 14.3576 deg-C; T_wb3= 16.3286 deg-C; mdot_t3= 757.1034 kg/min; |
| #  | mdot_v3= 8.0837 kg/min; mdot_g3= 11.5482 kg/min;                      |
| #  | State-4: MoistAir > MA-Model;   |
| #  | Given: p4= "p3" kPa; T4= 35.0 deg-C; Vel4= 0.0 m/s;                   |
| #  | z4= 0.0 m; mdot4= "mdot3" kg/s; RH4= 100.0 %;                         |
| #  | Calculated: v4= 0.9787 m^3/kg; u4= 46.2389 kJ/kg; h4= 134.678 kJ/kg;  |
| #  | e4= 46.2389 kJ/kg; j4= 134.678 kJ/kg; Voldot4= 733.0571 m^3/min;      |
| #  | A4= 1221762.0 m^2; p_v4= 5.6352 kPa; p_a4= 90.3648 kPa;               |
| #  | p_g4= 5.6352 kPa; omega4= 0.0388 kg-H2O/kg-d.a.; T_dp4= 35.0 deg-C;   |
| #  | T_wb4= 35.0 deg-C; mdot_t4= 778.0726 kg/min; mdot_v4= 29.053 kg/min;  |
| #  | mdot_g4= 29.053 kg/min;   |
| #  |   |
| #F | Property spreadsheet starts: #  |

| State | DBT(K) | WBT(K) | DPT(K)v(m3/kg | g-d.a.) | R.H. | h(kJ/kg) | Omega(kg-H2O/kg-d.a.) |
|-------|--------|--------|---------------|---------|------|----------|-----------------------|
| # 1   | 313.2  |        |               | 0.001   |      |          | 167.7                 |
| # 2   | 303.2  |        |               | 0.001   |      |          | 125.9                 |
| # 3   | 293.2  | 289.5  | 287.5         | 0.8916  | 0.7  | 47.5     | 0.0108                |
| #4    | 308.2  | 308.1  | 308.1         | 0.9787  | 1.0  | 134.7    | 0.0388                |

#### # Analysis

# Device-A: i-State = State-3, State-1; e-State = State-4, State-2; CoolingTower: true; #

Given: Qdot= 0.0 kW; Wdot\_ext= 0.0 kW;

\_\_\_\_\_\_

#### 7.6 References:

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## 8 Reactive Systems

#### Learning objectives:

- 1. In this chapter, basically, the topic of 'Combustion' is dealt with.
- 2. Combustion requires a fuel, an oxidizer, and the mixture should be brought up to the ignition temp.
- 3. Fuel may be in solid, liquid or gaseous state, and is essentially a hydrocarbon.
- 4. Oxygen is the oxidizer and is generally supplied as air.
- 5. Air contains 21% by volume of oxygen and 79% by volume is nitrogen. Composition by mass is 23% for O2 and 77% for N2.
- 6. Combustion equations are mole equations i.e. by volume.
- 7. When air is supplied for combustion, therefore, each mole of O2 that participates in combustion is accompanied by (79/21) = 3.76 moles of N2.
- 8. Combustion equations are balanced by atoms of each constituent in LHS and RHS.
- 9. Stoichiometric Air-Fuel (AF) ratio, actual AF ratio, percent excess air, equivalence ratio etc are explained.
- 10. Enthalpy of formation of compounds, enthalpy of combustion or enthalpy of reaction are explained.
- 11. Tables of enthalpies of formation and other tables for enthalpies of different species required for combustion calculations are presented.
- 12. Formulas and functions to determine molar sp. heats at constant pressure for different species are also presented.
- 13. First Law for Closed systems and Open systems with reference to combustion are mentioned.
- 14. Heat transfer during combustion and Adiabatic flame temp are explained.
- 15. Also, many useful functions are written in Mathcad and EES and several problems are solved using Mathcad, EES and TEST to illustrate the problem solving techniques in this chapter.

#### 8.1 Definitions, Statements and Formulas used [1–11]:

#### 8.1.1 Requirements of combustion:

Combustion is a chemical reaction during which a fuel is oxidized and energy is released. Thus, for combustion, we need: (i) a fuel, (ii) oxygen, generally supplied as air, and (iii) fuel must be brought above ignition temp.

*Ignition temps*: Petrol ... 260 C, Carbon ... 400 C, Hydrogen ... 580 C, Carbon Monoxide ... 610 C, Methane ... 630 C.

Fuel... may be solid (ex: coal, wood), liquid (ex: petroleum products, or gas (ex: natural gas)

80% of world's fuel is fossil fuels, i.e. hydrocarbons whose main composition is Hydrogen (H2), Carbon (C), Nitrogen (N2), Sulphur (S), ash, moisture etc.

Composition of coal varies depending on geographical location.

Analysis of coal: There are two types: Proximate analysis and Ultimate analysis.

*Proximate analysis* is mainly for moisture content, volatile matter, fixed carbon and ah. Mstly required for commercial purposes.

*Ultimate analysis* is to find percentage of ultimate constituents such as C, H2, O2, N2, S, ash etc. This is mainly required for combustion calculations and research.

#### Typical Ultimate analysis(%) of coal:

| Coal       | с     | Н    | 0     | N+S  | Ash  |
|------------|-------|------|-------|------|------|
| Anthracite | 90.27 | 3.0  | 2.32  | 1.44 | 2.97 |
| Bituminous | 74    | 5.98 | 13.01 | 2.26 | 4.75 |
| Lignite    | 56.52 | 5.72 | 31.89 | 1.62 | 4.25 |

8.1.2 Composition of Air: Generally taken as:

21% oxygen and 79% nitrogen .... by volume, and

23% oxygen and 77% nitrogen .... by mass

## Thus, each volume of oxygen entering a combustion chamber will be accompanied by 79/21 = 3.76 volume of nitrogen.

#### 8.1.3 Combustion equation:

Consider following typical equation:

$$C + O_2 = CO_2$$

This means:

1 mole of Carbon + 1 mole of Oxygen gives 1 mole of Carbon dioxide.
#### LHS is known as 'Reactants' and RHS as 'Products'.

Chemical equations are *mole equations*, i.e. coefficient of each constituent gives its no. of moles.

Since by Avogadro's Law, 1 mole of any Ideal gas occupies the same volume at the same P and T, chemical equations are also *volume equations*, i.e. coeffs give volumes.

#### Balancing the chemical equation:

Remember: no. of atoms of each H, O, N, C, S etc in the LHS should be equal to the numbers in RHS.

Balancing by mass: use the relative atomic mass of each element:

12 kg [C] + 32 kg [O2] = 44 kg [CO2]





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#### Relative atomic masses:

| Substance       | Symbol | Rel. atomic mass | Rel. molecular mass |
|-----------------|--------|------------------|---------------------|
| Carbon          | С      | 12               | -                   |
| Hydrogen        | H2     | 1                | 2                   |
| Oxygen          | 02     | 16               | 32                  |
| Nitrogen        | N2     | 14               | 28                  |
| Sulphur         | S      | 32               | -                   |
| Carbon monoxide | СО     | -                | 28                  |
| Carbon dioxide  | CO2    | -                | 44                  |
| Water           | H2O    | -                | 18                  |

Note: 1 mole = mass of substance / Mol. weight

8.1.4 Air/Fuel ratio (AF): Usually expressed on mass basis.

$$AF = \frac{m_{air}}{m_{fuel}}$$
 = ratio of mass of air to mass of fuel in a combustion process

Fuel-Air ratio = 1/AF

#### Complete and incomplete combustion:

Combustion process is *complete* when all carbon burns to CO2, all hydrogen burns to H2O, and all sulphur burns to SO2.

Combustion process is in*complete* when products contain any un-burnt fuel or components such as C, H, CO, OH.

If a fuel  $C_n H_m$  burns completely in a combustion chamber, we show it as follows:



Hydrogen in fuel normally burns to completion forming H2O since oxygen is more strongly attracted to hydrogen.

Carbon ends up as CO in incomplete combustion.

#### 8.1.5 'Stoichiometric' or 'Theoretical' Air:.

It is the minimum amount of air required for complete combustion of fuel.

#### It is also expressed as 'chemically correct' or '100% theoretical air'.

For example, for complete combustion of Methane (CH4):

CH4 + 2.[O2 + 3.76 N2] = CO2 + 2.H2O + 7.52 N2

In the above, LHS is the Reactants, RHS is the Products.

First term in LHS is fuel, second term is air (i.e. O2 + accompanying N2).

Note that there is no C, H2, CO, OH, or free O2 in products.

**Excess air:** Generally, excess air is supplied to ensure complete combustion (or, to reduce temp of products as in gas turbines). This is expressed in terma of stoichiometric air, as follows:

"50% excess air"  $\rightarrow$  means 150% theoretical air.

"90% Theoretical air"  $\rightarrow$  means 10% deficient air.

#### Equivalence ratio (φ):

It is defined as:

#### 8.1.6 Exhaust gas analysis – Orsat Apparatus:

When combustion is complete, composition of products is easily predicted by writing the combustion eqn. But, in practice, combustion processes are seldom complete, and composition of products is found out by direct measurement. Orsat apparatus is generally used for this purpose.

#### Principle of Orsat apparatus is as follows:

A known volume of products is collected at known P and T. Then, this sample is brought in contact with KOH, which absorbs CO2. Then, the remaining gas is brought back to same P and T and the new volume is measured. Assuming ideal gas behavior, ratio of reduction in volume to original volume gives the mole fraction of CO2 in products.

*For example*, if original P, T, and volume were 100 kPa, 25 C and 1 lit, and after absorption of CO2 the corresponding values were 100 kPa, 25 C and 0.9 lit, then:

Mole fraction of CO2 =  $y_{co2} = 0.1/1 = 0.1$ .

Next, by similar procedure, absorb O2 with pyragollic acid, bring the sample back to original P and T, and find out its mole fraction in products. Then, absorb CO with cuprous chloride and repeat the procedure to find out the mole fraction of CO.

Note that analysis by Orsat apparatus is on 'dry basis', i.e. water vapor is not found out.



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**Reactive Systems** 

#### 8.1.7 Enthalpy of formation:

Consider the steady flow combustion of carbon and oxygen to form CO2. Let the C and O2 enter the combustion chamber at 1 atm. pressure, 25 C, and let the products also leave at 1 atm. and 25 C. In this case, there will be heat transfer **out** of the combustion chamber, as shown below:



Measured value of heat transfer is -393522 kJ/kg mol of CO2 formed.

Applying the I Law to the reaction:

 $H_r + Q = H_p$  where  $H_r$  = enthalpy of reactants,  $H_p$  = enthalpy of products

i.e. 
$$\sum_{\mathbf{r}} \mathbf{n}_{\mathbf{i}} \cdot \mathbf{h}_{\mathbf{i}} + \mathbf{Q} = \sum_{\mathbf{p}} \mathbf{n}_{\mathbf{e}} \cdot \mathbf{h}_{\mathbf{e}}$$

Now, enthalpy of elements in the standard reference state of 25 C, 1 atm is assigned the value of zero. So, in the above reaction  $H_r = 0$ . So, the energy eqn gives:

 $Q = H_p = -393522 \text{ kJ/kg}$  mol. Negative sign indicates an *exothermic reaction*, i.e. heat is released.

#### This is known as enthalpy of formation $(h_{fi})$ of CO2 at 25 C, 1 atm.

Remember that enthalpy of formation for all stable elements such as C, H2, O2, N2 is zero. Enthalpy of formation for several compounds at 1 atm, 25 C, is given in the following Table: (Ref: [9], TEST Software)

| Table G-1,         | Reaction     | s: Enthal      | py of Fo                   | rmation                | Table       |
|--------------------|--------------|----------------|----------------------------|------------------------|-------------|
|                    | SI Units     |                | English Un                 | its                    |             |
| Molar Specific E   | nthalpy of F | ormation, G    | ibbs Functi                | ion of Form            | nation, and |
|                    | Absolute     | Entropy at     | 25°C, 1 atr                | n                      |             |
| Substanco          | Formula      | $\overline{M}$ | $\overline{h}_{f}^{\circ}$ | $\overline{g}_{f}^{o}$ | <u>s</u> °  |
| Substance          | (Phase)      | kg/kmol        | kJ/kmol                    | kJ/kmol                | kJ/kmol∙K   |
| Carbon             | C(s)         | 12.01          | 0                          | 0                      | 5.74        |
| Hydrogen           | H2(g)        | 2.02           | 0                          | 0                      | 130.68      |
| Nitrogen           | N2(g)        | 28.01          | 0                          | 0                      | 191.61      |
| Oxygen             | O2(g)        | 32.00          | 0                          | 0                      | 205.04      |
| Carbon Monoxide    | CO(g)        | 28.01          | -110,530                   | -137,150               | 197.65      |
| Carbon Dioxide     | CO2(g)       | 44.00          | -393,520                   | -394,360               | 213.80      |
| Water Vapor        | H20(g)       | 18.02          | -241,820                   | -228,590               | 188.83      |
| Water              | H20(I)       | 18.02          | -285,820                   | -237,180               | 69.92       |
| Hydrogen Peroxide  | H2O2(g)      | 34.02          | -136,310                   | -105,600               | 232.63      |
| Ammonia            | NH3(g)       | 17.03          | -46,190                    | -16,590                | 192.33      |
| Methane            | CH4(g)       | 16.04          | -74,850                    | -50,790                | 186.16      |
| Acetylene          | C2H2(g)      | 26.04          | 226,730                    | 209,170                | 200.85      |
| Ethylene           | C2H4(g)      | 28.05          | 52,280                     | 68,120                 | 219.83      |
| Ethane             | C2H6(g)      | 30.07          | -84,680                    | -32,890                | 229.49      |
| Propylene          | C3H6(g)      | 42.05          | 20,410                     | 62,720                 | 266.94      |
| Propane            | C3H8(g)      | 44.10          | -103,850                   | -23,490                | 269.91      |
| n-Butane           | C4H10(g)     | 58.12          | -126,150                   | -15,710                | 310.12      |
| n-Octane(I)        | C8H18(I)     | 114.23         | -249,950                   | 6,610                  | 360.79      |
| n-Octane(g)        | C8H18(g)     | 114.23         | -208,450                   | 16,530                 | 466.73      |
|                    |              |                |                            |                        |             |
| n-Dodecane         | C12H26(g)    | 170.22         | -291,010                   | 50,150                 | 622.83      |
| Benzene            | C6H6(g)      | 78.11          | 82,930                     | 129,660                | 269.20      |
| Methyl Alcohol     | CH3OH(g)     | 32.04          | -200,670                   | -162,000               | 239.70      |
| Methyl Alcohol     | CH3OH(I)     | 32.04          | -238,660                   | -166,360               | 126.80      |
| Ethyl Alcohol      | C2H5OH(g)    | 46.07          | -235,310                   | -168,570               | 282.59      |
| Ethyl Alcohol      | C2H5OH(I)    | 46.07          | -277,690                   | -174,890               | 160.70      |
| Oxygen (atomic)    | O(g)         | 16.00          | 249,190                    | 231,770                | 161.06      |
| Hydrogen (atomic)  | H(g)         | 1.01           | 218,000                    | 203,290                | 114.72      |
| Nitrogen (atomic)  | N(g)         | 14.01          | 472,650                    | 455,510                | 153.30      |
| Hydroxyl (radical) | OH(g)        | 17.01          | 39,460                     | 34,290                 | 183.70      |

#### 8.1.8 Evaluating Enthalpy:

We have seen that enthalpy of formation was defined when a compound is formed at the 'reference state' of 1atm, 25 C. In most cases, however, reactants and products are not at reference state, and then the specific enthalpy of a compound is determined by adding the specific enthalpy change  $\Delta h$  between the standard state and the state in question to the enthalpy of formation. i.e.

$$\mathbf{h}_{\mathrm{T},p} = \mathbf{h}_{\mathrm{f0}} + \left(\mathbf{h}(\mathrm{T},p) - \mathbf{h}(\mathrm{T}_{\mathrm{ref}},p_{\mathrm{ref}})\right) = \mathbf{h}_{\mathrm{f0}} + \Delta \mathbf{h}$$

Urieli has calculated the values of  $\Delta$ h for CO2, CO, H2O, N2, and O2, based on data from TEST software, and those Tables are given below [Ref. 10]. They will be useful to calculate the enthalpies at conditions other than the standard or reference state.

| Temp. [K] | Enthalpy<br>[kJ/kmol] | Temp.<br>[K] | Enthalpy<br>[kJ/kmol] | Temp.<br>[K] | Enthalpy<br>[kJ/kmol] | Temp.<br>[K] | Enthalpy<br>[kJ/kmol] |
|-----------|-----------------------|--------------|-----------------------|--------------|-----------------------|--------------|-----------------------|
| 298       | 0                     |              |                       |              |                       |              |                       |
| 300       | 67                    | 650          | 15310                 | 1000         | 33432                 | 1700         | 73492                 |
| 310       | 443                   | 660          | 15796                 | 1020         | 34495                 | 1720         | 74679                 |
| 320       | 822                   | 670          | 16284                 | 1040         | 35589                 | 1740         | 75867                 |
| 330       | 1206                  | 680          | 16774                 | 1060         | 36687                 | 1760         | 77056                 |
| 340       | 1595                  | 690          | 17267                 | 1080         | 37789                 | 1780         | 78248                 |
| 350       | 1987                  | 700          | 17761                 | 1100         | 38894                 | 1800         | 79442                 |
| 360       | 2384                  | 710          | 18258                 | 1120         | 40005                 | 1820         | 80636                 |
| 370       | 2784                  | 720          | 18757                 | 1140         | 41120                 | 1840         | 81832                 |
| 380       | 3188                  | 730          | 19258                 | 1160         | 42238                 | 1860         | 83030                 |
| 390       | 3596                  | 740          | 19760                 | 1180         | 43060                 | 1880         | 84229                 |
| 400       | 4008                  | 750          | 20265                 | 1200         | 44484                 | 1900         | 85429                 |
| 410       | 4423                  | 760          | 19771                 | 1220         | 45613                 | 1920         | 86631                 |
| 420       | 4842                  | 770          | 21280                 | 1240         | 46744                 | 1940         | 87833                 |
| 430       | 4964                  | 780          | 21790                 | 1260         | 47880                 | 1960         | 89037                 |
| 440       | 5690                  | 790          | 21801                 | 1280         | 49017                 | 1980         | 90242                 |
| 450       | 6119                  | 800          | 22815                 | 1300         | 50158                 | 2000         | 91440                 |
| 460       | 6552                  | 810          | 23330                 | 1320         | 51302                 | 2050         | 94471                 |

#### Ideal Gas Enthalpy of Carbon Dioxide (CO2) Enthalpy of Formation: -393,522 (kJ/kmol)

Molecular Weight: 44.01 (kg/kmol)

Applied Thermodynamics: Software Solutions: Part-IV (Psychrometrics, Reactive systems)

| 470 | 6987  | 820 | 23848 | 1340 | 52449 | 2100 | 97500  |
|-----|-------|-----|-------|------|-------|------|--------|
| 480 | 7427  | 830 | 24366 | 1360 | 53599 | 2150 | 100534 |
| 490 | 7868  | 840 | 24887 | 1380 | 54752 | 2200 | 103575 |
| 500 | 8314  | 850 | 25409 | 1400 | 55907 | 2250 | 106620 |
| 510 | 8762  | 860 | 25932 | 1420 | 57063 | 2300 | 109671 |
| 520 | 9212  | 870 | 26457 | 1440 | 58222 | 2350 | 112727 |
| 530 | 9665  | 880 | 26983 | 1460 | 59384 | 2400 | 115788 |
| 540 | 10121 | 890 | 27512 | 1480 | 57547 | 2450 | 118855 |
| 550 | 10581 | 900 | 28041 | 1500 | 61714 | 2500 | 121926 |
| 560 | 11043 | 910 | 28571 | 1520 | 62882 | 2550 | 125004 |
| 570 | 11506 | 920 | 29103 | 1540 | 64053 | 2600 | 128085 |
| 580 | 11973 | 930 | 29636 | 1560 | 65226 | 2650 | 131169 |
| 590 | 12443 | 940 | 30171 | 1580 | 67403 | 2700 | 134256 |
| 600 | 12916 | 950 | 30706 | 1600 | 67580 | 2750 | 137349 |
| 610 | 13390 | 960 | 31243 | 1620 | 68759 | 2800 | 140444 |
| 620 | 13867 | 970 | 31781 | 1640 | 69939 | 2850 | 143544 |
| 630 | 14345 | 980 | 32321 | 1660 | 71122 | 2900 | 146645 |
| 640 | 14826 | 990 | 32862 | 1680 | 72306 | 3000 | 152862 |



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#### Ideal Gas Enthalpy of Carbon Monoxide (CO)

Enthalpy of Formation: -110,527 (kJ/kmol)

Molecular Weight: 28.01 (kg/kmol)

| Temp. [K] | Enthalpy<br>[kJ/kmol] | Temp.<br>[K] | Enthalpy<br>[kJ/kmol] | Temp.<br>[K] | Enthalpy<br>[kJ/kmol] | Temp.<br>[K] | Enthalpy<br>[kJ/kmol] |
|-----------|-----------------------|--------------|-----------------------|--------------|-----------------------|--------------|-----------------------|
| 298       | 0                     |              |                       |              |                       |              |                       |
| 300       | 54                    | 650          | 10472                 | 1000         | 21686                 | 1700         | 45940                 |
| 310       | 345                   | 660          | 10780                 | 1020         | 22351                 | 1720         | 46654                 |
| 320       | 637                   | 670          | 11089                 | 1040         | 23019                 | 1740         | 47370                 |
| 330       | 928                   | 680          | 11399                 | 1060         | 23688                 | 1760         | 48087                 |
| 340       | 1220                  | 690          | 11709                 | 1080         | 24360                 | 1780         | 48804                 |
| 350       | 1512                  | 700          | 12021                 | 1100         | 25033                 | 1800         | 49522                 |
| 360       | 1804                  | 710          | 12333                 | 1120         | 25708                 | 1820         | 50241                 |
| 370       | 2096                  | 720          | 12646                 | 1140         | 26385                 | 1840         | 50960                 |
| 380       | 2389                  | 730          | 12959                 | 1160         | 27064                 | 1860         | 51682                 |
| 390       | 2682                  | 740          | 13274                 | 1180         | 27737                 | 1880         | 52403                 |
| 400       | 2975                  | 750          | 13589                 | 1200         | 28426                 | 1900         | 53125                 |
| 410       | 3269                  | 760          | 13904                 | 1220         | 29111                 | 1920         | 53847                 |
| 420       | 3563                  | 770          | 14221                 | 1240         | 29797                 | 1940         | 54569                 |
| 430       | 3857                  | 780          | 14539                 | 1260         | 30485                 | 1960         | 55292                 |
| 440       | 4152                  | 790          | 14857                 | 1280         | 31175                 | 1980         | 56015                 |
| 450       | 4447                  | 800          | 15175                 | 1300         | 31865                 | 2000         | 56739                 |
| 460       | 4743                  | 810          | 15495                 | 1320         | 32557                 | 2050         | 58555                 |
|           |                       |              |                       |              |                       |              |                       |
| 470       | 5020                  | 020          | 15014                 | 12.40        | 22250                 | 2100         | 60275                 |
| 4/0       | 5039                  | 820          | 15814                 | 1340         | 33250                 | 2100         | 60375                 |
| 480       | 5330                  | 830          | 16134                 | 1300         | 24640                 | 2150         | 62195                 |
| 490       | 5055                  | 840          | 10455                 | 1580         | 34640                 | 2200         | 64019                 |
| 500       | 5931                  | 850          | 16777                 | 1400         | 35358                 | 2250         | 65847                 |
| 510       | 6229                  | 860          | 17099                 | 1420         | 36038                 | 2300         | 6/6/6                 |
| 520       | 6928                  | 8/0          | 17422                 | 1440         | 30/39                 | 2350         | 71246                 |
| 530       | 7128                  | 880          | 1//40                 | 1400         | 37441                 | 2400         | 73183                 |
| 540       | 7128                  | 000          | 180/1                 | 1400         | 20040                 | 2450         | 75000                 |
| 550       | /428                  | 900          | 18397                 | 1500         | 38848                 | 2500         | /5023                 |
|           |                       |              |                       |              |                       |              |                       |
| 560       | 7730                  | 910          | 18723                 | 1520         | 39553                 | 2550         | 76868                 |
| 570       | 8032                  | 920          | 19050                 | 1540         | 40259                 | 2600         | 78714                 |
| 580       | 8334                  | 930          | 19377                 | 1560         | 40966                 | 2650         | 80561                 |
| 590       | 8638                  | 940          | 19706                 | 1580         | 41675                 | 2700         | 82408                 |
| 600       | 8942                  | 950          | 20034                 | 1600         | 42384                 | 2750         | 84261                 |
| 610       | 9246                  | 960          | 20364                 | 1620         | 43094                 | 2800         | 86115                 |
| 620       | 9552                  | 970          | 20693                 | 1640         | 43803                 | 2850         | 87970                 |
| 630       | 9858                  | 980          | 21024                 | 1660         | 44515                 | 2900         | 89826                 |
| 640       | 10164                 | 990          | 21355                 | 1680         | 45226                 | 3000         | 93541                 |

#### Ideal Gas Enthalpy of Water Vapor (H2O) Enthalpy of Formation: -241,826 (kJ/kmol) Molecular Weight: 18.015 (kg/kmol)

| Temp, [K] | Enthalpy  |   | Temp. | Enthalpy  |   | Temp. | Enthalpy  |   | Temp. | Enthalpy  |
|-----------|-----------|---|-------|-----------|---|-------|-----------|---|-------|-----------|
|           | [kJ/kmol] |   | [K]   | [kJ/kmol] |   | [K]   | [kJ/kmol] |   | [K]   | [kJ/kmol] |
| 298       | 0         |   |       |           |   |       |           |   |       |           |
| 300       | 62        |   | 650   | 12326     |   | 1000  | 25978     |   | 1700  | 57685     |
| 310       | 398       |   | 660   | 12696     |   | 1020  | 26805     |   | 1720  | 58663     |
| 320       | 735       |   | 670   | 13066     |   | 1040  | 27638     |   | 1740  | 59646     |
| 330       | 1072      |   | 680   | 13438     |   | 1060  | 28476     |   | 1760  | 60631     |
| 340       | 1410      |   | 690   | 13810     |   | 1080  | 29319     |   | 1780  | 61619     |
| 350       | 1748      |   | 700   | 14184     |   | 1100  | 30167     |   | 1800  | 62609     |
| 360       | 2088      |   | 710   | 14560     |   | 1120  | 31019     |   | 1820  | 63603     |
| 370       | 2427      |   | 720   | 14936     |   | 1140  | 31876     |   | 1840  | 64602     |
| 380       | 2768      |   | 730   | 15314     |   | 1160  | 32738     |   | 1860  | 65602     |
| 390       | 3110      |   | 740   | 15693     |   | 1180  | 33605     |   | 1880  | 66607     |
| 400       | 3452      |   | 750   | 16073     |   | 1200  | 34476     |   | 1900  | 67613     |
| 410       | 3795      |   | 760   | 16454     |   | 1220  | 35352     |   | 1920  | 68623     |
| 420       | 4139      |   | 770   | 16837     |   | 1240  | 36233     |   | 1940  | 69636     |
| 430       | 4484      |   | 780   | 17221     |   | 1260  | 37118     |   | 1960  | 70651     |
| 440       | 4830      |   | 790   | 17606     |   | 1280  | 38008     |   | 1980  | 71669     |
| 450       | 5176      |   | 800   | 17992     |   | 1300  | 38903     |   | 2000  | 72689     |
| 460       | 5524      |   | 810   | 18380     |   | 1320  | 39803     |   | 2050  | 75252     |
|           |           |   | ii    |           |   | ii    |           |   | i     |           |
|           |           |   |       |           |   |       |           | - |       | 1         |
| 470       | 5873      |   | 820   | 18768     | ļ | 1340  | 40708     | ļ | 2100  | 77849     |
| 480       | 6222      |   | 830   | 19158     |   | 1360  | 41617     |   | 2150  | 80426     |
| 490       | 6573      |   | 840   | 19550     |   | 1380  | 42530     |   | 2200  | 83036     |
| 500       | 6924      |   | 850   | 19942     | [ | 1400  | 43447     | [ | 2250  | 85658     |
| 510       | 7277      |   | 860   | 20336     | [ | 1420  | 44369     | [ | 2300  | 88295     |
| 520       | 7630      |   | 870   | 20731     | [ | 1440  | 45294     | [ | 2350  | 90942     |
|           |           |   | 1     |           | Г | 1     | )         | Г | 1     |           |
|           |           | , |       |           |   |       |           |   |       |           |
| 530       | 7985      |   | 880   | 21128     |   | 1460  | 46224     |   | 2400  | 93604     |
| 540       | 8341      |   | 890   | 21525     |   | 1480  | 47158     |   | 2450  | 96279     |
| 550       | 8697      | [ | 900   | 21924     |   | 1500  | 48095     |   | 2500  | 98964     |
| 560       | 9055      | [ | 910   | 22324     |   | 1520  | 49038     |   | 2550  | 101661    |
| 570       | 9414      | [ | 920   | 22725     |   | 1540  | 49984     |   | 2600  | 104379    |
| 580       | 9774      | [ | 930   | 23128     |   | 1560  | 50934     |   | 2650  | 107087    |
| 590       | 10135     | [ | 940   | 23532     |   | 1580  | 51888     |   | 2700  | 109813    |
| 600       | 10498     | [ | 950   | 23937     |   | 1600  | 52844     |   | 2750  | 112549    |
| 610       | 10861     | ĺ | 960   | 24343     | j | 1620  | 53805     |   | 2800  | 115294    |
| 620       | 11226     | ĺ | 970   | 24749     | İ | 1640  | 54771     |   | 2850  | 118048    |
| 630       | 11591     | ĺ | 980   | 25157     | İ | 1660  | 55739     |   | 2900  | 120813    |
| 640       | 11958     | [ | 990   | 25568     | İ | 1680  | 56710     |   | 3000  | 126360    |

#### Ideal Gas Enthalpy of Nitrogen (N2) Enthalpy of Formation: 0 (kJ/kmol)

Molecular Weight: 28.013 (kg/kmol)

| Temp. [K] | Enthalpy  |   | Temp. | Enthalpy    | Temp. | Enthalpy<br>[]a I/amati | Temp.    | Enthalpy  |
|-----------|-----------|---|-------|-------------|-------|-------------------------|----------|-----------|
| 208       | [KJ/KIIO] |   | [K]   | [KJ/KIIIOI] | [K]   | [KJ/KIIIOI]             | [L]      | [KJ/KIIO] |
| 298       | 0         |   | r     |             |       |                         |          |           |
| 300       | 54        |   | 650   | 10406       | 1000  | missing                 | 1700     | 45430     |
| 310       | 345       |   | 660   | 10711       | 1020  | 22115                   | 1720     | 46138     |
| 320       | 637       |   | 670   | 11016       | 1040  | 22773                   | 1740     | 46847     |
| 330       | 928       |   | 680   | 11322       | 1060  | 23432                   | 1760     | missing   |
| 340       | 1219      |   | 690   | 11628       | 1080  | 24093                   | 1780     | 48269     |
| 350       | 1511      |   | 700   | 11935       | 1100  | 24757                   | 1800     | 48982     |
| 360       | 1802      |   | 710   | 12243       | 1120  | 25423                   | 1820     | 49694     |
| 370       | 2094      |   | 720   | 12551       | 1140  | 26091                   | 1840     | 50406     |
| 380       | 2386      |   | 730   | 12860       | 1160  | 26761                   | 1860     | 51121     |
| 390       | 2678      |   | 740   | 13170       | 1180  | 27435                   | 1880     | 51835     |
| 400       | 2971      |   | 750   | 13480       | 1200  | 28108                   | 1900     | 52551     |
| 410       | 3263      |   | 760   | 13791       | 1220  | 28783                   | 1920     | 53267     |
| 420       | 3556      |   | 770   | 14103       | 1240  | 29460                   | 1940     | 53985     |
| 430       | 3849      |   | 780   | 14416       | 1260  | 30138                   | 1960     | 54712     |
| 440       | 4142      |   | 790   | 14729       | 1280  | 30819                   | 1980     | 55421     |
| 450       | 4436      |   | 800   | 15045       | 1300  | 31501                   | 2000     | 56141     |
| 460       | 4730      |   | 810   | 15358       | 1320  | 32184                   | 2050     | 57943     |
|           |           |   | ;;    |             |       |                         | <u> </u> |           |
| 470       | 5024      | Γ | 820   | 15673       | 1340  | 32870                   | 2100     | 59748     |
| 480       | 5319      | Ī | 830   | 15989       | 1360  | 33558                   | 2150     | 61557     |
| 490       | 5616      | Ī | 840   | 16305       | 1380  | 34246                   | 2200     | 63371     |
| 500       | 5912      | Γ | 850   | 16623       | 1400  | 34936                   | 2250     | 65187     |
| 510       | 6207      | Ĺ | 860   | 16941       | 1420  | 35626                   | 2300     | 67007     |
| 520       | 6503      | ľ | 870   | 17259       | 1440  | 36319                   | 2350     | 68827     |
| 530       | 6800      | Ī | 880   | 17579       | 1460  | 37013                   | 2400     | 70651     |
| 540       | 7097      | Ī | 890   | 17899       | 1480  | 37708                   | 2450     | 72480     |
| 550       | 7395      | Ē | 900   | 18221       | 1500  | 38404                   | 2500     | 74312     |
| 560       | 7694      | Ī | 910   | 18541       | 1520  | 39102                   | 2550     | 76145     |
| 570       | 7993      | Ī | 920   | 18863       | 1540  | 39801                   | 2600     | 77981     |
| 580       | 8293      | Ĺ | 930   | 19185       | 1560  | 40499                   | 2650     | 79819     |
| 590       | 8593      | Ī | 940   | 19509       | 1580  | 41200                   | 2700     | 81659     |
| 600       | missing   | ſ | 950   | 19832       | 1600  | 41902                   | 2750     | 83502     |
| 610       | missing   | Ē | 960   | 20157       | 1620  | 42606                   | 2800     | 85345     |
| 620       | missing   | Γ | 970   | 20482       | 1640  | 43311                   | 2850     | 87190     |
| 630       | 9799      | Ē | 980   | 20807       | 1660  | 44017                   | 2900     | 89036     |
| 640       | 10103     | Ī | 990   | 21134       | 1680  | 44724                   | 3000     | 92738     |

#### Ideal Gas Enthalpy of Oxygen (O2) Enthalpy of Formation: 0 (kJ/kmol)

Molecular Weight: 32 (kg/kmol)

| Temp. [K] | Enthalpy  | Temp. | Enthalpy  | Temp. | Enthalpy  | Temp. | Enthalpy  |
|-----------|-----------|-------|-----------|-------|-----------|-------|-----------|
|           | [kJ/kmol] | [K]   | [kJ/kmol] | [K]   | [kJ/kmol] | [K]   | [kJ/kmol] |
| 298       | 0         |       |           |       |           |       |           |
| 300       | 54        | 650   | 10862     | 1000  | missing   | 1700  | 47970     |
| 310       | 348       | 660   | 11188     | 1020  | missing   | 1720  | 48712     |
| 320       | 643       | 670   | 11515     | 1040  | 24107     | 1740  | 49454     |
| 330       | 938       | 680   | 11842     | 1060  | 24808     | 1760  | missing   |
| 340       | 1234      | 690   | 12172     | 1080  | 25512     | 1780  | missing   |
| 350       | 1531      | 700   | 12502     | 1100  | 26217     | 1800  | 51689     |
| 360       | 1829      | 710   | 12832     | 1120  | 26924     | 1820  | 52436     |
| 370       | 2127      | 720   | 13163     | 1140  | 27632     | 1840  | 53184     |
| 380       | 2427      | 730   | 13495     | 1160  | 28341     | 1860  | 53934     |
| 390       | 2727      | 740   | 13828     | 1180  | 29052     | 1880  | 54683     |
| 400       | 3029      | 750   | 14162     | 1200  | 29765     | 1900  | 55434     |
| ii        |           | ·     |           | ·     |           |       |           |
|           |           |       |           |       |           |       |           |
| 410       | 3330      | 760   | 14496     | 1220  | 30480     | 1920  | 56186     |
| 420       | 3632      | 770   | 14831     | 1240  | 31195     | 1940  | 56938     |
| 430       | 3936      | 780   | 15168     | 1260  | 31912     | 1960  | 57692     |
| 440       | 4241      | 790   | 15504     | 1280  | 32630     | 1980  | 58445     |
| 450       | 4546      | 800   | 15841     | 1300  | 33351     | 2000  | 59199     |
| 460       | 4843      | 810   | 16179     | 1320  | 34071     | 2050  | 61090     |
| 470       | 5160      | 820   | 16517     | 1340  | 34793     | 2100  | 62986     |
| 480       | 5469      | 830   | 16855     | 1360  | 35516     | 2150  | 64891     |
| 490       | 5778      | 840   | 17195     | 1380  | 36241     | 2200  | 66802     |
| 500       | 6088      | 850   | 17536     | 1400  | 36966     | 2250  | 68715     |
| 510       | 6400      | 860   | 17877     | 1420  | 37692     | 2300  | 70634     |
| 520       | 6713      | 870   | 18217     | 1440  | 38420     | 2350  | 72561     |
| 530       | 7026      | 880   | 18560     | 1460  | 39149     | 2400  | 74492     |
| 540       | 7340      | 890   | 18902     | 1480  | 39879     | 2450  | 76430     |
| 550       | 7656      | 900   | 19246     | 1500  | 40610     | 2500  | 78375     |
| 560       | 7972      | 910   | 19590     | 1520  | 41342     | 2550  | 80322     |
| 570       | 8289      | 920   | 19934     | 1540  | 42074     | 2600  | 82274     |
| 580       | 8608      | 930   | 20278     | 1560  | 42808     | 2650  | 84234     |
| 590       | 8927      | 940   | 20624     | 1580  | 43542     | 2700  | 86199     |
| 600       | 9247      | 950   | 20970     | 1600  | 44279     | 2750  | 88170     |
| 610       | 9568      | 960   | 21317     | 1620  | 45014     | 2800  | 90144     |
| 620       | 9890      | 970   | 21663     | 1640  | 45752     | 2850  | 92126     |
| 630       | 10213     | 980   | 22010     | 1660  | 46490     | 2900  | 94111     |
| 640       | 10537     | 990   | 22359     | 1680  | 47230     | 3000  | 98098     |

#### Alternatively:

Following Ideal gas tables can also be used, where the reference point is zero Kelvin: [Ref: 3]

```
TABLE A-22 Ideal Gas Properties of Air
```

|     | $T(\mathbf{K})$ , h and $u(\mathbf{k}J/\mathbf{kg})$ , s <sup>o</sup> (kJ/kg · K) |        |         |                       |       |     |        |        |         |                |       |  |  |  |
|-----|---|--------|---------|-----------------------|-------|-----|--------|--------|---------|----------------|-------|--|--|--|
|     |   |        | 1.1     | when $\Delta s = 0^1$ |       |     |        |        |         | when $\Delta$  | s = 0 |  |  |  |
| T   | h   | м      | s°      | Pr                    | v,    | T   | h      | ш      | s°      | p <sub>r</sub> | v,    |  |  |  |
| 200 | 199.97  | 142.56 | 1.29559 | 0.3363                | 1707. | 450 | 451.80 | 322.62 | 2.11161 | 5.775          | 223.6 |  |  |  |
| 210 | 209.97  | 149.69 | 1.34444 | 0.3987                | 1512. | 460 | 462.02 | 329.97 | 2.13407 | 6.245          | 211.4 |  |  |  |
| 220 | 219.97  | 156.82 | 1.39105 | 0.4690                | 1346. | 470 | 472.24 | 337.32 | 2.15604 | 6.742          | 200.1 |  |  |  |
| 230 | 230.02  | 164.00 | 1.43557 | 0.5477                | 1205. | 480 | 482.49 | 344.70 | 2.17760 | 7.268          | 189.5 |  |  |  |
| 240 | 240.02  | 171.13 | 1.47824 | 0.6355                | 1084. | 490 | 492.74 | 352.08 | 2.19876 | 7.824          | 179.7 |  |  |  |
| 250 | 250.05  | 178.28 | 1.51917 | 0.7329                | 979.  | 500 | 503.02 | 359.49 | 2.21952 | 8.411          | 170.6 |  |  |  |
| 260 | 260.09  | 185.45 | 1.55848 | 0.8405                | 887.8 | 510 | 513.32 | 366.92 | 2.23993 | 9.031          | 162.1 |  |  |  |
| 270 | 270.11  | 192.60 | 1.59634 | 0.9590                | 808.0 | 520 | 523.63 | 374.36 | 2.25997 | 9.684          | 154.1 |  |  |  |
| 280 | 280.13  | 199.75 | 1.63279 | 1.0889                | 738.0 | 530 | 533.98 | 381.84 | 2.27967 | 10.37          | 146.7 |  |  |  |
| 285 | 285.14  | 203.33 | 1.65055 | 1.1584                | 706.1 | 540 | 544.35 | 389.34 | 2.29906 | 11.10          | 139.7 |  |  |  |
| 290 | 290.16  | 206.91 | 1.66802 | 1.2311                | 676.1 | 550 | 554.74 | 396.86 | 2.31809 | 11.86          | 133.1 |  |  |  |
| 295 | 295.17  | 210.49 | 1.68515 | 1.3068                | 647.9 | 560 | 565.17 | 404.42 | 2.33685 | 12.66          | 127.0 |  |  |  |
| 300 | 300.19  | 214.07 | 1.70203 | 1.3860                | 621.2 | 570 | 575.59 | 411.97 | 2.35531 | 13.50          | 121.2 |  |  |  |
| 305 | 305.22  | 217.67 | 1.71865 | 1.4686                | 596.0 | 580 | 586.04 | 419.55 | 2.37348 | 14.38          | 115.7 |  |  |  |
| 310 | 310.24  | 221.25 | 1.73498 | 1.5546                | 572.3 | 590 | 596.52 | 427.15 | 2.39140 | 15.31          | 110.6 |  |  |  |
| 315 | 315.27  | 224.85 | 1.75106 | 1.6442                | 549.8 | 600 | 607.02 | 434.78 | 2.40902 | 16.28          | 105.8 |  |  |  |
| 320 | 320.29  | 228.42 | 1.76690 | 1.7375                | 528.6 | 610 | 617.53 | 442.42 | 2.42644 | 17.30          | 101.2 |  |  |  |
| 325 | 325.31  | 232.02 | 1.78249 | 1.8345                | 508.4 | 620 | 628.07 | 450.09 | 2.44356 | 18.36          | 96.92 |  |  |  |
| 330 | 330.34  | 235.61 | 1.79783 | 1.9352                | 489.4 | 630 | 638.63 | 457.78 | 2.46048 | 19.84          | 92.84 |  |  |  |
| 340 | 340.42  | 242.82 | 1.82790 | 2.149                 | 454.1 | 640 | 649.22 | 465.50 | 2.47716 | 20.64          | 88.99 |  |  |  |
| 350 | 350.49  | 250.02 | 1.85708 | 2.379                 | 422.2 | 650 | 659.84 | 473.25 | 2.49364 | 21.86          | 85.34 |  |  |  |
| 360 | 360.58  | 257.24 | 1.88543 | 2.626                 | 393.4 | 660 | 670.47 | 481.01 | 2.50985 | 23.13          | 81.89 |  |  |  |
| 370 | 370.67  | 264.46 | 1.91313 | 2.892                 | 367.2 | 670 | 681.14 | 488.81 | 2.52589 | 24.46          | 78.61 |  |  |  |
| 380 | 380.77  | 271.69 | 1.94001 | 3.176                 | 343.4 | 680 | 691.82 | 496.62 | 2.54175 | 25.85          | 75.50 |  |  |  |
| 390 | 390.88  | 278.93 | 1.96633 | 3.481                 | 321.5 | 690 | 702.52 | 504.45 | 2.55731 | 27.29          | 72.56 |  |  |  |
| 400 | 400.98  | 286.16 | 1.99194 | 3.806                 | 301.6 | 700 | 713.27 | 512.33 | 2.57277 | 28.80          | 69.76 |  |  |  |
| 410 | 411.12  | 293.43 | 2.01699 | 4.153                 | 283.3 | 710 | 724.04 | 520.23 | 2.58810 | 30.38          | 67.07 |  |  |  |
| 420 | 421.26  | 300.69 | 2.04142 | 4.522                 | 266.6 | 720 | 734.82 | 528.14 | 2.60319 | 32.02          | 64.53 |  |  |  |
| 430 | 431.43  | 307.99 | 2.06533 | 4.915                 | 251.1 | 730 | 745.62 | 536.07 | 2.61803 | 33.72          | 62.13 |  |  |  |
| 440 | 441.61  | 315.30 | 2.08870 | 5.332                 | 236.8 | 740 | 756.44 | 544.02 | 2.63280 | 35.50          | 59.82 |  |  |  |

TABLE A-22 (Continued)

|      |         |         |         | 1(14)  | , it and infrast | -D/1 - (- | and it's |         |            |        |                |
|------|---------|---------|---------|--------|------------------|-----------|----------|---------|------------|--------|----------------|
|      |         |         |         | when a | $\Delta s = 0^1$ |           |          |         |            | when a | $\Delta s = 0$ |
| Т    | h       | и       | s       | Pr     | U,               | T         | h        | и       | <i>s</i> ° | p,     | v,             |
| 750  | 767.29  | 551.99  | 2.64737 | 37.35  | 57.63            | 1300      | 1395.97  | 1022.82 | 3.27345    | 330.9  | 11.275         |
| 760  | 778.18  | 560.01  | 2.66176 | 39.27  | 55.54            | 1320      | 1419.76  | 1040.88 | 3.29160    | 352.5  | 10.747         |
| 770  | 789.11  | 568.07  | 2.67595 | 41.31  | 53.39            | 1340      | 1443.60  | 1058.94 | 3.30959    | 375.3  | 10.247         |
| 780  | 800.03  | 576.12  | 2.69013 | 43.35  | 51.64            | 1360      | 1467.49  | 1077.10 | 3.32724    | 399.1  | 9.780          |
| 790  | 810.99  | 584.21  | 2.70400 | 45.55  | 49.86            | 1380      | 1491.44  | 1095.26 | 3.34474    | 424.2  | 9.337          |
| 800  | 821.95  | 592.30  | 2.71787 | 47.75  | 48.08            | 1400      | 1515.42  | 1113.52 | 3.36200    | 450.5  | 8.919          |
| 820  | 843.98  | 608.59  | 2.74504 | 52.59  | 44.84            | 1420      | 1539.44  | 1131.77 | 3.37901    | 478.0  | 8.526          |
| 840  | 866.08  | 624.95  | 2.77170 | 57.60  | 41.85            | 1440      | 1563.51  | 1150.13 | 3.39586    | 506.9  | 8.153          |
| 860  | 888.27  | 641.40  | 2.79783 | 63.09  | 39.12            | 1460      | 1587.63  | 1168.49 | 3.41247    | 537.1  | 7.801          |
| 880  | 910.56  | 657.95  | 2.82344 | 68.98  | 36.61            | 1480      | 1611.79  | 1186.95 | 3.42892    | 568.8  | 7.468          |
| 900  | 932.93  | 674.58  | 2.84856 | 75.29  | 34.31            | 1500      | 1635.97  | 1205.41 | 3.44516    | 601.9  | 7.152          |
| 920  | 955.38  | 691.28  | 2.87324 | 82.05  | 32.18            | 1520      | 1660.23  | 1223.87 | 3.46120    | 636.5  | 6.854          |
| 940  | 977.92  | 708.08  | 2.89748 | 89.28  | 30.22            | 1540      | 1684.51  | 1242.43 | 3.47712    | 672.8  | 6.569          |
| 960  | 1000.55 | 725.02  | 2.92128 | 97.00  | 28.40            | 1560      | 1708.82  | 1260.99 | 3.49276    | 710.5  | 6.301          |
| 980  | 1023.25 | 741.98  | 2.94468 | 105.2  | 26.73            | 1580      | 1733.17  | 1279.65 | 3.50829    | 750.0  | 6.046          |
| 1000 | 1046.04 | 758.94  | 2.96770 | 114.0  | 25.17            | 1600      | 1757.57  | 1298.30 | 3.52364    | 791.2  | 5.804          |
| 1020 | 1068.89 | 776.10  | 2.99034 | 123.4  | 23.72            | 1620      | 1782.00  | 1316.96 | 3.53879    | 834.1  | 5.574          |
| 1040 | 1091.85 | 793.36  | 3.01260 | 133.3  | 22.39            | 1640      | 1806.46  | 1335.72 | 3.55381    | 878.9  | 5.355          |
| 1060 | 1114.86 | 810.62  | 3.03449 | 143.9  | 21.14            | 1660      | 1830.96  | 1354.48 | 3.56867    | 925.6  | 5.147          |
| 1080 | 1137.89 | 827.88  | 3.05608 | 155.2  | 19.98            | 1680      | 1855.50  | 1373.24 | 3.58335    | 974.2  | 4.949          |
| 1100 | 1161.07 | 845.33  | 3.07732 | 167.1  | 18.896           | 1700      | 1880.1   | 1392.7  | 3.5979     | 1025   | 4.761          |
| 1120 | 1184.28 | 862.79  | 3.09825 | 179.7  | 17.886           | 1750      | 1941.6   | 1439.8  | 3.6336     | 1161   | 4.328          |
| 1140 | 1207.57 | 880.35  | 3.11883 | 193.1  | 16.946           | 1800      | 2003.3   | 1487.2  | 3.6684     | 1310   | 3.944          |
| 1160 | 1230.92 | 897.91  | 3.13916 | 207.2  | 16.064           | 1850      | 2065.3   | 1534.9  | 3.7023     | 1475   | 3.601          |
| 1180 | 1254.34 | 915.57  | 3.15916 | 222.2  | 15.241           | 1900      | 2127.4   | 1582.6  | 3.7354     | 1655   | 3.295          |
| 1200 | 1277.79 | 933.33  | 3.17888 | 238.0  | 14.470           | 1950      | 2189.7   | 1630.6  | 3.7677     | 1852   | 3.022          |
| 1220 | 1301.31 | 951.09  | 3.19834 | 254.7  | 13.747           | 2000      | 2252.1   | 1678.7  | 3.7994     | 2068   | 2.776          |
| 1240 | 1324.93 | 968.95  | 3.21751 | 272.3  | 13.069           | 2050      | 2314.6   | 1726.8  | 3.8303     | 2303   | 2.555          |
| 1260 | 1348.55 | 986.90  | 3.23638 | 290.8  | 12.435           | 2100      | 2377.4   | 1775.3  | 3.8605     | 2559   | 2.356          |
| 1280 | 1372.24 | 1004.76 | 3.25510 | 310.4  | 11.835           | 2150      | 2440.3   | 1823.8  | 3.8901     | 2837   | 2.175          |
|      |         |         |         |        |                  | 2200      | 2503.2   | 1872.4  | 3.9191     | 3138   | 2.012          |
|      |         |         |         |        |                  | 2250      | 2566.4   | 1921.3  | 3.9474     | 3464   | 1.864          |

TABLE A-23 Ideal Gas Properties of Selected Gases

|     | $T(\mathbf{K}), h \text{ and } \overline{u}(kJ/kmol), \overline{s}^{*}(kJ/kmol - \mathbf{K})$ |                           |                              |                                   |                        |                   |                                |                            |                             |        |                        |         |                              |                          |                        |     |
|-----|---|---------------------------|------------------------------|-----------------------------------|------------------------|-------------------|--------------------------------|----------------------------|-----------------------------|--------|------------------------|---------|------------------------------|--------------------------|------------------------|-----|
|     | Carbo $(\bar{h}_{f}^{o} = -$  | on Dioxide,<br>-393,520 k | , CO <sub>2</sub><br>J/kmol) | Carbon $(\bar{h}_{f}^{\circ} = -$ | n Monoxia<br>110,530 I | ie, CO<br>J/kmol) | $\overline{h}_{f}^{\circ} = -$ | ter Vapor, I<br>-241,820 k | I <sub>2</sub> O<br>J/kmol) |        | Oxygen, O<br>= 0 kJ/kr | nol)    | (h <sup>o</sup> <sub>f</sub> | litrogen, N<br>= 0 kJ/ki | N <sub>2</sub><br>mol) |     |
| Τ   | $\overline{h}$  | ū                         | <u>5</u> °                   | $\overline{h}$                    | ū                      | <u>5</u> 0        | $\overline{h}$                 | ū                          | <u>s</u> °                  | h      | ū                      | 50      | h                            | ū                        | 30                     | Т   |
| 0   | 0   | 0                         | 0                            | 0                                 | 0                      | 0                 | 0                              | 0                          | 0                           | 0      | 0                      | 0       | 0                            | 0                        | 0                      | 0   |
| 220 | 6,601   | 4,772                     | 202.966                      | 6,391                             | 4,562                  | 188.683           | 7,295                          | 5,466                      | 178.576                     | 6,404  | 4,575                  | 196.171 | 6,391                        | 4,562                    | 182.638                | 220 |
| 230 | 6,938   | 5,026                     | 204.464                      | 6,683                             | 4,771                  | 189.980           | 7,628                          | 5,715                      | 180.054                     | 6,694  | 4,782                  | 197.461 | 6,683                        | 4,770                    | 183.938                | 230 |
| 240 | 7,280   | 5,285                     | 205.920                      | 6,975                             | 4,979                  | 191.221           | 7,961                          | 5,965                      | 181.471                     | 6,984  | 4,989                  | 198.696 | 6,975                        | 4,979                    | 185.180                | 240 |
| 250 | 7,627   | 5,548                     | 207.337                      | 7,266                             | 5,188                  | 192.411           | 8,294                          | 6,215                      | 182.831                     | 7,275  | 5,197                  | 199.885 | 7,266                        | 5,188                    | 186.370                | 250 |
| 260 | 7,979   | 5,817                     | 208.717                      | 7,558                             | 5,396                  | 193.554           | 8,627                          | 6,466                      | 184.139                     | 7,566  | 5,405                  | 201.027 | 7,558                        | 5,396                    | 187.514                | 260 |
| 270 | 8,335   | 6,091                     | 210.062                      | 7,849                             | 5,604                  | 194.654           | 8,961                          | 6,716                      | 185.399                     | 7,858  | 5,613                  | 202.128 | 7,849                        | 5,604                    | 188.614                | 270 |
| 280 | 8,697   | 6,369                     | 211.376                      | 8,140                             | 5,812                  | 195.173           | 9,296                          | 6,968                      | 186.616                     | 8,150  | 5,822                  | 203.191 | 8,141                        | 5,813                    | 189.673                | 280 |
| 290 | 9,063   | 6,651                     | 212.660                      | 8,432                             | 6,020                  | 196.735           | 9,631                          | 7,219                      | 187.791                     | 8,443  | 6,032                  | 204.218 | 8,432                        | 6,021                    | 190.695                | 290 |
| 298 | 9,364   | 6,885                     | 213.685                      | 8,669                             | 6,190                  | 197.543           | 9,904                          | 7,425                      | 188.720                     | 8,682  | 6,203                  | 205.033 | 8,669                        | 6,190                    | 191.502                | 298 |
| 300 | 9,431   | 6,939                     | 213.915                      | 8,723                             | 6,229                  | 197.723           | 9,966                          | 7,472                      | 188.928                     | 8,736  | 6,242                  | 205.213 | 8,723                        | 6,229                    | 191.682                | 300 |
| 310 | 9,807   | 7,230                     | 215.146                      | 9,014                             | 6,437                  | 198.678           | 10,302                         | 7,725                      | 190.030                     | 9,030  | 6,453                  | 206.177 | 9,014                        | 6,437                    | 192.638                | 310 |
| 320 | 10,186  | 7,526                     | 216.351                      | 9,306                             | 6,645                  | 199.603           | 10,639                         | 7,978                      | 191.098                     | 9,325  | 6,664                  | 207.112 | 9,306                        | 6,645                    | 193.562                | 320 |
| 330 | 10,570  | 7,826                     | 217.534                      | 9,597                             | 6,854                  | 200.500           | 10,976                         | 8,232                      | 192.136                     | 9,620  | 6,877                  | 208.020 | 9,597                        | 6,853                    | 194.459                | 330 |
| 340 | 10,959  | 8,131                     | 218.694                      | 9,889                             | 7,062                  | 201.371           | 11,314                         | 8,487                      | 193.144                     | 9,916  | 7,090                  | 208.904 | 9,888                        | 7,061                    | 195.328                | 340 |
| 350 | 11,351  | 8,439                     | 219.831                      | 10,181                            | 7,271                  | 202.217           | 11,652                         | 8,742                      | 194.125                     | 10,213 | 7,303                  | 209.765 | 10,180                       | 7,270                    | 196.173                | 350 |
| 360 | 11,748  | 8,752                     | 220.948                      | 10,473                            | 7,480                  | 203.040           | 11,992                         | 8,998                      | 195.081                     | 10,511 | 7,518                  | 210.604 | 10,471                       | 7,478                    | 196.995                | 360 |
| 370 | 12,148  | 9,068                     | 222.044                      | 10,765                            | 7,689                  | 203.842           | 12,331                         | 9,255                      | 196.012                     | 10,809 | 7,733                  | 211.423 | 10,763                       | 7,687                    | 197.794                | 370 |
| 380 | 12,552  | 9,392                     | 223.122                      | 11,058                            | 7,899                  | 204.622           | 12,672                         | 9,513                      | 196.920                     | 11,109 | 7,949                  | 212.222 | 11,055                       | 7,895                    | 198.572                | 380 |
| 390 | 12,960  | 9,718                     | 224.182                      | 11,351                            | 8,108                  | 205.383           | 13,014                         | 9,771                      | 197.807                     | 11,409 | 8,166                  | 213.002 | 11,347                       | 8,104                    | 199.331                | 390 |
| 400 | 13,372  | 10,046                    | 225.225                      | 11,644                            | 8,319                  | 206.125           | 13,356                         | 10,030                     | 198.673                     | 11,711 | 8,384                  | 213.765 | 11,640                       | 8,314                    | 200.071                | 400 |
| 410 | 13,787  | 10,378                    | 226.250                      | 11,938                            | 8,529                  | 206.850           | 13,699                         | 10,290                     | 199.521                     | 12,012 | 8,603                  | 214.510 | 11,932                       | 8,523                    | 200,794                | 410 |
| 420 | 14,206  | 10,714                    | 227.258                      | 12,232                            | 8,740                  | 207.549           | 14,043                         | 10,551                     | 200.350                     | 12,314 | 8,822                  | 215.241 | 12,225                       | 8,733                    | 201.499                | 420 |
| 430 | 14,628  | 11,053                    | 228.252                      | 12,526                            | 8,951                  | 208.252           | 14,388                         | 10,813                     | 201.160                     | 12,618 | 9,043                  | 215.955 | 12,518                       | 8,943                    | 202.189                | 430 |
| 440 | 15,054  | 11,393                    | 229.230                      | 12,821                            | 9,163                  | 208.929           | 14,734                         | 11,075                     | 201.955                     | 12,923 | 9,264                  | 216.656 | 12,811                       | 9,153                    | 202.863                | 440 |
| 450 | 15,483  | 11,742                    | 230.194                      | 13,116                            | 9,375                  | 209.593           | 15,080                         | 11,339                     | 202.734                     | 13,228 | 9,487                  | 217.342 | 13,105                       | 9,363                    | 203.523                | 450 |
| 460 | 15,916  | 12,091                    | 231.144                      | 13,412                            | 9,587                  | 210.243           | 15,428                         | 11,603                     | 203.497                     | 13,535 | 9,710                  | 218.016 | 13,399                       | 9,574                    | 204.170                | 460 |
| 470 | 16,351  | 12,444                    | 232.080                      | 13,708                            | 9,800                  | 210.880           | 15,777                         | 11,869                     | 204.247                     | 13,842 | 9,935                  | 218.676 | 13,693                       | 9,786                    | 204.803                | 470 |
| 480 | 16,791  | 12,800                    | 233.004                      | 14,005                            | 10,014                 | 211.504           | 16,126                         | 12,135                     | 204.982                     | 14,151 | 10,160                 | 219.326 | 13,988                       | 9,997                    | 205.424                | 480 |

TADLE A 22 (Continued)

| 490 | 17,232 | 13,158 | 233.916 | 14,302 | 10,228 | 212.117 | 16,477 | 12,403 | 205.705 | 14,460 | 10,386 | 219.963 | 14,285 | 10,210 | 206.033 | 490 |
|-----|--------|--------|---------|--------|--------|---------|--------|--------|---------|--------|--------|---------|--------|--------|---------|-----|
| 500 | 17,678 | 13,521 | 234.814 | 14,600 | 10,443 | 212.719 | 16,828 | 12,671 | 206.413 | 14,770 | 10,614 | 220.589 | 14,581 | 10,423 | 206.630 | 500 |
| 510 | 18,126 | 13,885 | 235.700 | 14,898 | 10,658 | 213.310 | 17,181 | 12,940 | 207.112 | 15,082 | 10,842 | 221.206 | 14,876 | 10,635 | 207.216 | 510 |
| 520 | 18,576 | 14,253 | 236.575 | 15,197 | 10,874 | 213.890 | 17,534 | 13,211 | 207.799 | 15,395 | 11,071 | 221.812 | 15,172 | 10,848 | 207.792 | 520 |
| 530 | 19,029 | 14,622 | 237.439 | 15,497 | 11,090 | 214.460 | 17,889 | 13,482 | 208.475 | 15,708 | 11,301 | 222.409 | 15,469 | 11,062 | 208.358 | 530 |
| 540 | 19,485 | 14,996 | 238.292 | 15,797 | 11,307 | 215.020 | 18,245 | 13,755 | 209.139 | 16,022 | 11,533 | 222.997 | 15,766 | 11,277 | 208.914 | 540 |
| 550 | 19,945 | 15,372 | 239.135 | 16,097 | 11,524 | 215.572 | 18,601 | 14,028 | 209.795 | 16,338 | 11,765 | 223.576 | 16,064 | 11,492 | 209.461 | 550 |
| 560 | 20,407 | 15,751 | 239.962 | 16,399 | 11,743 | 216.115 | 18,959 | 14,303 | 210.440 | 16,654 | 11,998 | 224.146 | 16,363 | 11,707 | 209.999 | 560 |
| 570 | 20,870 | 16,131 | 240.789 | 16,701 | 11,961 | 216.649 | 19,318 | 14,579 | 211.075 | 16,971 | 12,232 | 224.708 | 16,662 | 11,923 | 210.528 | 570 |
| 580 | 21,337 | 16,515 | 241.602 | 17,003 | 12,181 | 217.175 | 19.678 | 14,856 | 211.702 | 17,290 | 12,467 | 225.262 | 16,962 | 12,139 | 211.049 | 580 |
| 590 | 21,807 | 16,902 | 242.405 | 17,307 | 12,401 | 217.693 | 20,039 | 15,134 | 212.320 | 17,609 | 12,703 | 225.808 | 17,262 | 12,356 | 211.562 | 590 |

| _   |                                  |                           |                              |                                     |   | TIK     | ). $\overline{h}$ and $\overline{u}$ | (J/kmol), 3   | (kJ/kmol · | K)             |   |         |        |  |            |     |
|-----|----------------------------------|---------------------------|------------------------------|-------------------------------------|---|---------|--------------------------------------|---|------------|----------------|---|---------|--------|--|------------|-----|
|     | Carbo $(\bar{h}_{f}^{\circ} = -$ | on Dioxide<br>- 393,520 k | , CO <sub>2</sub><br>J/kmol) | Carbo<br>$(\bar{h}_{f}^{\circ} = -$ | Carbon Monoxide, CO<br>$\bar{h}_{1}^{o} = -110,530 \text{ kJ/kmol}$ |         |                                      | Water Vapor, H <sub>2</sub> O<br>( $\bar{h}_1^o = -241,820 \text{ kJ/kmol}$ ) |            |                | Oxygen, O <sub>2</sub><br>$(\bar{h}_{1}^{\circ} = 0 \text{ kJ/kmol})$ |         |        | Nitrogen, N <sub>2</sub><br>$(\overline{h}_{1}^{o} = 0 \text{ kJ/kmol})$ |            |     |
| Т   | ħ                                | ū                         | 50                           | h                                   | ū   | 50      | $\overline{h}$                       | ū   | <u></u> 5° | $\overline{h}$ | ū   | 50      | ħ      | ū  | <u>5</u> ° | Т   |
| 600 | 22,280                           | 17,291                    | 243.199                      | 17,611                              | 12,622  | 218.204 | 20,402                               | 15,413  | 212.920    | 17,929         | 12,940  | 226.346 | 17,563 | 12,574   | 212.066    | 600 |
| 610 | 22,754                           | 17,683                    | 243.983                      | 17,915                              | 12,843  | 218.708 | 20,765                               | 15,693  | 213.529    | 18,250         | 13,178  | 226.877 | 17,864 | 12,792   | 212.564    | 610 |
| 620 | 23,231                           | 18,076                    | 244.758                      | 18,221                              | 13,066  | 219.205 | 21,130                               | 15,975  | 214.122    | 18,572         | 13,417  | 227.400 | 18,166 | 13,011   | 213.055    | 620 |
| 630 | 23,709                           | 18,471                    | 245.524                      | 18,527                              | 13,289  | 219.695 | 21,495                               | 16,257  | 214.707    | 18,895         | 13,657  | 227.918 | 18,468 | 13,230   | 213.541    | 630 |
| 640 | 24,190                           | 18,869                    | 246.282                      | 18,833                              | 13,512  | 220.179 | 21,862                               | 16,541  | 215.285    | 19,219         | 13,898  | 228.429 | 18,772 | 13,450   | 214.018    | 640 |
| 650 | 24,674                           | 19,270                    | 247.032                      | 19,141                              | 13,736  | 220.656 | 22,230                               | 16,826  | 215.856    | 19,544         | 14,140  | 228.932 | 19,075 | 13,671   | 214.489    | 650 |
| 660 | 25,160                           | 19,672                    | 247,773                      | 19,449                              | 13,962  | 221.127 | 22,600                               | 17,112  | 216.419    | 19,870         | 14,383  | 229.430 | 19,380 | 13,892   | 214.954    | 660 |
| 670 | 25,648                           | 20,078                    | 248.507                      | 19,758                              | 14,187  | 221.592 | 22,970                               | 17,399  | 216.976    | 20,197         | 14,626  | 229.920 | 19,685 | 14,114   | 215.413    | 670 |
| 680 | 26,138                           | 20,484                    | 249.233                      | 20,068                              | 14,414  | 222.052 | 23,342                               | 17,688  | 217.527    | 20,524         | 14,871  | 230.405 | 19,991 | 14,337   | 215.866    | 680 |
| 690 | 26,631                           | 20,894                    | 249.952                      | 20,378                              | 14,641  | 222.505 | 23,714                               | 17,978  | 218.071    | 20,854         | 15,116  | 230.885 | 20,297 | 14,560   | 216.314    | 690 |
| 700 | 27,125                           | 21,305                    | 250.663                      | 20,690                              | 14,870  | 222.953 | 24,088                               | 18,268  | 218.610    | 21,184         | 15,364  | 231.358 | 20,604 | 14,784   | 216.756    | 700 |
| 710 | 27,622                           | 21,719                    | 251.368                      | 21,002                              | 15,099  | 223.396 | 24,464                               | 18,561  | 219.142    | 21,514         | 15,611  | 231.827 | 20,912 | 15,008   | 217.192    | 710 |
| 720 | 28,121                           | 22,134                    | 252.065                      | 21,315                              | 15,328  | 223.833 | 24,840                               | 18,854  | 219.668    | 21,845         | 15,859  | 232.291 | 21,220 | 15,234   | 217.624    | 720 |
| 730 | 28,622                           | 22,552                    | 252.755                      | 21,628                              | 15,558  | 224.265 | 25,218                               | 19,148  | 220.189    | 22,177         | 16,107  | 232.748 | 21,529 | 15,460   | 218.059    | 730 |
| 740 | 29,124                           | 22,972                    | 253.439                      | 21,943                              | 15,789  | 224.692 | 25,597                               | 19,444  | 220.707    | 22,510         | 16,357  | 233.201 | 21,839 | 15,686   | 218.472    | 740 |
| 750 | 29,629                           | 23,393                    | 254.117                      | 22,258                              | 16,022  | 225.115 | 25,977                               | 19,741  | 221.215    | 22,844         | 16,607  | 233.649 | 22,149 | 15,913   | 218.889    | 750 |
| 760 | 30,135                           | 23,817                    | 254.787                      | 22,573                              | 16,255  | 225.533 | 26,358                               | 20,039  | 221.720    | 23,178         | 16,859  | 234.091 | 22,460 | 16,141   | 219.301    | 760 |
| 770 | 30,644                           | 24,242                    | 255.452                      | 22,890                              | 16,488  | 225.947 | 26,741                               | 20,339  | 222.221    | 23,513         | 17,111  | 234.528 | 22,772 | 16,370   | 219.709    | 770 |
| 780 | 31,154                           | 24,669                    | 256.110                      | 23,208                              | 16,723  | 226.357 | 27,125                               | 20,639  | 222.717    | 23,850         | 17,364  | 234.960 | 23,085 | 16,599   | 220.113    | 780 |
| 790 | 31,665                           | 25,097                    | 256.762                      | 23,526                              | 16,957  | 226.762 | 27,510                               | 20,941  | 223.207    | 24,186         | 17,618  | 235.387 | 23,398 | 16,830   | 220.512    | 790 |
| 800 | 32,179                           | 25,527                    | 257.408                      | 23,844                              | 17,193  | 227.162 | 27,896                               | 21,245  | 223.693    | 24,523         | 17,872  | 235.810 | 23,714 | 17,061   | 220.907    | 800 |
| 810 | 32,694                           | 25,959                    | 258.048                      | 24,164                              | 17,429  | 227.559 | 28,284                               | 21,549  | 224.174    | 24,861         | 18,126  | 236.230 | 24,027 | 17,292   | 221.298    | 810 |
| 820 | 33,212                           | 26,394                    | 258.682                      | 24,483                              | 17,665  | 227.952 | 28,672                               | 21,855  | 224.651    | 25,199         | 18,382  | 236.644 | 24,342 | 17,524   | 221.684    | 820 |
| 830 | 33,730                           | 26,829                    | 259.311                      | 24,803                              | 17,902  | 228.339 | 29,062                               | 22,162  | 225.123    | 25,537         | 18,637  | 237.055 | 24,658 | 17,757   | 222.067    | 830 |
| 840 | 34,251                           | 27,267                    | 259.934                      | 25,124                              | 18,140  | 228.724 | 29,454                               | 22,470  | 225.592    | 25,877         | 18,893  | 237.462 | 24,974 | 17,990   | 222.447    | 840 |

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| 850 | 34,773 | 27,706 | 260.551 | 25,446 | 18,379 | 229,106 | 29,846 | 22,779 | 226.057 | 26,218 | 19,150 | 237.864 | 25,292 | 18,224 | 222.822 | 850 |
|-----|--------|--------|---------|--------|--------|---------|--------|--------|---------|--------|--------|---------|--------|--------|---------|-----|
| 860 | 35,296 | 28,125 | 261.164 | 25,768 | 18,617 | 229,482 | 30,240 | 23,090 | 226.517 | 26,559 | 19,408 | 238.264 | 25,610 | 18,459 | 223.194 | 860 |
| 870 | 35,821 | 28,588 | 261.770 | 26.091 | 18,858 | 229.856 | 30,635 | 23,402 | 226.973 | 26,899 | 19,666 | 238.660 | 25,928 | 18,695 | 223.562 | 870 |
| 880 | 36,347 | 29,031 | 262.371 | 26,415 | 19,099 | 230.227 | 31,032 | 23,715 | 227.426 | 27,242 | 19,925 | 239.051 | 26,248 | 18,931 | 223.927 | 880 |
| 890 | 36,876 | 29,476 | 262.968 | 26,740 | 19,341 | 230.593 | 31,429 | 24,029 | 227.875 | 27,584 | 20,185 | 239.439 | 26,568 | 19,168 | 224.288 | 890 |
| 900 | 37,405 | 29,922 | 263.559 | 27,066 | 19,583 | 230.957 | 31,828 | 24,345 | 228.321 | 27,928 | 20,445 | 239.823 | 26,890 | 19,407 | 224.647 | 900 |
| 910 | 37,935 | 30,369 | 264.146 | 27,392 | 19,826 | 231.317 | 32,228 | 24,662 | 228.763 | 28,272 | 20,706 | 240.203 | 27,210 | 19,644 | 225.002 | 910 |
| 920 | 38,467 | 30,818 | 264.728 | 27,719 | 20,070 | 231.674 | 32,629 | 24,980 | 229.202 | 28,616 | 20,967 | 240.580 | 27,532 | 19,883 | 225.353 | 920 |
| 930 | 39,000 | 31,268 | 265.304 | 28,046 | 20,314 | 232.028 | 33,032 | 25,300 | 229.637 | 28,960 | 21,228 | 240.953 | 27,854 | 20,122 | 225.701 | 930 |
| 940 | 39,535 | 31,719 | 265.877 | 28,375 | 20,559 | 232.379 | 33,436 | 25,621 | 230.070 | 29,306 | 21,491 | 241.323 | 28,178 | 20,362 | 226.047 | 940 |
| 950 | 40,070 | 32,171 | 266.444 | 28,703 | 20,805 | 232.727 | 33,841 | 25,943 | 230.499 | 29,652 | 21,754 | 241.689 | 28,501 | 20,603 | 226.389 | 950 |
| 960 | 40,607 | 32,625 | 267.007 | 29,033 | 21,051 | 233.072 | 34,247 | 26,265 | 230.924 | 29,999 | 22,017 | 242.052 | 28,826 | 20,844 | 226.728 | 960 |
| 970 | 41,145 | 33,081 | 267.566 | 29,362 | 21,298 | 233.413 | 34,653 | 26,588 | 231.347 | 30,345 | 22,280 | 242.411 | 29,151 | 21,086 | 227.064 | 970 |
| 980 | 41,685 | 33,537 | 268.119 | 29,693 | 21,545 | 233.752 | 35,061 | 26,913 | 231.767 | 30,692 | 22,544 | 242.768 | 29,476 | 21,328 | 227.398 | 980 |
| 990 | 42,226 | 33,995 | 268,670 | 30.024 | 21.793 | 234,088 | 35,472 | 27,240 | 232,184 | 31.041 | 22,809 | 243.120 | 29,803 | 21.571 | 227.728 | 990 |

|      |                          |                         |                                |                                 |                       | T(K                | (), $\overline{h}$ and $\overline{u}$ | kJ/kmol), 3                 | (kJ/kmol ·                  | K)     |                        |           |        |                          |           |     |
|------|--------------------------|-------------------------|--------------------------------|---------------------------------|-----------------------|--------------------|---------------------------------------|-----------------------------|-----------------------------|--------|------------------------|-----------|--------|--------------------------|-----------|-----|
|      | $Car (\bar{h}_{f}^{o} =$ | bon Dioxid<br>- 393,520 | e, CO <sub>2</sub><br>kJ/kmol) | Carbo<br>$(\bar{h}_{f}^{o} = -$ | n Monoxi<br>- 110,530 | de, CO<br>kJ/kmol) | $\overline{h}_{f}^{\circ} = -$        | ter Vapor, I<br>- 241,820 k | I <sub>2</sub> O<br>J/kmol) | (h;    | Oxygen, O<br>= 0 kJ/kn | 2<br>nol) |        | litrogen, N<br>= 0 kJ/kn | 2<br>nol) |     |
| Т    | h                        | ū                       | 50                             | h                               | ū                     | 50                 | h                                     | ū                           | 50                          | h      | ū                      | 50        | ħ      | ū                        | 50        | Т   |
| 1000 | 42,769                   | 34,455                  | 269.215                        | 30,355                          | 22,041                | 234.421            | 35,882                                | 27,568                      | 232.597                     | 31,389 | 23,075                 | 243.471   | 30,129 | 21,815                   | 228.057   | 100 |
| 1020 | 43,859                   | 35,378                  | 270.293                        | 31,020                          | 22,540                | 235.079            | 36,709                                | 28,228                      | 233.415                     | 32,088 | 23,607                 | 244.164   | 30,784 | 22,304                   | 228.706   | 102 |
| 1040 | 44,953                   | 36,306                  | 271.354                        | 31,688                          | 23,041                | 235.728            | 37,542                                | 28,895                      | 234.223                     | 32,789 | 24,142                 | 244.844   | 31,442 | 22,795                   | 229.344   | 104 |
| 1060 | 46,051                   | 37,238                  | 272.400                        | 32,357                          | 23,544                | 236.364            | 38,380                                | 29,567                      | 235.020                     | 33,490 | 24,677                 | 245.513   | 32,101 | 23,288                   | 229.973   | 106 |
| 1080 | 47,153                   | 38,174                  | 273.430                        | 33,029                          | 24,049                | 236.992            | 39,223                                | 30,243                      | 235.806                     | 34,194 | 25,214                 | 246.171   | 32,762 | 23,782                   | 230.591   | 108 |
| 1100 | 48,258                   | 39,112                  | 274.445                        | 33,702                          | 24,557                | 237.609            | 40,071                                | 30,925                      | 236.584                     | 34,899 | 25,753                 | 246.818   | 33,426 | 24,280                   | 231.199   | 110 |
| 1120 | 49,369                   | 40,057                  | 275.444                        | 34,377                          | 25,065                | 238.217            | 40,923                                | 31,611                      | 237.352                     | 35,606 | 26,294                 | 247.454   | 34,092 | 24,780                   | 231.799   | 112 |
| 1140 | 50,484                   | 41,006                  | 276.430                        | 35,054                          | 25,575                | 238.817            | 41,780                                | 32,301                      | 238.110                     | 36,314 | 26,836                 | 248.081   | 34,760 | 25,282                   | 232.391   | 114 |
| 1160 | 51,602                   | 41,957                  | 277.403                        | 35,733                          | 26,088                | 239.407            | 42,642                                | 32,997                      | 238.859                     | 37,023 | 27,379                 | 248.698   | 35,430 | 25,786                   | 232.973   | 116 |
| 1180 | 52,724                   | 42,913                  | 278.362                        | 36,406                          | 26,602                | 239.989            | 43,509                                | 33,698                      | 239.600                     | 37,734 | 27,923                 | 249.307   | 36,104 | 26,291                   | 233.549   | 118 |
| 1200 | 53,848                   | 43,871                  | 279.307                        | 37,095                          | 27,118                | 240.663            | 44,380                                | 34,403                      | 240.333                     | 38,447 | 28,469                 | 249.906   | 36,777 | 26,799                   | 234.115   | 120 |
| 1220 | 54,977                   | 44,834                  | 280.238                        | 37,780                          | 27,637                | 241.128            | 45,256                                | 35,112                      | 241.057                     | 39,162 | 29,018                 | 250.497   | 37,452 | 27,308                   | 234.673   | 122 |
| 1240 | 56,108                   | 45,799                  | 281.158                        | 38,466                          | 28,426                | 241.686            | 46,137                                | 35,827                      | 241.773                     | 39,877 | 29,568                 | 251.079   | 38,129 | 27,819                   | 235.223   | 124 |
| 1260 | 57,244                   | 46,768                  | 282.066                        | 39,154                          | 28,678                | 242.236            | 47,022                                | 36,546                      | 242.482                     | 40,594 | 30,118                 | 251.653   | 38,807 | 28,331                   | 235.766   | 126 |
| 1280 | 58,381                   | 47,739                  | 282.962                        | 39,884                          | 29,201                | 242.780            | 47,912                                | 37,270                      | 243.183                     | 41,312 | 30,670                 | 252.219   | 39,488 | 28,845                   | 236.302   | 128 |
| 1300 | 59,522                   | 48,713                  | 283.847                        | 40,534                          | 29,725                | 243.316            | 48,807                                | 38,000                      | 243.877                     | 42,033 | 31,224                 | 252.776   | 40,170 | 29,361                   | 236.831   | 130 |
| 1320 | 60,666                   | 49,691                  | 284.722                        | 41,266                          | 30,251                | 243.844            | 49,707                                | 38,732                      | 244.564                     | 42,753 | 31,778                 | 253.325   | 40,853 | 29,878                   | 237.353   | 132 |
| 1340 | 61,813                   | 50,672                  | 285.586                        | 41,919                          | 30,778                | 244.366            | 50,612                                | 39,470                      | 245.243                     | 43,475 | 32,334                 | 253.868   | 41,539 | 30,398                   | 237.867   | 134 |
| 1360 | 62,963                   | 51,656                  | 286.439                        | 42,613                          | 31,306                | 244.880            | 51,521                                | 40,213                      | 245.915                     | 44,198 | 32,891                 | 254.404   | 42,227 | 30,919                   | 238.376   | 130 |
| 380  | 04,110                   | 52,045                  | 287.283                        | 43,309                          | 31,830                | 245.388            | 52,434                                | 40,960                      | 240.582                     | 44,923 | 33,449                 | 254.932   | 42,915 | 31,441                   | 238.878   | 138 |
| 1400 | 65,271                   | 53,631                  | 288.106                        | 44,007                          | 32,367                | 245.889            | 53,351                                | 41,711                      | 247.241                     | 45,648 | 34,008                 | 255.454   | 43,605 | 31,964                   | 239.375   | 140 |
| 1420 | 66,427                   | 54,621                  | 288.934                        | 44,707                          | 32,900                | 246.385            | 54,273                                | 42,466                      | 247.895                     | 46,374 | 34,567                 | 255.968   | 44,295 | 32,489                   | 239.865   | 142 |
| 1440 | 67,586                   | 55,614                  | 289.743                        | 45,408                          | 33,434                | 246.876            | 55,198                                | 43,226                      | 248.543                     | 47,102 | 35,129                 | 256.475   | 44,988 | 33,014                   | 240.350   | 144 |
| 1460 | 68,/48                   | 57,609                  | 290.542                        | 40,110                          | 33,9/1                | 247.300            | 57,062                                | 43,989                      | 249.185                     | 47,851 | 35,692                 | 250.978   | 45,682 | 33,343                   | 240.827   | 140 |
|      | 0,,11                    | 57,000                  | 271.355                        | 40,015                          | 54,000                | 247.007            | 57,002                                | 44,750                      | 249.020                     | 40,501 | 50,250                 | 231.414   | 10,577 | 54,071                   | 241.501   | 140 |
| 0    | 71,078                   | 58,606                  | 292.114                        | 47,517                          | 35,046                | 248.312            | 57,999                                | 45,528                      | 250.450                     | 49,292 | 36,821                 | 257.965   | 47,073 | 34,601                   | 241.768   |     |
|      | 72,246                   | 59,609                  | 292.888                        | 48,222                          | 35,584                | 248.778            | 58,942                                | 46,304                      | 251.074                     | 50,024 | 37,387                 | 258.450   | 4/,//1 | 35,133                   | 242.228   |     |
|      | 73,417                   | 61,620                  | 292.654                        | 48,928                          | 30,124                | 249.240            | 59,888                                | 47,084                      | 251.095                     | 51,400 | 37,952                 | 258.928   | 48,470 | 35,005                   | 242.683   |     |
|      | 76,767                   | 62 620                  | 294.411                        | 49,033                          | 30,003                | 249.095            | 61 702                                | 47,808                      | 252.305                     | 52,224 | 30,520                 | 259.402   | 49,108 | 36,197                   | 243.137   |     |
|      | 10,101                   | 02,030                  | 295.101                        | 50,544                          | 51,201                | 230.147            | 01,792                                | 48,033                      | 252.912                     | 52,224 | 39,088                 | 239.870   | 49,809 | 30,732                   | 243.383   |     |
| 0    | 76,944                   | 63,741                  | 295.901                        | 51,053                          | 37,750                | 250.592            | 62,748                                | 49,445                      | 253.513                     | 52,961 | 39,658                 | 260.333   | 50,571 | 37,268                   | 244.028   |     |
| 0    | 78,123                   | 64,653                  | 296.632                        | 51,763                          | 38,293                | 251.033            | 63,709                                | 52,240                      | 254.111                     | 53,696 | 40,227                 | 260.791   | 51,275 | 37,806                   | 244.464   |     |
| 0    | 79,303                   | 65,668                  | 297.356                        | 52,472                          | 38,837                | 251.470            | 64,675                                | 51,039                      | 254.703                     | 54,434 | 40,799                 | 261.242   | 51,980 | 38,344                   | 244.896   |     |
| 0    | 80,486                   | 66,592                  | 298.072                        | 53,184                          | 39,382                | 251.901            | 65,643                                | 51,841                      | 255.290                     | 55,172 | 41,370                 | 261.690   | 52,686 | 38,884                   | 245.324   |     |
| 0    | 81,670                   | 67,702                  | 298.781                        | 53,895                          | 39,927                | 252.329            | 66,614                                | 52,646                      | 255.873                     | 55,912 | 41,944                 | 262.132   | 53,393 | 39,424                   | 245.747   | 1   |
| 0    | 82,856                   | 68,721                  | 299.482                        | 54,609                          | 40,474                | 252.751            | 67,589                                | 53,455                      | 256.450                     | 56,652 | 42,517                 | 262.571   | 54,099 | 39,965                   | 246.166   |     |
| 0    | 84,043                   | 69,742                  | 300.177                        | 55,323                          | 41,023                | 253.169            | 68,567                                | 54,267                      | 257.022                     | 57,394 | 43,093                 | 263.005   | 54,807 | 40,507                   | 246.580   |     |
| 0    | 85,231                   | 70,764                  | 300.863                        | 56,039                          | 41.572                | 253,582            | 69,550                                | 55.083                      | 257.589                     | 58,136 | 43.669                 | 263,435   | 55,516 | 41.049                   | 246,990   |     |

TABLE A-23 (Continued)

|      |                                 |                           |                              |                                 |                      | T(K                | (), $\overline{h}$ and $\overline{u}$  | kJ/kmol), s | °(kJ/kmol | K)      |                        |         |         |                         |                        |      |
|------|---------------------------------|---------------------------|------------------------------|---------------------------------|----------------------|--------------------|--|-------------|-----------|---------|------------------------|---------|---------|-------------------------|------------------------|------|
|      | $Carb (\bar{h}_{f}^{\circ} = -$ | on Dioxide<br>- 393,520 1 | , CO <sub>2</sub><br>J/kmol) | Carbo<br>$(\bar{h}_{f}^{o} = -$ | n Monoxi<br>-110,530 | de, CO<br>kJ/kmol) | $\begin{array}{l} \text{O} & \text{Water Vapor, } \text{H}_2\text{O} \\ \text{nol}) & (\overline{h}_1^o = -241,820 \text{ kJ/kmol}) \end{array}$ |             |           | (ħ°     | Oxygen, O<br>= 0 kJ/kr | nol)    | (ħ°     | litrogen, 1<br>= 0 kJ/k | N <sub>2</sub><br>mol) |      |
| Т    | ħ                               | ū                         | 30                           | ħ                               | ū                    | <u>5</u> 0         | ħ  | ū           | 50        | ħ       | ū                      | 30      | h       | ū                       | <u>s</u> °             | T    |
| 1760 | 86,420                          | 71,787                    | 301.543                      | 56,756                          | 42,123               | 253.991            | 70,535   | 55,902      | 258.151   | 58,800  | 44,247                 | 263.861 | 56,227  | 41,594                  | 247.396                | 1760 |
| 1780 | 87,612                          | 72,812                    | 302.271                      | 57,473                          | 42,673               | 254.398            | 71,523   | 56,723      | 258.708   | 59,624  | 44,825                 | 264.283 | 56,938  | 42,139                  | 247.798                | 1780 |
| 1800 | 88,806                          | 73,840                    | 302.884                      | 58,191                          | 43,225               | 254.797            | 72,513   | 57,547      | 259.262   | 60,371  | 45,405                 | 264.701 | 57,651  | 42,685                  | 248.195                | 1800 |
| 1820 | 90,000                          | 74,868                    | 303.544                      | 58,910                          | 43,778               | 255.194            | 73,507   | 58,375      | 259.811   | 61,118  | 45,986                 | 265.113 | 58,363  | 43,231                  | 248.589                | 1820 |
| 1840 | 91,196                          | 75,897                    | 304.198                      | 59,629                          | 44,331               | 255.587            | 74,506   | 59,207      | 260.357   | 61,866  | 46,568                 | 265.521 | 59,075  | 43,777                  | 248.979                | 1840 |
| 1860 | 92,394                          | 76,929                    | 304.845                      | 60,351                          | 44,886               | 255.976            | 75,506   | 60,042      | 260.898   | 62,616  | 47,151                 | 265.925 | 59,790  | 44,324                  | 249.365                | 1860 |
| 1880 | 93,593                          | 77,962                    | 305.487                      | 61,072                          | 45,441               | 256.361            | 76,511   | 60,880      | 261.436   | 63,365  | 47,734                 | 266.326 | 60,504  | 44,873                  | 249.748                | 1880 |
| 1900 | 94,793                          | 78,996                    | 306.122                      | 61,794                          | 45,997               | 256.743            | 77,517   | 61,720      | 261.969   | 64,116  | 48,319                 | 266.722 | 61,220  | 45,423                  | 250.128                | 1900 |
| 1920 | 95,995                          | 80,031                    | 306.751                      | 62,516                          | 46,552               | 257.122            | 78,527   | 62,564      | 262.497   | 64,868  | 48,904                 | 267.115 | 61,936  | 45,973                  | 250.502                | 1920 |
| 1940 | 97,197                          | 81,067                    | 307.374                      | 63,238                          | 47,108               | 257.497            | 79,540   | 63,411      | 263.022   | 65,620  | 49,490                 | 267.505 | 62,654  | 46,524                  | 250.874                | 1940 |
| 1960 | 98,401                          | 82,105                    | 307.992                      | 63,961                          | 47,665               | 257.868            | 80,555   | 64,259      | 263.542   | 66,374  | 50,078                 | 267.891 | 63,381  | 47,075                  | 251.242                | 1960 |
| 1980 | 99,606                          | 83,144                    | 308.604                      | 64,684                          | 48,221               | 258.236            | 81,573   | 65,111      | 264.059   | 67,127  | 50,665                 | 268.275 | 64,090  | 47,627                  | 251.607                | 1980 |
| 2000 | 100,804                         | 84,185                    | 309.210                      | 65,408                          | 48,780               | 258.600            | 82,593   | 65,965      | 264.571   | 67,881  | 51,253                 | 268.655 | 64,810  | 48,181                  | 251.969                | 2000 |
| 2050 | 103,835                         | 86,791                    | 310.701                      | 67,224                          | 50,179               | 259.494            | 85,156   | 68,111      | 265.838   | 69,772  | 52,727                 | 269.588 | 66,612  | 49,567                  | 252.858                | 2050 |
| 2100 | 106,864                         | 89,404                    | 312.160                      | 69,044                          | 51,584               | 260.370            | 87,735   | 70,275      | 267.081   | 71,668  | 54,208                 | 270.504 | 68,417  | 50,957                  | 253.726                | 2100 |
| 2150 | 109,898                         | 92,023                    | 313.589                      | 70,864                          | 52,988               | 261.226            | 90,330   | 72,454      | 268.301   | 73,573  | 55,697                 | 271.399 | 70,226  | 52,351                  | 254.578                | 2150 |
| 2200 | 112,939                         | 94,648                    | 314.988                      | 72,688                          | 54,396               | 262.065            | 92,940   | 74,649      | 269.500   | 75,484  | 57,192                 | 272.278 | 72,040  | 53,749                  | 255.412                | 2200 |
| 2250 | 115,984                         | 97,277                    | 316.356                      | 74,516                          | 55,809               | 262.887            | 95,562   | 76,855      | 270.679   | 77,397  | 58,690                 | 273.136 | 73,856  | 55,149                  | 256.227                | 2250 |
| 2300 | 119,035                         | 99,912                    | 317.695                      | 76,345                          | 57,222               | 263.692            | 98,199   | 79,076      | 271.839   | 79,316  | 60,193                 | 273.981 | 75,676  | 56,553                  | 257.027                | 2300 |
| 2350 | 122,091                         | 102,552                   | 319.011                      | 78,178                          | 58,640               | 264.480            | 100,846  | 81,308      | 272.978   | 81,243  | 61,704                 | 274.809 | 77,496  | 57,958                  | 257.810                | 2350 |
| 2400 | 125,152                         | 105,197                   | 320.302                      | 80,015                          | 60,060               | 265.253            | 103,508  | 83,553      | 274.098   | 83,174  | 63,219                 | 275.625 | 79,320  | 59,366                  | 258.580                | 2400 |
| 2450 | 128,219                         | 107,849                   | 321.566                      | 81,852                          | 61,482               | 266.012            | 106,183  | 85,811      | 275.201   | 85,112  | 64,742                 | 276.424 | 81,149  | 60,779                  | 259.332                | 2450 |
| 2500 | 131,290                         | 110,504                   | 322.808                      | 83,692                          | 62,906               | 266.755            | 108,868  | 88,082      | 276.286   | 87,057  | 66,271                 | 277.207 | 82,981  | 62,195                  | 260.073                | 2500 |
| 2550 | 134,368                         | 113,166                   | 324.026                      | 85,537                          | 64,335               | 267.485            | 111,565  | 90,364      | 277.354   | 89,004  | 67,802                 | 277.979 | 84,814  | 63,613                  | 260.799                | 2550 |
| 2600 | 137,449                         | 115,832                   | 325.222                      | 87,383                          | 65,766               | 268.202            | 114,273  | 92,656      | 278.407   | 90,956  | 69,339                 | 278.738 | 86,650  | 65,033                  | 261.512                | 2600 |
|      |                                 |                           |                              |                                 |                      |                    | •  |             |           |         |                        |         |         |                         |                        |      |
| 2650 | 140,533                         | 118,500                   | 326.396                      | 89,230                          | 67,197               | 268.905            | 116,991  | 94,958      | 279,441   | 92,916  | 70,883                 | 279.485 | 88,488  | 66,455                  | 262.213                | 2650 |
| 2700 | 143,620                         | 121,172                   | 327.549                      | 91,077                          | 68,628               | 269.596            | 119,717  | 97,269      | 280.462   | 94,881  | 72,433                 | 280.219 | 90,328  | 67,880                  | 262.902                | 2700 |
| 2750 | 146,713                         | 123,849                   | 328.684                      | 92,930                          | 70,066               | 270.285            | 122,453  | 99,588      | 281.464   | 96,852  | 73,987                 | 280.942 | 92,171  | 69,306                  | 263.577                | 2750 |
| 2800 | 149,808                         | 126,528                   | 329.800                      | 94,784                          | 71,504               | 270.943            | 125,198  | 101,917     | 282.453   | 98,826  | 75,546                 | 281.654 | 94,014  | 70,734                  | 264.241                | 2800 |
| 2850 | 152,908                         | 129,212                   | 330.896                      | 96,639                          | 72,945               | 271.602            | 127,952  | 104,256     | 283.429   | 100,808 | 77,112                 | 282.357 | 95,859  | 72,163                  | 264.895                | 2850 |
| 2900 | 156,009                         | 131,898                   | 331.975                      | 98,495                          | 74,383               | 272.249            | 130,717  | 106,605     | 284.390   | 102,793 | 78,682                 | 283.048 | 97,705  | 73,593                  | 265.538                | 2900 |
| 2950 | 159,117                         | 134,589                   | 333.037                      | 100,352                         | 75,825               | 272.884            | 133,486  | 108,959     | 285.338   | 104,785 | 80,258                 | 283.728 | 99,556  | 75,028                  | 266.170                | 2950 |
| 3000 | 162,226                         | 137,283                   | 334.084                      | 102,210                         | 77,267               | 273.508            | 136,264  | 111,321     | 286.273   | 106,780 | 81,837                 | 284.399 | 101,407 | 76,464                  | 266.793                | 3000 |
| 3050 | 165,341                         | 139,982                   | 335.114                      | 104,073                         | 78,715               | 274.123            | 139,051  | 113,692     | 287.194   | 108,778 | 83,419                 | 285.060 | 103,260 | 77,902                  | 267.404                | 3050 |
| 3100 | 168,456                         | 142,681                   | 336.126                      | 105,939                         | 80,164               | 274.730            | 141,846  | 116,072     | 288.102   | 110,784 | 85,009                 | 285.713 | 105,115 | 79,341                  | 268.007                | 3100 |
| 3150 | 171,576                         | 145,385                   | 337.124                      | 107,802                         | 81,612               | 275.326            | 144,648  | 118,458     | 288.999   | 112,795 | 86,601                 | 286.355 | 106,972 | 80,782                  | 268.601                | 3150 |
| 3200 | 174,695                         | 148,089                   | 338.109                      | 109,667                         | 83,061               | 275.914            | 147,457  | 120,851     | 289.884   | 114,809 | 88,203                 | 286.989 | 108,830 | 82,224                  | 269.186                | 3200 |
| 3250 | 177,822                         | 150,801                   | 339.069                      | 111,534                         | 84,513               | 276.494            | 150,272  | 123,250     | 290.756   | 116,827 | 89,804                 | 287.614 | 110,690 | 83,668                  | 269.763                | 3250 |

**Another way** is not to use the Tables, but calculate  $\Delta h$  as (cp .  $\Delta T$ ), cp being calculated from the formulas given in Thermodynamics Text books for CO2, CO, O2, N2 etc.

We have the following relations for cp (kJ/kmol) of some commonly required substances in chemical reactions, with temp T in Kelvin. [Ref. 11]:

$$cp_{CO2}(T) := (45.369 + 3.688 \cdot 10^{-3} \cdot T - 9.619 \cdot 10^{5} \cdot T^{-2}) kJ/kmol$$

$$cp_{CO}(T) := (28.068 + 4.631 \cdot 10^{-3} \cdot T - 0.258 \cdot 10^{5} \cdot T^{-2})$$
 kJ/kmol

 $cp_{H2O}(T) \coloneqq 28.85 + 12.055 \cdot 10^{-3} \cdot T + 1.066 \cdot 10^{5} \cdot T^{-2} \qquad kJ/kmol$ 

$$\begin{split} cp_{O2}(T) &:= \left( 30.255 + 4.207 \cdot 10^{-3} \cdot T - 1.887 \cdot 10^{5} \cdot T^{-2} \right) & \text{kJ/kmol} \\ cp_{N2}(T) &:= 27.27 + 4.930 \cdot 10^{-3} \cdot T + 0.333 \cdot 10^{5} \cdot T^{-2} & \text{kJ/kmol} \\ cp_{H2}(T) &:= 27.012 + 3.509 \cdot 10^{-3} \cdot T + 0.69 \cdot 10^{5} \cdot T^{-2} & \text{kJ/kmol} \\ cp_{NH3}(T) &:= \left( 29.747 + 25.108 \cdot 10^{-3} \cdot T - 1.546 \cdot 10^{5} \cdot T^{-2} \right) & \text{kJ/kmol} \\ cp_{CH4}(T) &:= \left( 17.449 + 60.449 \cdot 10^{-3} \cdot T + 1.117 \cdot 10^{-6} \cdot T^{2} - 7.204 \cdot 10^{-9} \cdot T^{3} \right) & \text{kJ/kmol} \\ cp_{SO2}(T) &:= \left( 47.381 + 6.66 \cdot 10^{-3} \cdot T - 8.439 \cdot 10^{5} \cdot T^{-2} \right) & \text{kJ/kmol} \\ Then: & \Delta h = \int_{T1}^{T2} cp(T) \, dT \end{split}$$

#### Also, following Table from [Ref: 3] gives some equations for cp:

|                  |       | $\frac{\overline{c}_p}{\overline{R}} = \alpha + \beta T +$ | $\gamma T^2 + \delta T^3 + \varepsilon T^4$ |                            |                              |
|------------------|-------|--|---|----------------------------|------------------------------|
| 200              | T is  | in K, equations va   | lid from 300 to 10                          | 00 K                       |                              |
| Gas              | α     | $\beta \times 10^{\circ}$                                  | $\gamma \times 10^{\circ}$                  | $\delta \times 10^{\circ}$ | $\varepsilon \times 10^{-2}$ |
| CO               | 3.710 | -1.619   | 3.692                                       | -2.032                     | 0.240                        |
| CO <sub>2</sub>  | 2.401 | 8.735  | -6.607                                      | 2.002                      | 0                            |
| H <sub>2</sub>   | 3.057 | 2.677  | -5.810                                      | 5.521                      | -1.812                       |
| H <sub>2</sub> O | 4.070 | -1.108   | 4.152                                       | -2.964                     | 0.807                        |
| O2               | 3.626 | -1.878   | 7.055                                       | -6.764                     | 2.156                        |
| N <sub>2</sub>   | 3.675 | -1.208   | 2.324                                       | -0.632                     | -0.226                       |
| Air              | 3.653 | -1.337   | 3.294                                       | -1.913                     | 0.2763                       |
| SO <sub>2</sub>  | 3.267 | 5.324  | 0.684                                       | -5.281                     | 2.559                        |
| CH <sub>4</sub>  | 3.826 | -3.979   | 24.558                                      | -22.733                    | 6.963                        |
| C2H2             | 1.410 | 19.057   | -24.501                                     | 16.391                     | -4.135                       |
| $C_2H_4$         | 1.426 | 11.383   | 7.989                                       | -16.254                    | 6.749                        |
| Monatomic        |       |  |   |                            |                              |

"For monatomic gases, such as He, Ne, and Ar,  $\overline{c}_p$  is constant over a wide temperature range and is very nearly equal to  $5/2 \overline{R}$ .

Source: Adapted from K. Wark, *Thermodynamics*, 4th ed., McGraw-Hill, New York, 1983, as based on NASA SP-273, U.S. Government Printing Office, Washington, DC, 1971.

#### 8.1.9 Enthalpy of combustion:

**Enthalpy of combustion** is defined as the difference between enthalpy of the products and the enthalpy of reactants when complete combustion occurs at a given temp and pressure. It is also known as 'heating value' and is expressed in kJ/kg or kJ/kg mol.

Note that *two heating values* are defined:

Higher Heating Value (HHV) or Higher Calorific Value (HCV) and Lower Heating Value (LHV) or Lower Calorific Value (LCV):

HCV is the heat transferred when H2O in the products is in *liquid state*.

LCV is the heat transferred in the reaction when H2O in the products is *in vapor state*. And:

 $LCV = HCV = m_{_{H2O}} \times h_{_{fg}}$ 

HCV is given by [Ref:6]:

$$HCV = \frac{1}{100} \left[ 35000 \cdot C + 143000 \cdot \left( H - \frac{O}{8} \right) + 9160 \cdot S \right] \qquad kJ/kg$$

where C, H, O and S are percentages of carbon, hydrogen, oxygen and sulphur.

$$LCV = HCV - \frac{9}{100} \cdot H \cdot 2460 \qquad kJ/kg$$

| Values of enthalpy of combustion for some common hydrocarbon fuels at 25 C, 1 atm are give |
|--|
| below. [Ref: 9, TEST software]:  |

| [                | Table G-2, Re   | actions:       | Heating              | Values of C                              | òmmon F                       | uels                                    |  |
|------------------|---|----------------|----------------------|--|-------------------------------|---|--|
|                  | <ul> <li>Image: A start of the start of</li></ul> | SI Units       |                      | English Units                            |                               |   |  |
|                  | Propertie   | es of Some     | Common               | Fuels and Hydro                          | carbons                       |   |  |
|                  |   | Molar<br>Mass  | Density <sup>1</sup> | Enthalpy of<br>Vaporization <sup>2</sup> | Specific<br>Heat <sup>1</sup> | Higher<br>Heating<br>Value <sup>3</sup> | Lower<br>Heating<br>Value <sup>4</sup> |
| Fuel (Phase)     | Formula   | kg/kmol        | kg/L                 | kJ/kg                                    | kJ/kg·K                       | kJ/kg                                   | kJ/kg                                  |
|                  |   | $\overline{M}$ | ρ                    | $\Delta h_{v}$                           | $c_p$                         | HHV                                     | LHV                                    |
| Carbon(s)        | С   | 12.01          | 2.000                | -  | 0.708                         | 32,800                                  | 32,800                                 |
| Hydrogen(g)      | H2  | 2.02           | -                    | -  | 14.40                         | 141,800                                 | 120,000                                |
| Carbon Monoxide( | g) CO   | 28.01          | -                    | -  | 1.05                          | 10,100                                  | 10,100                                 |
| Methane(g)       | CH4   | 16.04          | -                    | 509                                      | 2.20                          | 55,530                                  | 50,050                                 |
| Methanol(I)      | CH4O  | 32.04          | 0.790                | 1168                                     | 2.53                          | 22,660                                  | 19,920                                 |
| Acetylene(g)     | C2H2  | 26.04          | -                    | -  | 1.69                          | 49,970                                  | 48,280                                 |
| Ethane(g)        | C2H6  | 30.07          | -                    | 172                                      | 1.75                          | 51,900                                  | 47,520                                 |
| Ethanol(I)       | C2H6O   | 46.07          | 0.790                | 919                                      | 2.44                          | 29,670                                  | 26,810                                 |
| Propane(I)       | СЗН8  | 44.10          | 0.500                | 420                                      | 2.77                          | 50,330                                  | 46,340                                 |
| Butane(I)        | C4H10   | 58.12          | 0.579                | 362                                      | 2.42                          | 49,150                                  | 45,370                                 |
| 1-Pentene(I)     | C5H10   | 70.13          | 0.641                | 363                                      | 2.20                          | 47,760                                  | 44,630                                 |
| Isopentane(I)    | C5H12   | 72.15          | 0.626                | -  | 2.32                          | 48,570                                  | 44,910                                 |
| Benzene(I)       | C6H6  | 78.11          | 0.877                | 433                                      | 1.72                          | 41,800                                  | 40,100                                 |
| Hexene(I)        | C6H12   | 84.16          | 0.673                | 392                                      | 1.84                          | 47,500                                  | 44,400                                 |
| Hexane(I)        | C6H14   | 86.18          | 0.660                | 366                                      | 2.27                          | 48,310                                  | 44,740                                 |
| Toluene(I)       | C7H8  | 92.14          | 0.867                | 412                                      | 1.71                          | 42,400                                  | 40,500                                 |
| Heptane(I)       | C7H16   | 100.20         | 0.684                | 365                                      | 2.24                          | 48,100                                  | 44,600                                 |
| Octane(I)        | C8H18   | 114.23         | 0.703                | 363                                      | 2.23                          | 47,890                                  | 44,430                                 |
| Decane(I)        | C10H22  | 142.29         | 0.730                | 361                                      | 2.21                          | 47,640                                  | 44,240                                 |
| Gasoline(I)      | CnH1.87n  | 100 - 110      | 0.72 - 0.78          | 350                                      | 2.4                           | 47,300                                  | 44,000                                 |
| Light Diesel(I)  | CnH1.8n   | 170            | 0.78 - 0.84          | 270                                      | 2.2                           | 46,100                                  | 43,200                                 |
| Heavy Diesel(I)  | CnH1.7n   | 200            | 0.82 - 0.88          | 230                                      | 1.9                           | 45,500                                  | 42,800                                 |
| Natural Gas(g)   | CnH3.8nN0.1n  | 18             | -                    | -  | 2.0                           | 50,000                                  | 45,000                                 |

1: 1 atm and 20°C.

2: At 25°C for liquid fuels, and at saturation temperature at 1 atm for gaseous fuels.

3: H<sub>2</sub>O in liquid phase in products.

4: H<sub>2</sub>O in vapor phase in products.

#### 8.1.10 Adiabatic Flame temperature:

If the combustion occurs adiabatically, without work and heat transfers, then the I Law reduces to:

$$H_r = H_p$$

i.e. 
$$\sum_{\mathbf{r}} \mathbf{n}_{\mathbf{i}} \cdot \mathbf{h}_{\mathbf{i}} = \sum_{\mathbf{p}} \mathbf{n}_{\mathbf{e}} \cdot \mathbf{h}_{\mathbf{e}}$$

i.e. 
$$\sum_{\mathbf{r}} \mathbf{n}_{\mathbf{i}} \left( \mathbf{h}_{\mathbf{f}\mathbf{0}} + \Delta \mathbf{h} \right)_{\mathbf{i}} = \sum_{\mathbf{p}} \mathbf{n}_{\mathbf{e}} \left( \mathbf{h}_{\mathbf{f}\mathbf{0}} + \Delta \mathbf{h} \right)_{\mathbf{e}}$$

Here, the temp of products is known as '*Adiabatic Flame temp*', which is the max. temp achieved for given reactants. This is important in Gas turbines. Temp is controlled by adjusting the excess air supplied. Flame temp is a maximum for stoichiometric mixtures.

Since the temp of products is not known to start with, adiabatic flame temp has to be *calculated by trial and error* using the combustion tables given above.

#### In this connection, Urieli [Ref. 10] has given following suggestion:

"A quick approximation to the adiabatic flame temperature can be obtained by assuming that the products consist entirely of air. This approach was introduced to us by <u>Potter</u> and Somerton in their <u>Schaum's</u> <u>Outline of Thermodynamics for Engineers</u>, in which they assumed all the products to be N<sub>2</sub>. We find it more convenient to use air assuming a representative value of the <u>Specific Heat Capacity of Air</u>:  $C_{p,1000K} = 1.142 [kJ/kg.K]$ ."

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165

#### 8.2 Problems solved with Mathcad:

**Prob.8.2.1** Write combustion equations for C, H2, S and CH4 (i.e. Methane) for complete combustion and find out the amount of air required for complete combustion.

#### Mathcad Solution:

For Carbon:

 $C + O_2 = CO_2$  ....combustion eqn.

By volume: one mole of C + 1 mole of O2 = 1 mole of CO2, since combustion eqns are mole eqns.

By mass: 12 kg C + 32 kg O2 = 44 kg CO2

Therefore: 1 kg of C requires (32/12) = (8/3) kg of O2 for complete combustion

But, 1 kg of O2 is contained in 1/0.23 kg of air since air contains 23% oxygen by mass

#### Therefore: 1 kg of C requires (8/3)/0.23 = 11.5 kg of Air, for complete combustion

For Hydrogen:

 $2H_2 + O_2 = 2 \cdot H2O$  ....combustion eqn.

By volume: 2 mol of H2 + 1 mol of O2 = 2 mol of H2O, since combustion eqns are mole eqns.

By mass: 4 kg H2 + 32 kg O2 = 36 kg H2O

Therefore: 1 kg of H2 requires 8 kg of O2 for complete combustion

But, 1 kg of O2 is contained in 1/0.23 kg of air since air contains 23% oxygen by mass

Therefore: 1 kg of H2 requires (8/0.23) = 34.783 kg of Air, for complete combustion

**Reactive Systems** 

#### For Sulphur:

 $S + O_2 = SO_2$  ....combustion eqn.

By volume: 1 mol of S + 1 mol of O2 = 1 mol of SO2, since combustion eqns are mole eqns.

By mass: 32 kg S + 32 kg O2 = 64 kg SO2

Therefore: 1 kg of S requires 1 kg of O2 for complete combustion

But, 1 kg of O2 is contained in 1/0.23 kg of air since air contains 23% oxygen by mass

Therefore: 1 kg of S requires (1/0.23) = 4.348 kg of Air, for complete combustion



#### For Mehane (CH4):

 $CH_4 + 2O_2 = CO_2 + 2 \cdot H2O$  ....combustion eqn.

By volume: 1 mol of CH4 + 2 mol of O2 = 1 mol of CO2 + 2 mol of H2O, since combustion eqns are mole eqns.

By mass: 16 kg CH4 + 64 kg O2 = 44 kg CO2 + 36 kg H2O

Therefore: 1 kg of CH4 requires 4 kg of O2 for complete combustion

But, 1 kg of O2 is contained in 1/0.23 kg of air since air contains 23% oxygen by mass

Therefore: 1 kg of CH4 requires (4/0.23) = 17.39 kg of Air, for complete combustion

#### Analysis by volume:

By volume: 1 mol of CH4 + 2 mol of O2 = 1 mol of CO2 + 2 mol of H2O, since combustion eqns are mole eqns.

i.e. 1 volume of CH4 + 2 volumes of O2 = 1 vol of CO2 + 2 vol of H2O

i.e. 1 m<sup>3</sup> of CH4 + 2 m<sup>3</sup> of O2 = 1 m<sup>3</sup> of CO2 + 2 m<sup>3</sup> of H2O

Now, since air contains 21% by volume of O2, we get:

1 m^3 of CH4 requires (2/0.21) = 9.524 m^3 of Air for complete combustion.

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**Prob.8.2.2** A sample of fuel has following percentage composition by weight: C = 84%, O2 = 3.5%, H2 = 10%, Ash = 1%, N2 = 1.5%. Determine: (i) stoichiometric AF ratio by mass (ii) if 20% excess air is supplied, find the percentage composition of dry flue gases by volume. [VTU]

#### Mathcad Solution:

Data: Considering 1 kg of fuel:

C := 0.84 H2 := 0.1 N2 := 0.015 O2 := 0.035 Ash := 0.01

#### Theoretical O2 required.... see problem 8.2.1:

| For C:  | $\mathbf{C} \cdot \frac{8}{3} = 2.24$ | kg O2 per kg fuel |
|---------|---------------------------------------|-------------------|
| For H2: | $H2 \cdot 8 = 0.8$                    | kg O2 per kg fuel |

Therefore: total O2 required: 2.24 + 0.8 = 3.04 kg O2 per kg fuel

Less: amount of O2 supplied by fuel= 0.035 kg

And, amount of theoretical O2 required to be supplied: 3.04 - 0.035 = 3.005 kg O2 per kg fuel

And, amount of theoretical O2 required to be supplied: 3.04 - 0.035 = 3.005 kg O2 per kg fuel

i.e. Amount of air to be supplied:  $\frac{3.005}{0.23} = 13.065$  kg Air per kg fuel....Ans.

#### i.e. Stoichiometric AF ratio = 13.065 kg Air/kg fuel .... Ans.

#### Dry prodcts of combustion:

CO2:  $C \cdot \frac{11}{3} = 3.08$  kg CO2 per kg fuel

N2: coming from air supplied + from fuel itself: 13.065-0.77 + 0.015 = 10.075 kg

Therefore, total dry products: CO2 + N2 = 3.08 + 10.075 = 13.155 kg

Then, mass analysis of dry products:

CO2: 
$$\frac{3.08}{13.155} \cdot 100 = 23.413$$
 %

N2: 
$$\frac{10.075}{13.155} \cdot 100 = 76.587 \%$$

#### If 20% excess air is supplied, then, products of combustion are:

CO2 = 3.08 kg

N2: comes from air supplied + from fuel:  $13.065 \cdot 1.2 \cdot 0.77 + 0.015 = 12.087$  kg O2: comes only from excess air supplied:  $13.065 \cdot 0.2 \cdot 0.23 = 0.601$  kg Therefore, total dry products formed per kg of fuel:

$$CO2 + N2 + O2 = 3.08 + 12.087 + 0.601 = 15.768$$
 kg

Then, mass analysis of dry products is:

N2: 
$$\frac{12.087}{15.768} \cdot 100 = 76.655$$
 %

CO2: 
$$\frac{3.08}{15.768} \cdot 100 = 19.533$$
 %

O2:  $\frac{0.601}{15.768} \cdot 100 = 3.812$  %

#### Mass analysis is converted to volume analysis as follows:

- N2: proportional volume:  $\frac{76.655}{28} = 2.738$
- CO2: proportional volume:  $\frac{19.533}{44} = 0.444$



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\* Figures taken from London Business School's Masters in Management 2010 employment report



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Applied Thermodynamics: Software Solutions: Part-IV (Psychrometrics, Reactive systems)

O2: proportional volume: 
$$\frac{3.812}{32} = 0.119$$

Total proportional vol: 2.738 + 0.444 + 0.119 = 3.301

#### Therefore, percentage of dry products by volume:

| N2:         | $\frac{2.738}{3.301} \cdot 100 = 82.945$ | % |
|-------------|--|---|
| CO2:        | $\frac{0.444}{3.301} \cdot 100 = 13.45$  | % |
| <b>O2</b> : | $\frac{0.119}{3.301} \cdot 100 = 3.605$  | % |

#### Alternative method:

Consider 100 kg of fuel.

Convert the components to kmol and write down the combustion eqn.

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#### Data:

Considering 100 kg of fuel. It contains:

C = 84 H2 = 10 N2 = 1.5 O2 = 3.5 Ash = 1 kg

Converting to kmols:

$$N_{C} := \frac{84}{12}$$
 i.e.  $N_{C} = 7$  kmol

$$N_{H2} := \frac{10}{2}$$
 i.e.  $N_{H2} = 5$  kmol

- ${\rm N}_{N2} := \frac{1.5}{28} \quad \mbox{i.e.} \qquad {\rm N}_{N2} = 0.054 \qquad \mbox{kmol}$
- $N_{O2} := \frac{3.5}{32}$  i.e.  $N_{O2} = 0.109$  kmol

**Reactive Systems** 

#### Disregard ash, which does not react.

7 C + 5 H2 + 0.054 N2 + 0.109 O2 + a (O2 + 3.76 N2) = x CO2 + y H2O + z N2

Equating coeffs of C: 7 = x

Equating coeffs of H: 10 = 2.y i.e. y = 5

Equating coeffs of O: 0.109 \* 2 + 2.a = 2. x + y = 19 i.e. a = 9.391

Equating coeffs of N2: 0.054 + a \* 3.76 = z i.e. z = 35.364

Therefore, the combustion eqn is:

7 C + 5 H2 + 0.054 N2 + 0.109 O2 + 9.391 (O2 + 3.76 N2) = 7 CO2 + 5 H2O + 35.364 N2

Therefore, AF ratio:

$$AF = \frac{9.391 \cdot 4.76 \cdot 29}{100} = 12.963 \quad \text{....stoichiometric AF ratio}$$

#### This matches well with the earlier AF value of 13.065

Then, mass analysis of dry products:

CO2: 
$$\frac{7 \cdot 44}{7 \cdot 44 + 35.364 \cdot 28} \cdot 100 = 23.725$$
 %  
N2:  $\frac{35.364 \cdot 28}{7 \cdot 44 + 35.364 \cdot 28} \cdot 100 = 76.275$  %

These values also match well with the earlier values.

## If 20% excess air is used: It will reflect in excess O2 and N2 in the products:

Products will contain:

7 CO2 + 5 H2O + ( 35.364 + 9.391 \* 0.2 \* 3.76) N2 + (9.391 \* 0.2) O2

Percentage of CO2, N2 and O2 by volume in products (remembering that the combustion eqn is a 'mole eqn' or 'volume eqn.'):

CO2: 
$$\frac{7}{7 + (35.364 + 9.391 \cdot 0.2 \cdot 3.76) + 9.391 \cdot 0.2} \cdot 100 = 13.644$$
 %

N2:

 $\frac{(35.364 + 9.391 \cdot 0.2 \cdot 3.76)}{7 + (35.364 + 9.391 \cdot 0.2 \cdot 3.76) + 9.391 \cdot 0.2} \cdot 100 = 82.695$ %

O2: 
$$\frac{9.391 \cdot 0.2}{7 + (35.364 + 9.391 \cdot 0.2 \cdot 3.76) + 9.391 \cdot 0.2} \cdot 100 = 3.661$$
%

Note again, that these values match well with the values obtained earlier.



173

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**Prob.8.2.3** Write down the complete combustion eqn for Propane (C3H8) and determine the theoretical AF ratio.

#### Mathcad Solution:

Let the combustion eqn be:

C3H8 + a. (O2 + 3.76 N2) = x. CO2 + y. H2O + (3.76.a). N2

(remember that 1 mole of O2 is accompanied by 3.76 moles of N2)

Equating coeffs of C: 3 = x

Equating coeffs of H: 8 = 2.y i.e. y = 4

Equating coeffs of O: 2.a = 2.x + y = 10 i.e. a = 5

Therefore, the combustion eqn is:

C3H8 + 5. (O2 + 3.76 N2) = 3. CO2 + 4. H2O + 18.8. N2

#### Therefore, stoichiometric AF ratio by mass:

$$AF := \frac{5 \cdot 4.76 \cdot 29}{12 \cdot 3 + 8}$$

i.e. AF = 15.686 ....AF ratio

**Prob.8.2.4** Propane gas burns with 150% theoretical air at a pressure of 1 bar. If the air is dry, determine the mole amounts of products and the dew point temp of the mixture.

\_\_\_\_\_

b) Plot dew point temp vs percent excess air.

#### Mathcad Solution:

Since we need sat. temp against sat. pressure of steam to find out dew point temp, let us first write two simple Mathcad Functions for PSAT and TSAT:

We have taken tabular data from TEST.

#### For Sat. water vapor (Ref: TEST)

|         | kPa      |         | deg.C    |  |
|---------|----------|---------|----------|--|
|         | (0.6113) |         | ( 0.01 ) |  |
|         | 1        |         | 6.98     |  |
|         | 1.5      |         | 13.03    |  |
|         | 2        |         | 17.5     |  |
|         | 2.5      |         | 21.08    |  |
|         | 3        |         | 24.08    |  |
|         | 4        |         | 28.96    |  |
|         | 5        | 32.88   |          |  |
|         | 7.5      |         | 40.29    |  |
| psat := | 10       | tsat := | 45.81    |  |
|         | 15       |         | 53.97    |  |
|         | 20       |         | 60.06    |  |
|         | 25       |         | 64.97    |  |
|         | 30       |         | 69.1     |  |
|         | 40       |         | 75.87    |  |
|         | 50       | 50      |          |  |
|         | 75       |         | 91.78    |  |
|         | 100      |         | 99.63    |  |
|         | 125      |         | 105.99   |  |

Examples:

| TSAT(P) := linterp(psat, tsat, P) | TSAT(10) = 45.81  | С   |
|-----------------------------------|-------------------|-----|
| PSAT(T) := linterp(tsat, psat, T) | PSAT(66) = 26.247 | kPa |

In the previous problem, we have already obtained the combustion eqn with 100% theoretical air as:

C3H8 + 5. (O2 + 3.76 N2) = 3. CO2 + 4. H2O + 18.8. N2

#### With 150% theoretical air, the excess O2 and N2 will show up in Products:

#### So, we have:

Therefore: Total no. of moles in Products:

 $N_{tot} := 3 + 4 + 18.8 + 2.5 + 2.5 \cdot 3.76$  i.e.  $N_{tot} = 37.7$  kmol

Therefore, mole fraction of each component of products:

$$y_{CO2} := \frac{3}{N_{tot}} \cdot 100$$
 i.e.  $y_{CO2} = 7.958$  %

$$y_{H2O} := \frac{4}{N_{tot}} \cdot 100$$
 i.e.  $y_{H2O} = 10.61$  %

$$y_{O2} := \frac{2.5}{N_{tot}} \cdot 100$$
 i.e.  $y_{O2} = 6.631$  %

$$y_{N2} := \frac{18.8 + 2.5 \cdot 3.76}{N_{tot}} \cdot 100$$
 i.e.  $y_{N2} = 74.801$  %

#### Dew point temp of mixture:

Find, first, partial pressure of water vapor in mixture. Then, sat. temp at that partial pressure is the dew point temp.

P := 1 bar.... total pressure, by data

### $\mathbf{p}_w = \mathbf{y}_{H2O} \cdot \mathbf{P} \quad \dots \text{partial pressure of water vapor}$

Now, mole fraction of water vapor = 10.61% = 0.1061

- i.e.  $p_w = 0.1061$  bar
- i.e. p<sub>w</sub> := 10.61 kPa

#### Now, corresponding to this $p_w$ , find the sat. temp from the Mathcad Function written above:

$$T_{dewpoint} := TSAT(p_w)$$

i.e. T<sub>dewpoint</sub> = 46.806 C .... Ans.





#### (b) Plot dew point temp vs excess air:

#### Write Dew point temp as a function of per-cent excess air:

In the previous problem, we have already obtained the combustion eqn with 100% theoretical air as:

C3H8 + 5. (O2 + 3.76 N2) = 3. CO2 + 4. H2O + 18.8. N2

With excess air (in percent), the excess O2 and N2 end up in products.

Therefore, if the Percent excess air is included, we have:

C3H8 + (1 + percent\_excess\_air/100) \* 5 \* (O2 + 3.76 N2) = 3. CO2 + 4. H2O + 18.8. N2 +(percent\_excess\_air/100) \* 5 \* O2 + (percent\_excess\_air/100) \* 5 \* 3.76 \* N2

Let: percent\_excess\_air := 50 P := 1 bar.... total pressure, by data

Then, total no. of moles in products:

$$N_{tot}(percent\_excess\_air) := 3 + 4 + \frac{percent\_excess\_air}{100} \cdot 5 + \left(18.8 + \frac{percent\_excess\_air}{100} \cdot 3.76 \cdot 5\right)$$

Then. mole fraction of water in products:

 $y_{\text{H2O}}(\text{percent}_\text{excess}_\text{air}) \coloneqq \frac{4}{N_{\text{tot}}(\text{percent}_\text{excess}_\text{air})}$ 

#### Dew point temp of mixture:

Find, first, partial pressure of water vapor in mixture. Then, sat. temp at that partial pressure is the dew point temp.

pw(percent\_excess\_air,P) := yH2O(percent\_excess\_air) P bar...partial pressure of water vapor

Now, dew point temp is the sat. temp. of water vapor corresponding to this pw.

T<sub>dewpoint</sub>(percent\_excess\_air,P) := TSAT(p<sub>w</sub>(percent\_excess\_air,P)·100) ....pressure in kPa

T<sub>dewpoint</sub>(percent\_excess\_air,P) = 46.806 C ... Ans.

#### Now, plot T<sub>dewpoint</sub> vs percent excess air:

percent\_excess\_air := 0,20..300

...define a range variable

| percent_excess_air | T <sub>dewpoint</sub> (percent_excess_air,P) |
|--------------------|--|
| 0                  | 54.584                                       |
| 20                 | 50.851                                       |
| 40                 | 47.972                                       |
| 60                 | 45.766                                       |
| 80                 | 43.427                                       |
| 100                | 41.536                                       |
| 120                | 39.87  |
| 140                | 38.114                                       |
| 160                | 36.62  |
| 180                | 35.333                                       |
| 200                | 34.213                                       |
| 220                | 33.229                                       |
| 240                | 32.19  |
| 260                | 31.163                                       |
| 280                | 30.242                                       |
| 300                | 29.412                                       |





**Reactive Systems** 

**Prob.8.2.5** Octane (C8H18) gas is burnt with dry air. Volumetric analysis of the products by Orsat apparatus is: CO2 = 10.02%, O2 = 5.62%, CO = 0.88%, and N2 = 83.48% (by balance). Determine: (i) AF ratio (ii) percentage of theoretical air used (iii) excess air

#### Mathcad Solution:

Note: Analysis by Orsat apparatus is on 'dry basis', i.e. water is not included. While writing combustion eqn, we will have to remember add water.

Writing for 100 kmol of dry products, combustion eqn for the given conditions is:

x. C8H18 + a. (O2 + 3.76 N2) = 10.02. CO2 + 0.88.CO + 5.62. O2 + 83.48. N2 + b.H2O

Equating coeffs of N2: a 3.76= 83.48 i.e. a = 22.202

Equating coeffs of C: 8.x = 10.02 + 0.88 = 10.9 i.e. x = 1.363

Equating coeffs of H: 18.x = 2.b i.e. b = 12.267

Therefore, the combustion eqn is:

1.363. C8H18 + 22.202. (O2 + 3.76 N2) = 10.02. CO2 + 0.88.CO + 5.62. O2 + 83.48. N2 + 12.267.H2O

Therefore: AF ratio is:

$$AF := \frac{22.202 \cdot 4.76 \cdot 29}{1.363 \cdot (12 \cdot 8 + 18)}$$

i.e. AF = 19.724 Actual AF ratio for this reaction .... Ans.

#### Theoretical air or stoichiometric air:

We have the eqn:

C8H18 + 12.5. (O2 + 3.76 N2) = 8.CO2 + 9.H2O + 12.5 \* 3.76 \* N2
Then, stoichiometric or Theoretical AF ratio:

$$AF_{stoich} := \frac{12.5 \cdot 4.76 \cdot 29}{12 \cdot 8 + 18}$$

i.e. AF<sub>stoich</sub> = 15.136 Theoretical AF ratio .... Ans.

#### Therefore, excess air:

$$Excess_air := \frac{AF}{AF_{stoich}}$$

i.e. Excess\_air = 1.303 i.e. 30.3% excess air ... Ans.

**Prob.8.2.6** An unknown hydrocarbon CxHy reacts with air. Orsat analysis of products gives: CO2 = 12.1%, O2 = 3.8%, CO = 0.9%. Determine: (i) chemical eqn for actual reaction (ii) composition of fuel (iii) AF ratio, and (iv) excess or deficiency of air used.[VTU]

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#### Mathcad Solution:

Note: Analysis by Orsat apparatus is on 'dry basis', i.e. water is not included. While writing combustion eqn, we will have to remember add water.

Also, by balance, percentage of N2 in products = 83.2%.

Writing for 100 kmol of dry products, combustion eqn for the given conditions is:

C<sub>x</sub>H<sub>v</sub> + a. (O2 + 3.76 N2) = 12.1. CO2 + 3.8. O2 + 0.9. CO + 83.2. N2 + b.H2O

Equating coeffs of N2: a 3.76= 83.2 i.e. a = 22.128

Equating coeffs of O: 2.22.128 = 2.12.1 + 2.3.8 + 0.9 + b i.e. b = 11.556

Equating coeffs of C: x = 12.1 + 0.9 i.e. x = 13

Equating coeffs of H: y = 2.b i.e. b = 23.112

Therefore, the combustion eqn is:

C<sub>13</sub>H<sub>23.112</sub> + 22.128. (O2 + 3.76 N2) = 12.1. CO2 + 3.8. O2 + 0.9. CO + 83.2. N2 + 11.556.H2O

Therefore, AF ratio:

$$AF := \frac{22.128 \cdot 4.76 \cdot 29}{13 \cdot 12 + 23.112 \cdot 1}$$

i.e. AF = 17.054 ... AF ratio by mass. for this reaction .... Ans.

Note: C<sub>13</sub>H<sub>23.112</sub> is not the chemical formula of fuel. It only gives the carbon to hydrogen ratio in the fuel.

#### Stoichiometric AF rato:

We have the eqn for reaction:

C<sub>13</sub>H<sub>23,112</sub> + (37.556/2) (O2 + 3.76 N2) = 13. CO2 + (23.112/2).H2O + 70.605.N2

Therefore, stoichiometric AF ratio:

 $AF_{stoich} := \frac{18.778 \cdot 4.76 \cdot 29}{13 \cdot 12 + 23.112 \cdot 1}$ 

i.e. AF<sub>stoich</sub> = 14.472 ...Stoichiometric AF ratio by mass. .... Ans.

#### Excess Air used:

Since actual  $AF > AF_{stoich}$ , excess air is used:

$$\frac{AF}{AF_{stoich}} = 1.178$$
 .... 17.8% excess air is used .... Ans.

**Prob.8.2.7** An I.C. engine uses gasoline (C8H18) as fuel. The engine is supplied with 150% theoretical air at 1 bar, 25 C. Analysis of exhaust gases shows that 75% of carbon in fuel is converted to CO2 and the rest to CO. Combustion products leave the engine at 400 K. Calculate the amount of energy transferred to the engine per kg of gasoline. Given: Enthalpy o formation for n-octane (gas) (i.e. gasoline) is -208,450 kJ/kmol. [Ref: 11]

#### Mathcad Solution:

From I Law, energy transferred is calculated as:

$$Q = H_{products} - H_{Reactants}$$

i.e. 
$$Q = \sum_{p} n_{e} \cdot (h_{f0} + \Delta h)_{e} - \sum_{r} n_{i} \cdot (h_{f0} + \Delta h)_{i}$$

Now, the eqn for the chemical reaction for stoichiometric combustion is:

C<sub>8</sub>H<sub>18</sub> + 12.5 (O2 + 3.76 N2) = 8 CO2 + 9 H2O + 12.5 \* 3.76 \* N2

Therefore, AF ratio (on mass basis) is:

$$AF := \frac{12.5 \cdot 4.76 \cdot 29}{12 \cdot 8 + 18 \cdot 1}$$

i.e. AF = 15.136 kg of air per kg of fuel

Now, with 150% air, and 75% of C converted to CO2 and 25% to CO, the combustion eqn becomes:

C<sub>8</sub>H<sub>18</sub>+1.5\*12.5\*(O2 + 3.76 N2) = 6 CO2 + 2 CO + 9 H2O + 7.25 O2 + 70.5 N2

All reactants and products are in gaseous condition.



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## Enthalpies of formation ( $h_{f0}$ ) at standard condition of 298 K, for the compounds (from the Table in section 8.1.7 (from TEST):

C8H18 (g) --> -208,450 kJ/kmol CO2 (g) --> -393,520 kJ/kmol CO (g) --> -110,530 kJ/kmol

H2O (g) --> -241,820 kJ/kmol

Remember that: enthalpy of formation for stable elements such as O2, N2, H2 is zero.

Now, calculate H<sub>prod</sub> and H<sub>react</sub> separately, to apply the I Law:

$$H_{\text{products}} = \sum_{p} n_{e} \cdot (h_{f0} + \Delta h)_{e}$$

Now,  $\Delta h$  values (from Urieli's Tables, given in section 8.1.8) for products at 400 K:

CO2 (g) --> 4008 kJ/kmol CO (g) --> 2975 kJ/kmol H2O (g) --> 3452 kJ/kmol O2 (g) --> 3029 kJ/kmol N2 (g) --> 2971 kJ/kmol

Then, we have:

 $H_{\text{products}} := 6 \cdot (-393520 + 4008) + 2 \cdot (-110530 + 2975) + 9 \cdot (-241820 + 3452) + 7.25 \cdot (0 + 3029) + 70.5 \cdot (0 + 2971) + 2971 \cdot (0 + 2971$ 

i.e.  $H_{products} = -4.466 \times 10^6$  kJ/kmol fuel

And, 
$$H_{reactants} = \sum_{r} n_{i} (h_{f0} + \Delta h)_{i}$$

i.e.  $H_{reactants} := 1 \cdot (-208450) + 1.5 \cdot 12.5 \cdot (0 + 0)$  ....siince  $h_{f0} = 0$  for O2 and N2

i.e.  $H_{reactants} = -2.084 \times 10^5$  kJ/kmol fuel

Therefore: Q := H<sub>products</sub> - H<sub>reactants</sub>

i.e.  $Q = -4.258 \times 10^6$  kJ/kmol fuel

Now, 1 kg of C8H18 = 1/114 kmol = 8.772 \* 10^-3 kmol

Therefore:  $Q := \frac{-4.258 \cdot 10^6}{114}$  kJ/kg fuel

i.e.  $Q = -3.735 \times 10^4$  kJ/kg fuel ....-ve sign indicating heat flowing out .... Ans.

b) In the above,  $\Delta h = (h_T - h_{298})$ , and  $\Delta h$  values were taken from Urieli's Tables, where the datum was 298 K (i.e. h = 0 at 298 K).

Now, we can also use the conventional Ideal gas tables, given in section 8.1.8. Here, the only difference is that datum is at 0 K, and we have to take enthalpy readings at temp T as well as at 298 K and subtract.

This procedure is shown below:

 $\Delta h = h_T - h_{298}$  values from Ideal Gas Tables:

CO2 (g) --> (h<sub>400</sub> - h<sub>298</sub>) = (13372 - 9364) = 4008 kJ/kmol

CO (g) --> (h<sub>400</sub> - h<sub>298</sub>) = (11644 - 8669) = 2975 kJ/kmol

H2O (g) --> (h400 - h298) = (13356 - 9904) = 3452 kJ/kmol

O2 (g) --> (h<sub>400</sub> - h<sub>298</sub>) = (11711 - 8682) = 3029 kJ/kmol

N2 (g) --> (h<sub>400</sub> - h<sub>298</sub>) = (11640 - 8669) = 2971 kJ/kmol

These values match very well with values from Urieli's Tables. Rest of the calculations are done as earlier.

c) Another way is not to use the Tables, but calculate  $\Delta h$  as (cp.  $\Delta T$ ), cp being calculated from the formulas given in Thermodynamics Text books for Ideal gases such as: CO2, CO, O2, N2 etc. [Ref: 11]

We have:

 $cp_{CO2}(T) := (45.369 + 3.688 \cdot 10^{-3} \cdot T - 9.619 \cdot 10^{5} \cdot T^{-2})$ kJ/kmol

 $cp_{CO}(T) := \left(28.068 + 4.631 \cdot 10^{-3} \cdot T - 0.258 \cdot 10^{5} \cdot T^{-2}\right)$ kJ/kmol

 $cp_{H2O}(T) := 28.85 + 12.055 \cdot 10^{-3} \cdot T + 1.066 \cdot 10^{5} \cdot T^{-2}$ kJ/kmol

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$$cp_{O2}(T) := (30.255 + 4.207 \cdot 10^{-3} \cdot T - 1.887 \cdot 10^{5} \cdot T^{-2})$$
 kJ/kmol

$$cp_{N2}(T) := 27.27 + 4.930 \cdot 10^{-3} \cdot T + 0.333 \cdot 10^{5} \cdot T^{-2}$$
 kJ/kmol

$$cp_{H2}(T) := 27.012 + 3.509 \cdot 10^{-3} \cdot T + 0.69 \cdot 10^{5} \cdot T^{-2}$$
 kJ/kmol

$$cp_{NH3}(T) := (29.747 + 25.108 \cdot 10^{-3} \cdot T - 1.546 \cdot 10^{5} \cdot T^{-2}) kJ/kmol$$

$$cp_{CH4}(T) := \left(17.449 + 60.449 \cdot 10^{-3} \cdot T + 1.117 \cdot 10^{-6} \cdot T^{2} - 7.204 \cdot 10^{-9} \cdot T^{3}\right) \quad kJ/kmol$$

$$cp_{SO2}(T) := (47.381 + 6.66 \cdot 10^{-3} \cdot T - 8.439 \cdot 10^{5} \cdot T^{-2}) kJ/kmol$$

Therefore, we have:

 $\Delta h$  =  $h_T^{}-h_{298}^{}$   $\,$  values from sp. heat formulas:

CO2 (g) -> 
$$(h_{400} - h_{298}) = \int_{298}^{400} cp_{CO2}(T) dT = 3.936 \times 10^3$$
 kJ/kmol

CO (g) --> 
$$(h_{400} - h_{298}) = \int_{298}^{400} cp_{CO}(T) dT = 3.006 \times 10^3$$
 kJ/kmol

H2O (g) --> 
$$(h_{400} - h_{298}) = \int_{298}^{400} cp_{H2O}(T) dT = 3.463 \times 10^3$$
 kJ/kmol

O2 (g) --> (h<sub>400</sub> - h<sub>298</sub>) = 
$$\int_{298}^{400} cp_{O2}(T) dT = 3.074 \times 10^3$$
 kJ/kmol

N2 (g) --> (h<sub>400</sub> - h<sub>298</sub>) = 
$$\int_{298}^{400} cp_{N2}(T) dT = 2.986 \times 10^{3}$$
 kJ/kmol

Then, we have:

 $H_{products} := 6 \cdot (-393520 + 3936) + 2 \cdot (-110530 + 3006) + 9 \cdot (-241820 + 3463) + 7.25 \cdot (0 + 3074) + 70.5 \cdot (0 + 2986) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 200 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 2006 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 2006 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 2006 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 2006 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 2006 \cdot (-241820 + 3006) + 2006 \cdot (-241820 + 3463) + 70.5 \cdot (0 + 2006) + 2006 \cdot (-2006) 

i.e.  $H_{products} = -4.465 \times 10^6$  kJ/kol fuel

And, 
$$H_{reactants} = \sum_{r} n_{i} (h_{f0} + \Delta h)_{i}$$

i.e.  $H_{reactants} := 1 \cdot (-208450) + 1.5 \cdot 12.5 \cdot (0 + 0)$  ....siince  $h_{f0} = 0$  for O2 and N2

i.e. 
$$H_{reactants} = -2.084 \times 10^{\circ}$$
 kJ/kmol fuel

Therefore: Q := H<sub>products</sub> - H<sub>reactants</sub>

i.e. 
$$Q = -4.257 \times 10^{\circ}$$
 kJ/kmol fuel

Now, 1 kg of C8H18 = 1/114 kmol = 8.772 \* 10^-3 kmol

Therefore:  $Q := \frac{-4.257 \cdot 10^6}{114}$  kJ/kgl fuel

i.e.  $Q = -3.734 \times 10^4$  kJ/kg fuel ...-ve sign indicating heat flowing out .... Ans.

\_\_\_\_\_\_

**Prob.8.2.8** Determine the adiabatic flame temp when liquid octane (C8H18) at 25 C is burned with 300% theoretical air in a steady flow process.

#### Mathcad Solution:

For complete combustion of C<sub>8</sub>H<sub>18</sub>, stoichiometric eqn is:

C8H18 + 12.5 (O2 + 3.76) N2 = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2

Therefore, with 300 % theoretical air, we have the combustion eqn:

C<sub>8</sub>H<sub>18</sub> + 3 \* 12.5 (O2 + 3.76) N2 = 8 CO2 + 9 H2O + 25 O2 + 141 N2

For adiabatic flame temp, Q = 0:

Then:

- And,  $H_{reactants} = \sum_{r} n_{i} (h_{f0} + \Delta h)_{i}$
- i.e.  $H_{reactants} := 1 \cdot (-249950) + 3 \cdot 12.5 \cdot (0 + 0)$  ....siince  $h_{f0} = 0$  for O2 and N2
- i.e.  $H_{reactants} = -2.499 \times 10^5$  kJ/kmol fuel .





And,

$$H_{\text{products}} = \sum_{p} n_{e} \left( h_{f0} + \Delta h \right)_{e}$$

i.e. 
$$H_{\text{products}} = 8 \cdot (-393520 + \Delta h_{\text{CO2}}) + 9 \cdot (-241820 + \Delta h_{\text{H2O}}) + 25 \cdot (0 + \Delta h_{\text{O2}}) + 141 \cdot (0 + \Delta h_{\text{N2}})$$

....siince h<sub>f0</sub> = 0 for O2 and N2

i.e. 
$$H_{products} = -8.393520 - 9.241820 + 8.\Delta h_{CO2} + 9.\Delta h_{H2O} + 25.\Delta h_{O2} + 141.\Delta h_{N2}$$

i.e. 
$$H_{\text{products}} = -5.325 \cdot 10^6 + (8 \cdot \Delta h_{\text{CO2}} + 9 \cdot \Delta h_{\text{H2O}} + 25 \cdot \Delta h_{\text{O2}} + 141 \cdot \Delta h_{\text{N2}})$$

In the above, the temp of products which satisfies eqn. (A) is the Adiabatic Flame temp.

This has to be found out by trial and error.

Then from eqn.(A):

$$(8 \cdot \Delta \mathbf{h}_{CO2} + 9 \cdot \Delta \mathbf{h}_{H2O} + 25 \cdot \Delta \mathbf{h}_{O2} + 141 \cdot \Delta \mathbf{h}_{N2}) = 5.325 \cdot 10^6 - 2.499 \cdot 10^5$$

i.e. 
$$(\$ \cdot \Delta h_{CO2} + 9 \cdot \Delta h_{H2O} + 25 \cdot \Delta h_{O2} + 141 \cdot \Delta h_{N2}) = 5.075 \times 10^6$$
 .....eqn. (B)

Assuming that all the products are only N2, we get an approx. value for T<sub>flame</sub>. Then use it as starting point to narrow down on the actual adiabatic flame temp.

Total no. of moles in products = 8 + 9 + 25 + 141 = 183

Therefore: 
$$\Delta h_{N2} = \frac{5.075 \times 10^6}{183} = 2.773 \times 10^4$$
 kJ/kmol

Now, we can use Urieli's tables for N2 to get an initial value of T<sub>flame</sub>.

We get, approx: T<sub>flame</sub> = 1190 K

Now, start trial and error process to satisfy eqn. (B):

T = 1100 K: LHS of eqn. (B) becomes:

T = 1140 K: LHS of eqn. (B) becomes:

8-41120 + 9-31876 + 25-27632 + 141-26091 = 4.985 × 10<sup>6</sup> ...slightly less than RHS of eqn. (B)

T = 1200 K: LHS of eqn. (B) becomes:

Therefore, interpolate between 1140 K and 1200 K to get the value of  $T_{flame}$  to satisfy eqn. (B):

For 1 deg: 
$$\frac{5.374 \times 10^6 - 4.985 \times 10^6}{60} = 6.483 \times 10^3$$

Therefore: 
$$T_{flame} := 1200 - \frac{(5.374 \times 10^6 - 5.075 \times 10^6)}{(6.483 \times 10^3)}$$

 $T_{flame} = 1.154 \times 10^3$  K ....Adiabatic flame temp ... Ans.

#### Alternatively:

We can use eqns for cp to get  $\Delta h$  for the different components of products, and determine T<sub>fame</sub> as follows:

We have the eqn. (B):

$$(8 \cdot \Delta h_{CO2} + 9 \cdot \Delta h_{H2O} + 25 \cdot \Delta h_{O2} + 141 \cdot \Delta h_{N2}) = 5.075 \times 10^{\circ}$$
 .....eqn. (B)

Start with a guess value:

TTflame := 1000 K ..... guess value

Given

 $\begin{bmatrix} 8 \cdot \int_{298}^{TT \text{flame}} cp_{CO2}(T) \, dT + 9 \cdot \int_{298}^{TT \text{flame}} cp_{H2O}(T) \, dT + 25 \cdot \int_{298}^{TT \text{flame}} cp_{O2}(T) \, dT \end{bmatrix} \dots = 5.075 \cdot 10^{6}$ + 141 \cdot \int\_{298}^{TT \text{flame}} cp\_{N2}(T) \, dT = 0.075 \cdot 10^{6}

Find(TTflame) =  $1.1599 \times 10^3$ 

Thus: Tflame = 1160 K .....Adiabatic Flame temp.... Ans.

Note: See the ease with which Tflame is calculated.

This method is surely easier than the earlier method of referring to Tables and interpolating.





#### (b) Plot the adiabatic flame temp as percent excess air varies from 0 to 300%:

#### Note: 300% theoretical air means 200% excess air.

percent excess air := 200 ... for the above problem

Now, we have the stoichiometric eqn:

C8H18 + 12.5 (O2 + 3.76) N2 = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2

Then, with percent\_excess\_air, excess O2 and N2 show up in products, and, we have the eqn for combustion:

C8H18 + (1 + percent\_excess\_air / 100) \* 12.5 \* (O2 + 3.76) N2 = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2 + (percent\_excess\_air/100) \* 12.5 \* O2 + (percent\_excess\_air/100) \* 12.5 \* 3.76 \* N2

For adiabatic flame temp, Q = 0:

Then:

And, 
$$H_{reactants} = \sum_{r} n_{i} (h_{f0} + \Delta h)_{i}$$

i.e. H<sub>reactants</sub> := 1·(-249950) + 3·12.5·(0 + 0) ....siince h<sub>f0</sub> = 0 for O2 and N2

i.e.  $H_{reactants} = -2.499 \times 10^5$  kJ/kmol fuel .

#### Note that H<sub>reactants</sub> at 25 C does not depend on excess air.

And, we will write H<sub>products</sub> as a function of percent\_excess\_air:

$$H_{\text{products}} = \sum_{p} n_{e} (h_{f0} + \Delta h)_{e}$$

i.e.

$$\begin{split} H_{\text{products}}(\text{percent}\_\text{excess}\_\text{air}) &= 8 \cdot \left(-393520 + \Delta h_{\text{CO2}}\right) + 9 \cdot \left(-241820 + \Delta h_{\text{H2O}}\right) \dots \\ &+ 12.5 \cdot \frac{\text{percent}\_\text{excess}\_\text{air}}{100} \cdot \left(0 + \Delta h_{\text{O2}}\right) \dots \\ &+ 12.5 \cdot 3.76 \cdot \left(1 + \frac{\text{percent}\_\text{excess}\_\text{air}}{100}\right) \cdot \left(0 + \Delta h_{\text{N2}}\right) \end{split}$$

....siince  $h_{f0} = 0$  for O2 and N2

Writing  $\Delta h$  as integral of cp. $\Delta T$ , we get:

$$\begin{split} H_{\text{products}}(\text{percent\_excess\_air}) \coloneqq & \left[ \$ \cdot \left( -393520 + \int_{298}^{\text{TTflame}} \text{cp}_{\text{CO2}}(\text{T}) \, \text{dT} \right) + 9 \cdot \left( -241820 + \int_{298}^{\text{TTflame}} \text{cp}_{\text{H2O}}(\text{T}) \, \text{dT} \right) \dots \right. \\ & + 12.5 \cdot \frac{\text{percent\_excess\_air}}{100} \cdot \left( 0 + \int_{298}^{\text{TTflame}} \text{cp}_{\text{O2}}(\text{T}) \, \text{dT} \right) \dots \\ & + 12.5 \cdot 3.76 \cdot \left( 1 + \frac{\text{percent\_excess\_air}}{100} \right) \cdot \left( 0 + \int_{298}^{\text{TTflame}} \text{cp}_{\text{N2}}(\text{T}) \, \text{dT} \right) \dots \\ & \left. \right] \end{split}$$

We shall use the Solve block of Mathcad to get Adiabatic flame temp, TTflame, by equating  $H_{reactants} = H_{products}$ .

Start with a guess value for TTflame:

TTflame := 1000 K

Given

$$\begin{bmatrix} 8 \cdot \left(-393520 + \int_{298}^{TT \text{flame}} \text{cp}_{\text{CO2}}(T) \, dT \right) + 9 \cdot \left(-241820 + \int_{298}^{TT \text{flame}} \text{cp}_{\text{H2O}}(T) \, dT \right) \dots \\ + 12.5 \cdot \frac{\text{percent\_excess\_air}}{100} \cdot \left(0 + \int_{298}^{TT \text{flame}} \text{cp}_{\text{O2}}(T) \, dT \right) \dots \\ + 12.5 \cdot 3.76 \cdot \left(1 + \frac{\text{percent\_excess\_air}}{100} \right) \cdot \left(0 + \int_{298}^{TT \text{flame}} \text{cp}_{\text{N2}}(T) \, dT \right) \end{bmatrix} = -2.499 \times 10^{5}$$

Tflame(percent\_excess\_air) := Find(TTflame) ...Get Tflame as a function of percent\_excess\_air

i.e.  $Tflame(percent_excess_air) = 1.16 \times 10^3$  K

Note: In the above, we have written Tflame as a function of percent\_excess\_air, so that it becomes very easy to draw plots. See below:

#### Now, plot Tflame for different values of percent\_excess\_air:

percent\_excess\_air := 0,20.. 300 ....define a range variable

| percent_excess_air | Tflame(percent_excess_air) |
|--------------------|----------------------------|
| 0                  | 2413.84                    |
| 20                 | 2144.13                    |
| 40                 | 1935.7                     |
| 60                 | 1769.72                    |
| 80                 | 1634.4                     |
| 100                | 1521.94                    |
| 120                | 1426.99                    |
| 140                | 1345.74                    |
| 160                | 1275.42                    |
| 180                | 1213.97                    |
| 200                | 1159.8                     |
| 220                | 1111.69                    |
| 240                | 1068.68                    |
| 260                | 1029.99                    |
| 280                | 995                        |
| 300                | 963.21                     |
|                    |                            |



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#### 8.3 Problems solved with EES:

"**Prob.8.3.1** A sample of fuel has following percentage composition by weight: C = 86%, O2 = 2%, Ash = 1%, H2 = 8%, S = 3%. For an AF ratio of 12:1, determine: (i) stoichiometric AF ratio, and mixture strength as percentage of rich or weak (ii) the percentage composition of dry flue gases by volume. [VTU]"

#### **"EES Solution:"**

"Remembering that combustion eqns are 'mole equations', let us convert the components of fuel to respective moles and then write the combustion eqn. for 100 kg of fuel:"

 $N_C = 86/12$ "...no of kmols of Carbon"

N\_O2 = 2/32"...no of kmols of oxygen"

N\_H2 = 8/2"...no of kmols of hydrogen"

 $N_S = 3/32$ "...no of kmols of sulphur"

#### "Stoichiometric eqn. for combustion is:"

"N\_C [C] + N\_O2[O2] + N\_H2[H2] + N\_S[S] + a (O2 + 3.76 N2) = × [H2O] + y [CO2] + z [SO2] + w [N2]"

"Collect coeffs of carbon atoms:"

 $N_C = y$ 

"Collect coeffs of oxygen atoms:"

 $N_02 + a = x/2 + y + z$ 

"Collect coeffs of hydrogen atoms:"

 $N_H2 = x$ 

"Collect coeffs of nitrogen atoms:"

3.76 \* a = w

"Collect coeffs of sulphur atoms:"

 $N_S = z$ 

"Solving the above eqns we get the coeffs N\_C, N\_O2, N\_H2, N\_S, a, x, y, z and w, and then we write the combustion eqn:"

" $N_C = 7.167$   $N_O2 = 0.0625$   $N_H2 = 4$   $N_N2 = 0.0625]$   $N_S = 0.09375$  a = 9.198 x = 4 y = 7.167 z = 0.09375w = 34.58

#### and, the combustion eqn is:"

"7.167 [C] + 0.0625[O2] + 4[H2] + 0.09375[S] + 9.198 (O2 + 3.76 N2) = 4 [H2O] + 7.167 [CO2] + 0.09375 [SO2] + 34.58 [N2]"

#### "Therefore, Stoichoimetric AF ratio:"

AF\_stoichio = (a \* 4.76 \* 29) / 100 "kg air/ kg fuel .....since 100 kg of fuel was taken"

#### "But, given that:"

 $AF_actual = 12$ 

#### "Therefore:"

Ratio = AF\_actual/AF\_stoichio

#### "Volumetric analysis of dry combustion products:"

#### "Total no. of kmols of dry products is:"

 $N_tot = y + z + w$ 

#### "Therefore, vol. analysis is:"

Vol\_CO2 = y \* 100 / N\_tot "% by vol for CO2"

Vol\_SO2 = z \* 100 / N\_tot "% by vol for SO2"

Vol\_N2 = w \* 100 / N\_tot "% by vol for N2"

#### **Results:**

#### Unit Settings: SI C kPa kJ mass deg

| a=9.198 [kmol]                  | AF <sub>actual</sub> = 12       | AF <sub>stoichio</sub> = 12.7   |
|---------------------------------|---------------------------------|---------------------------------|
| N <sub>C</sub> = 7.167 [kmol]   | N <sub>H2</sub> = 4 [kmol]      | N <sub>02</sub> = 0.0625 [kmol] |
| N <sub>S</sub> = 0.09375 [kmol] | N <sub>tot</sub> = 41.84 [kmol] | Ratio = 0.9451                  |
| Vol <sub>CO2</sub> = 17.13 [%]  | Vol <sub>N2</sub> = 82.65 [%]   | Vol <sub>SO2</sub> = 0.224 [%]  |
| w = 34.58 [kmol]                | x = 4 [kmol]                    | y = 7.167 [kmol]                |
| z = 0.09375 [kmol]              |                                 |                                 |

Thus:

We see that AF\_stoichio = 12.7, and the Ratio = 0.9451

#### Therefore:

It is a weak mixture, with 94.51% of theoretical air .... Ans.

Vol. analysis of dry combustion products is:

CO2 = 17.13%, N2 = 82.65%, SO2 = 0.224% ... Ans.



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"**Prob.8.3.2** Octane (C8H18) is burnt in air and an Orsat analysis of products yields: CO2 = 10.5%, CO = 1.8%, O2 = 5.3%, and N2 = 82.4%. Determine: (i) actual AF ratio on mol basis (ii) actual AF ratio on mass basis, (iii) percent excess air, and (iv) dew point temp of the products. [VTU]"

#### **"EES Solution:"**

"Remember that Orsat analysis is on 'dry basis'. So, we have to add H2O in the products. Considering 100 kMol of dry products, we write the combustion eqn.:"

"x. [C8H18] + a [O2 + 3.76 N2] = 10.5 [CO2] + 1.8 [CO] + 5.3 [O2] + 82.4 [N2] + b. [H2O]"

"Collect coeffs of carbon atoms:"

 $8 \times x = 10.5 + 1.8$ 

"Collect coeffs of hydrogen atoms:"

$$18 * x = 2 * b$$

"Collect coeffs of nitrogen atoms:"

3.76 \* a = 82.4

"Therefore, actual AF ratio, on kmol basis:"

 $AF_kmolbasis = (a^4.76)/x$ 

#### "And, actual AF ratio, on mass basis:"

 $AF_{massbasis} = (a * 4.76 * 29)/(x * (12 * 8 + 18))$ 

"Stoichiometric eqn is:"

"C8H18 + (12.5) (O2 + 3.76 N2) = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2"

#### "Therefore, stoichiometric AF ratio:"

 $AF_{stoichio} = (12.5 * 4.76 * 29) / (12 * 8 + 18)$ 

#### "Percent excess air:"

Percent\_theor\_air = (AF\_massbasis / AF\_stoichio) \* 100

#### "Dew point temp:"

N\_tot = 100 + b "...total no. of moles in products"

y\_H2O = b / N\_tot "...mole fraction of H2O in products"

p\_w = y\_H2O \* 1.01325 \* 100 "kPa ... partial pressure of water vapor in products"

"Dew point temp is the sat. temp. at p\_w:"

T\_dewpoint = T\_sat(Steam\_NBS,P=p\_w) "C ... dew point temp"

#### **Results:**

| Unit Settings: SI C kPa kJ mass deg    |                                 |
|--|---------------------------------|
| a=21.91 [kmol]                         | AF <sub>kmolbasis</sub> = 67.85 |
| AF <sub>massbasis</sub> = 17.26        | AF <sub>stoichio</sub> = 15.14  |
| b = 13.84 [kmol]                       | N <sub>tot</sub> = 113.8 [kmol] |
| Percent <sub>theor,air</sub> = 114 [%] | p <sub>w</sub> =12.32 [kPa]     |
| T <sub>dewpoint</sub> = 49.95 [C]      | x = 1.538 [kmol]                |
| y <sub>H20</sub> = 0.1216              |                                 |

Thus:

Actual AF ratio on mol basis = 67.85 ..... Ans.

Actual AF ratio on mass basis = 17.26 .... Ans.

Stoichio. AF ratio (mass basis) = 15.14 .... Ans.

Percent theoretical air = 114 % ...i.e. 14% excess air .... Ans.

Dew point temp of products = 49.95 C .... Ans.

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"Prob.8.3.3 Octane (C8H18) is burnt with 20% excess air. Determine: (i) stoichiometric AF ratio on mass basis (ii) actual AF ratio on mass basis, and, (iii) dew point temp of the products. (b) Also, plot the actual AF ratio and dew point temp as excess air varies from 0 to 200%"

#### "EES Solution:"

#### "Data:"

percent\_excess\_air = 20 "%"

#### "Soichiometric eqn for combustion is, from earlier problem:"

"C8H18 + (12.5) (O2 + 3.76 N2) = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2"

#### "Therefore, stoichiometric AF ratio:"

AF\_stoichio = (12.5 \* 4.76 \* 29) / (12 \* 8 + 18)

"Combustion eqn when there is excess air:

#### Now, the excess O2 and N2 show up in products:"

"C8H18 + (1 + percent\_excess\_air/100) \* (12.5) \* (O2 + 3.76 N2) = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2 + aa \* O2 + bb \* N2"



203

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#### "where:"

aa = (percent\_excess\_air/100) \* 12.5

bb = (percent\_excess\_air/100) \* 12.5 \* 3.76

"Therefore, actual AF ratio on mass basis:"

AF\_actual = (1 + percent\_excess\_air/100)\* 12.5 \* 4.76 \* 29 / (8 \* 12 + 18)

#### "Dew point temp:"

N\_tot = 8 + 9 + (12.5 \* 3.76) + aa + bb "...total no. of moles in products"

y\_H2O = 9 / N\_tot "...mole fraction of H2O in products"

p\_w = y\_H2O \* 101.325 "kPa ... partial pressure of water vapor in products"

#### "Dew point temp is the sat. temp. at p\_w:"

T\_dewpoint = T\_sat(Steam\_NBS,P=p\_w) "C ... dew point temp"

#### **Results:**

# Unit Settings: SI C kPa kJ mass deg aa = 2.5 [kmol] $AF_{actual} = 18.16$ $AF_{stoichio} = 15.14$ bb = 9.4 [kmol] $N_{tot} = 75.9$ [kmol] percent\_{excess,air} = 20 [%] $p_w = 12.01$ [kPa] $T_{dewpoint} = 49.46$ [C] $y_{H20} = 0.1186$ $F_{H20} = 0.1186$

Thus:

Actual AF ratio on mass basis, with 20% excess air = 18.16 .... Ans.

Stoichiometric AF ratio (mass basis) = 15.14 .... Ans.

Dew point temp of products, with 20% excess air = 49.46 C .... Ans.

#### (b) Also, plot the actual AF ratio and dew point temp as excess air varies from 0 to 200%:

| Table 1 |   |                                   |                                    |
|---------|---|-----------------------------------|------------------------------------|
| 111     | 1 I<br>percent <sub>excess,a</sub><br>[%] | <sup>2</sup> AF <sub>actual</sub> | <sup>3</sup> T <sub>dewpoint</sub> |
| Run 1   | 0   | 15.14                             | 52.92                              |
| Run 2   | 20  | 18.16                             | 49.46                              |
| Run 3   | 40  | 21.19                             | 46.56                              |
| Run 4   | 60  | 24.22                             | 44.08                              |
| Run 5   | 80  | 27.24                             | 41.92                              |
| Run 6   | 100                                       | 30.27                             | 40.01                              |
| Run 7   | 120                                       | 33.3                              | 38.29                              |
| Run 8   | 140                                       | 36.33                             | 36.74                              |
| Run 9   | 160                                       | 39.35                             | 35.32                              |
| Run 10  | 180                                       | 42.38                             | 34.02                              |
| Run 11  | 200                                       | 45.41                             | 32.82                              |

#### First, compute the Parametric Table:



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#### Now, plot the Results:



"**Prob.8.3.4** The products of combustion of an unknown hydrocarbon fuel have the following composition, as measured by Orsat apparatus: CO2 = 8%, CO = 0.9%, O2 = 8.8%, N2 = 82.3%. Calculate: (i) AF ratio (ii) composition of fuel on mass basis (iii) percentage of theoretical air, on mass basis. [VTU]"

#### "EES Solution:"

"Note that Orsat analysis gives composition of products on dry basis, and by volume. So, we have to add water to products while writing the combustion eqn.

#### Writing the combustion eqn on 100 kmol dry products basis:"

"CxHy + a (O2 + 3.76 N2) = 8 CO2 + 0.9 CO + 8.8 O2 + 82.3 N2 + b. H2O"

"Collect coeffs of carbon atoms:"

x = 8 + 0.9

"Collect coeffs of oxygen atoms:"

2 \* a = 2 \* 8 + 0.9 + 8.8 \* 2 + b

"Collect coeffs of nitrogen atoms:"

3.76 \* a = 82.3

"Collect coeffs of hydrogen atoms:"

y = 2 \* b

"Then, actual AF ratio, on mass basis:"

 $AF_{massbasis} = (a * 4.76 * 29)/(x * 12 + y * 1)$ 

"Composition of fuel, on mass basis:"

 $percent_carbon = (x * 12 * 100) / (x * 12 + y)$ 

 $percent_hydrogen = (y * 1 * 100) / (x * 12 + y)$ 

#### "Then, Stoichiometric AF ratio:"

"Consider 100 kg of fuel. It contains (85.2) kg C and (14.8) kg H2.

Air required for complete combustion of 85.2 kg C is: from C + O2 = CO2 "

Air\_for\_C = 85.2 \* (32/12)/0.23 "kg Air"

"Air required for complete combustion of 14.8 kg H2 is: from H2 + O = H2O"

Air\_for\_H2 = 14.8 \* (16/2)/0.23 "kg air"

"Therefore: for 100 kg fuel, total air required:"

Air\_total = Air\_for\_C + Air\_for\_H2

"Therefore, stoichio. AF ratio:"

AF\_stoichio = Air\_total / 100

"Therefore, excess air:"

Ratio = AF\_massbasis \* 100 / AF\_stoichio

#### "Excess air:"

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Excess\_air = Ratio - 100 "%"

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#### **Results:**

#### Unit Settings: SI C kPa kJ mass deg

| a=21.89 [kmol]                       | AF <sub>massbasis</sub> = 24.1         |
|--------------------------------------|--|
| AF <sub>stoichio</sub> = 15.03       | Air <sub>for,C</sub> = 987.8 [kg]      |
| Air <sub>for,H2</sub> = 514.8 [kg]   | Air <sub>total</sub> =1503 [kg]        |
| b = 9.277 [kmol]                     | Excess <sub>air</sub> = 60.41 [%]      |
| percent <sub>carbon</sub> = 85.2 [%] | percent <sub>hydrogen</sub> = 14.8 [%] |
| Ratio = 160.4                        | × = 8.9 [kmol]                         |
| y = 18.55 [kmol]                     |  |

#### Thus:

Stoichiometric AF ratio, on mass basis = 15.03 .... Ans.

Actual AF ratio, on mass basis = 24.1 ... Ans.

Excess air = 60.41% .... Ans.

Composition of fuel on mass basis: C = 85.2%, H2 = 14.8% .... Ans.

\_\_\_\_\_

"**Prob.8.3.5** Write EES Functions for molar sp. heats at const. pressure, of a few species, which are useful in combustion calculations".

#### **EES Solution:**

\$UnitSysyem SI kPa K kJ

FUNCTION cp\_CO2(T)

{Gives the sp. heat of CO2 (ideal gas), in kJ/kmol

Input: T in K}

A := 45.369; B := 8.688E-03; E := -9.619E05

 $cp\_CO2 := A + B * T + E / T^2$ 

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#### END

"\_\_\_\_\_"

FUNCTION cp\_CO(T)

{Gives the sp. heat of CO (ideal gas), in kJ/kmol

Input: T in K}

A := 28.068; B := 4.631E-03; E := -0.258E05

 $cp\_CO := A + B * T + E / T^2$ 

END

"\_\_\_\_\_"

FUNCTION cp\_H2O(T)

{Gives the sp. heat of H2O (ideal gas), in kJ/kmol

Input: T in K}

A := 28.85; B := 12.055E-03; E := 1.006E05

 $cp_H2O := A + B * T + E / T^2$ 

END

"\_\_\_\_\_"

FUNCTION cp\_O2(T)

{Gives the sp. heat of O2 (ideal gas), in kJ/kmol

Input: T in K}

A := 30.255; B := 4.207E-03; E := -1.887E05

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 $cp\_O2 := A + B * T + E / T^2$ 

END

"\_\_\_\_\_"

FUNCTION cp\_N2(T)

{Gives the sp. heat of N2 (ideal gas), in kJ/kmol

Input: T in K}

A := 27.27; B := 4.93E-03; E := 0.333E05

 $cp_N2 := A + B * T + E / T^2$ 

END

"\_\_\_\_\_"



211

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#### FUNCTION cp\_H2(T)

{Gives the sp. heat of H2 (ideal gas), in kJ/kmol

Input: T in K}

A := 27.012; B := 3.509E-03; E := 0.690E05

 $cp_H2 := A + B * T + E / T^2$ 

END

"\_\_\_\_\_"

FUNCTION cp\_NH3(T)

{Gives the sp. heat of NH3 (ideal gas), in kJ/kmol

Input: T in K}

A := 29.747; B := 25.108E-03; E := -1.546E05

 $cp_NH3 := A + B * T + E / T^2$ 

END

"\_\_\_\_\_"

FUNCTION cp\_CH4(T)

{Gives the sp. heat of CH4 (ideal gas), in kJ/kmol

Input: T in K}

A := 17.449; B := 60.449E-03; C := 1.117E-06; D := -7.204E-09

 $cp_CH4 := A + B * T + C * T^2 + D * T^3$ 

END

\_\_\_\_\_

"**Prob. 8.3.6** Calculate the enthalpy of combustion of gaseous methane in kJ/kg of fuel: (a) at 25 C, 1 atm, with liquid water in products (b) at 25 C, 1 atm, with water vapor in products, and (c) at 1000 K, 1 atm. [Ref: 3]"

#### **"EES Solution:"**

"The combustion eqn is:"

"CH4 + 2 (O2 + 3.76 N2) = CO2 + 2 H2O + 7.52 N2"

"Enthalpy of combustion (h\_RP) is given by:

 $h_RP = (H_P - H_R)$ , where  $H_P =$  enthalpy of products,  $H_R =$  enthalpy of reactants.

 $H_P = 1.$  (h\_fo\_CO2(g) + DELTAH\_CO2) + 2. (h\_fo\_H2O(liq) + DELTAH\_H2O)

 $H_R = 1.$  (h\_fo\_CH4(g) + DELTAH\_CH4) + 2. (h\_fo\_O2 + DELTAH\_O2)

All the DELTAH terms in the above are zero since the temp is 25 C. Also, remember that for N2, O2 enthalpy of formation,  $h_f 0 = 0$ .

#### Getting enthalpy of formation (h\_fo) values for CH4 (g), CO2, H2O from Tables:"

h\_f0\_CH4\_g = -74850 "kJ/kmol"

h\_f0\_H2O\_liq = -285820"kJ/kmol"

h\_f0\_CO2\_g = -393520"kJ/kmol"

#### "Then, we have:"

 $H_P_case_a = 1^* h_f0_CO2_g + 2^* h_f0_H2O_liq "kJ/kmol of fuel"$ 

H\_R\_case\_a= 1 \* h\_f0\_CH4\_g + 0"kJ/kmol of fuel"

"And, enthalpy of combustion:"

h\_RP\_case\_a = H\_P\_case\_a - H\_R\_case\_a"kJ/kmol of fuel"

#### "Per unit mass of fuel:"

h\_RP\_perkg\_case\_a = h\_RP\_case\_a/16 "kJ/kg of CH4....16 being the Mol. wt. of CH4"

"\_\_\_\_\_"

#### "(b) When H2O in products is in vapor state:

Now, only change is in enthalpy of formation of water.

#### From Tables, we get:"

h\_f0\_H2O\_vap = -241820"kJ/kmol"

#### "Therefore:"

H\_P\_case\_b = 1\* h\_f0\_CO2\_g + 2 \* h\_f0\_H2O\_vap "kJ/kmol of fuel"

 $H_R_case_b = 1 * h_f0_CH4_g + 0"kJ/kmol of fuel"$ 

#### "And, enthalpy of combustion:"

h\_RP\_case\_b = H\_P\_case\_b - H\_R\_case\_b"kJ/kmol of fuel"

#### "Per unit mass of fuel:"

h\_RP\_caseb\_perkg = h\_RP\_case\_b/16 "kJ/kg of CH4....16 being the Mol. wt. of CH4"



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#### "(c) When the temp of reactants and products is 1000 K:

Now, we will have to include the DELTAh values. We can, of course, refer to Tables, but, we do the following:

DELTAh is calculated as: Deltah = cp \* DELTAT, and we use the EES Functions written earlier for molar sp. heats, to get DELTAh as integral of (cp.DELTAT) from 298K to 1000K, using the built-in EES Function INTEGRAL."

#### "Therefore, we have:"

H\_P\_case\_c = 1\* (h\_f0\_CO2\_g + integral(cp\_CO2(T), T, 298, 1000)) + 2\* (h\_f0\_H2O\_vap + integral(cp\_H2O(T), T, 298, 1000)) "kJ/kmol of fuel"

 $H_R_case_c = 1 * (h_f0_CH4_g + integral(cp_CH4(T), T, 298, 1000)) + 2 * integral(cp_O2(T), T, 298, 1000) "kJ/kmol of fuel"$ 

#### "And, enthalpy of combustion:"

h\_RP\_case\_c = H\_P\_case\_c - H\_R\_case\_c"kJ/kmol of fuel"

#### "Per unit mass of fuel:"

h\_RP\_casec\_perkg = h\_RP\_case\_c/16 "kJ/kg of CH4....16 being the Mol. wt. of CH4"

"Case (d): Use built-in ehthalpy functions of EES to solve case (c):

Note the great advantage here: you just enter the function for enthalpy, need not separately include enthalpy of formation."

H\_P\_case\_d = 1\* Enthalpy(CO2,T=1000) + 2 \* Enthalpy(H2O,T=1000)"kJ/kmol of fuel"

 $H_R_case_d = 1 * Enthalpy(CH4,T=1000) + 2 * Enthalpy(O2,T=1000)"kJ/kmol of fuel"$ 

"And, enthalpy of combustion:"

h\_RP\_case\_d = H\_P\_case\_d - H\_R\_case\_d"kJ/kmol of fuel"

"Per unit mass of fuel:"

h\_RP\_cased\_perkg = h\_RP\_case\_d/16 "kJ/kg of CH4....16 being the Mol. wt. of CH4"

\_\_\_\_\_

#### **Results:**

#### Unit Settings: SI K kPa kJ molar deg

```
h<sub>f0,CH4,g</sub> = -74850 [kJ/kmol]

h<sub>f0,H20,liq</sub> = -285820 [kJ/kmol]

H<sub>P,case,a</sub> = -965160 [kJ/kmol]

H<sub>P,case,c</sub> = -791656 [kJ/kmol]

h<sub>RP,caseb,perkg</sub> = -50144 [kJ/kg]

h<sub>RP,case,b</sub> = -802310 [kJ/kmol]

h<sub>RP,case,d</sub> = -801097

H<sub>R,case,a</sub> = -74850 [kJ/kmol]

H<sub>R,case,c</sub> = 8937 [kJ/kmol]

T = 1000 [K]
```

h<sub>f0,C02,g</sub> = -393520 [kJ/kmol] h<sub>f0,H20,vap</sub> = -241820 [kJ/kmol] H<sub>P,case,b</sub> = -877160 [kJ/kmol] H<sub>P,case,d</sub> = -791695 [kJ/kmol] h<sub>RP,case,a</sub> = -890310 [kJ/kmol] h<sub>RP,case,c</sub> = -800593 [kJ/kmol] h<sub>RP,perkg,case,a</sub> = -55644 [kJ/kg] H<sub>R,case,b</sub> = -74850 [IJ/kmol] H<sub>R,case,d</sub> = 9402

#### Thus:

Case (a):

Enthalpy of combustion at 25 C, 1 atm, (H2O in products in liq. state) = -55644 kJ/kg ... Ans.

Case (b):

Enthalpy of combustion at 25 C, 1 atm, (H2O in products in vapor state) = -50144 kJ/kg ... Ans.

Case (c):

Enthalpy of combustion at 1000 K, 1 atm. = -50037 kJ/kg ... Ans.

Case (d): Using built-in enthalpy functions of EES:

Enthalpy of combustion at 1000 K, 1 atm. = -50069 kJ/kg ... Ans.

"**Prob. 8.3.7** Liquid Octane (C8H18) at 25 C, 1 atm burns with 400% theoretical air which is also at the same temp and pressure. Determine the temp of products of combustion. [Ref: 3]"

#### **"EES Solution:"**

T1 = 25 + 273 "K"
# "Eqn for stoichiometric combustion is:

C8H18 + (12.5) (O2 + 3.76 N2) = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2"

#### "Therefore, combustion eqn when there is 400% theoretical air:

Now, the excess O2 and N2 show up in products:

C8H18 + 4 \* (12.5) (O2 + 3.76 N2) = 8 CO2 + 9 H2O + 37.5 O2 + (4 \* 12.5 \* 3.76) N2

i.e. C8H18 + 50 O2 + 188 N2 = 8 CO2 + 9 H2O + 37.5 O2 + 188 N2"

"Therefore, to find the adiabatic flame temp, put H\_P = H\_R:

For H\_R, we get the enthalpy of formation of C8H18 from Tables:"

h\_f0\_C8H18\_liq = -249950 "kJ/kmol"

# "And: to find Adiabatic flame temp, put H\_P = H\_R:"

 $H_R = h_{f0}C8H18_{liq} + 50 * Enthalpy(O2,T=T1) + 188 * Enthalpy(N2,T=T1)"kJ/kmol fuel"$ 

H\_P = 8 \* Enthalpy(CO2,T=T\_flame) + 9 \* Enthalpy(H2O,T=T\_flame) + 37.5 \* Enthalpy(O2,T=T\_flame) + 188 \* Enthalpy(N2,T=T\_flame) "kJ/kmol fuel"

 $H_P = H_R$  "..finds  $T_{flame}$  (K)"

#### **Results:**

# Unit Settings: SI K kPa kJ molar deg

 $\label{eq:hf0,C8H18,liq} \begin{array}{ll} \text{H}_{\text{P}} = -249950 \ [\text{kJ/kmol}] & \text{H}_{\text{P}} = -250989 \ [\text{kJ/kmol}] \\ \text{H}_{\text{R}} = -250989 \ [\text{kJ/kmol}] & \text{T1} = 298 \ [\text{K}] \\ \hline $T_{\text{flame}} = 961.7 \ [\text{K}] \end{array}$ 

Thus:

Adiabatic flame temp = 961.7 K ... Ans.

Note: It is a great advantage with EES that we don't have to resort to trial and error solution, as we did while referring to Tables.

"**Prob.8.3.8** liq. Octane (C8H18) at 25 C, 1 atm. is burnt with 100% excess air, also entering at same temp and pressure. Determine the adiabatic flame temp.

(b) Also, plot the adiabatic flame temp as excess air varies from 0 to 300%"

**"EES Solution:"** 

"Data:"

T1 = 25 + 273 "K"

percent\_excess\_air = 100 "%"

"Soichiometric eqn for combustion is, from earlier problem:"

"C8H18 + (12.5) (O2 + 3.76 N2) = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2"

"Combustion eqn when there is excess air:

Now, the excess O2 and N2 show up in products:"





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"C8H18 + (1 + percent\_excess\_air/100) \* (12.5) \* (O2 + 3.76 N2) = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2 + aa \* O2 + bb \* N2"

"where:"

aa = (percent\_excess\_air/100) \* 12.5

bb = (percent\_excess\_air/100) \* 12.5 \* 3.76

"Therefore, to find the adiabatic flame temp, put H\_P = H\_R:

For H\_R, we get the enthalpy of formation of C8H18 from Tables:"

h\_f0\_C8H18\_liq = -249950 "kJ/kmol"

"And: to find Adiabatic flame temp, put H\_P = H\_R:"

 $H_R = h_{f0}C8H18_{liq} + (1 + percent_excess_air/100) * 12.5 * Enthalpy(O2,T=T1) + (1 + percent_excess_air/100) * (12.5) * 3.76 * Enthalpy(N2,T=T1)"kJ/kmol fuel"$ 

H\_P=8\*Enthalpy(CO2,T=T\_flame)+9\*Enthalpy(H2O,T=T\_flame)+(12.5\*3.76)\*Enthalpy(N2,T=T\_flame)+bb \* Enthalpy(N2,T=T\_flame)+ aa \* Enthalpy(O2,T=T\_flame) "kJ/kmol fuel"

 $H_P = H_R$  "..finds  $T_{flame}$  (K)"

# **Results:**

# Unit Settings: SI K kPa kJ molar deg aa = 12.5 [kmol] bb = 47 [kmol]

| h <sub>f0,C8H18,lig</sub> = -249950 [kJ/kmol] | Hp =-250470 [kJ/kmol]                   |  |  |  |  |  |
|---|---|--|--|--|--|--|
| H <sub>R</sub> = -250470 [kJ/kmol]            | percent <sub>excess,air</sub> = 100 [%] |  |  |  |  |  |
| T1 = 298 [K]                                  | T <sub>flame</sub> = 1507 [K]           |  |  |  |  |  |

Thus:

Adiabatic flame temp for 100% excess air = 1507 K ... Ans.

# (b) Also, plot the adiabatic flame temp as excess air varies from 0 to 300%: First, compute the Parametric Table:

| 121    | 1 vercent <sub>excess,a</sub> | ² ▼<br>T <sub>flame</sub><br>[K] |
|--------|-------------------------------|----------------------------------|
| Run 1  | 0                             | 2392                             |
| Run 2  | 20                            | 2120                             |
| Run 3  | 40                            | 1913                             |
| Run 4  | 60                            | 1749                             |
| Run 5  | 80                            | 1617                             |
| Run 6  | 100                           | 1507                             |
| Run 7  | 120                           | 1414                             |
| Run 8  | 140                           | 1335                             |
| Run 9  | 160                           | 1267                             |
| Run 10 | 180                           | 1207                             |
| Run 11 | 200                           | 1154                             |
| Run 12 | 220                           | 1107                             |
| Run 13 | 240                           | 1065                             |
| Run 14 | 260                           | 1027                             |
| Run 15 | 280                           | 992.9                            |
| Run 16 | 300                           | 961.7                            |
| Run 17 | 320                           | 933.2                            |
| Run 18 | 340                           | 907.1                            |
| Run 19 | 360                           | 883                              |
| Run 20 | 380                           | 860.7                            |
| Run 21 | 400                           | 840.1                            |



#### Now, plot the Results:

"**Prob.8.3.9** Methane (CH4) gas is burnt with 130% theoretical air in a closed tank. Both CH4 and air are at 200 kPa and 298 K to start with, and the final temp in tank is 1000 K. Find the final pressure in the tank and also the heat transfer.

\_\_\_\_\_

(b) Plot final pressure and heat transfer as the final temp varies from 400 K to 1100 K."

**"EES Solution:"** 

T1 = 298 **"K"** 

P1 = 200 **"kPa"** 

Tf = 1000 **"K"** 

 $R_u = 8.314$  "kJ/kmol.K"

"Since it is a closed tank, we get heat transfer as Q = change in Internal energies at the initial and final states. Also, U = H - P.v

And, final pressure is easily calculated from Ideal gas eqn."

# "Stoichiometric eqn for combustion of CH4 is:"

"CH4 + 2 (O2 + 3.76 N2) = CO2 + 2 H2O + 7.52 N2"

# "Then, combustion eqn with 130% theoretical air is:

CH4 + (1 + 0.3) \* 2 \* (O2 + 3.76 N2) = CO2 + 2 H2O + 7.52 N2 + 0.6 O2 + (0.6 \* 3.76) N2

i.e. CH4 + 2.6 (O2 + 3.76 N2) = CO2 + 2 H2O + 0.6 O2 + 9.776 N2"

# " To find final pressure:"

"P1 \* V = N\_reactants \*  $R_u$  \* T1

Pf \* V = N\_products \* R\_u \* Tf, where N\_reactants = no. of moles of reactants, N\_products = no. of moles of products."

"Therefore:"

 $N_{reactants} = 1 + 2.6 + (2.6 * 3.76)$ 

 $N_{products} = 1 + 2 + 7.52 + 0.6 + (0.6 * 3.76)$ 

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# P1 / Pf = (N\_reactants / N\_products) \* (T1 / Tf) "....finds Pf, kPa"

# "Now, to find heat transfer, Q: Apply the I Law:"

 $\label{eq:U_R} U_R = 7.5 * (Enthalpy(CH4,T=T1) - R_u * T1) + 2.6 * (Enthalpy(O2,T=T1) - R_u * T1) + (2.6 * 3.76) * (Enthalpy(N2,T=T1) - R_u * T1) "kJ/kmol fuel"$ 

 $\label{eq:U_P} U_P = 1 * (Enthalpy(CO2,T=Tf) - R_u * Tf) + 2 * (Enthalpy(H2O,T=Tf) - R_u * Tf) + 0.6 * (Enthalpy(O2,T=Tf) - R_u * Tf) + 9.776 * (Enthalpy(N2,T=Tf) - R_u * Tf) "kJ/kmol fuel"$ 

 $Q = U_R - U_P$ 

# **Results:**

# Unit Settings: SI K kPa kJ molar deg

| N <sub>products</sub> = 13.38      | N <sub>reactants</sub> = 13.38 | P1 = 200 [kPa]                     |
|------------------------------------|--------------------------------|------------------------------------|
| Pf = 671.1 [kPa]                   | Q = 70647 [kJ/kmol]            | R <sub>u</sub> = 8.314 [kJ/kmol-K] |
| T1 = 298 [K]                       | Tf = 1000 [K]                  | Up = -679451 [kJ/kmol]             |
| U <sub>B</sub> = -608804 [kJ/kmol] |                                |                                    |

# Thus:

Final pressure, Pf = 671.1 kPa .... Ans.

Heat transfer, Q = 70647 kJ/kmol fuel ... Ans.

# (b) Plot final pressure and heat transfer as the final temp varies from 400 K to 1100 K:

# First, compute the Parametric Table:

| 18    | 1    | ² ₽f<br>[kPa] | ³ Q<br>[kJ/kmol] |  |  |
|-------|------|---------------|------------------|--|--|
| Run 1 | 400  | 268.5         | 271061           |  |  |
| Run 2 | 500  | 335.6         | 240322           |  |  |
| Run 3 | 600  | 402.7         | 208546           |  |  |
| Run 4 | 700  | 469.8         | 175676           |  |  |
| Run 5 | 800  | 536.9         | 141712           |  |  |
| Run 6 | 900  | 604           | 106686           |  |  |
| Run 7 | 1000 | 671.1         | 70647            |  |  |
| Run 8 | 1100 | 738.3         | 33658            |  |  |

Now, plot the Results:





"**Prob. 8.3.10** A small gas turbine uses C8H18 (L) for fuel, and 400% theoretical air. The air and fuel enter at 25 C and the products of combustion leave at 900 K. The output of engine and the fuel consumption are measured and it is found that the specific fuel consumption is 0.25 kg/s of fuel per Megawatt output. Determine the heat transfer from the engine. Assume complete combustion. [Ref: 2]"

**"EES Solution:"** 

T1 = 25 + 273 "K"

T2 = 900 **"K"** 

# "Eqn for stoichiometric combustion is:

C8H18 + (12.5) (O2 + 3.76 N2) = 8 CO2 + 9 H2O + (12.5 \* 3.76) N2"

# "Combustion eqn when there is 400% theoretical air:

Now, the excess O2 and N2 show up in products:

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C8H18 + 4 \* (12.5) (O2 + 3.76 N2) = 8 CO2 + 9 H2O + 37.5 O2 + (4 \* 12.5 \* 3.76) N2

i.e. C8H18 + 50 O2 + 188 N2 = 8 CO2 + 9 H2O + 37.5 O2 + 188 N2"

"Therefore, to find the heat transfer, Q, put: Q + H\_R = W + H\_P:

For H\_R, we get the enthalpy of formation of C8H18 from Tables:"

h\_f0\_C8H18\_liq = -249950 "kJ/kmol .... enthalpy of formation of liq. octane"

"And:"

H\_R = h\_f0\_C8H18\_liq + 50 \* Enthalpy(O2,T=T1) + 188 \* Enthalpy(N2,T=T1)"kJ/kmol fuel"

 $H_P = 8 * Enthalpy(CO2,T=T2) + 9 * Enthalpy(H2O,T=T2) + 37.5 * Enthalpy(O2,T=T2) + 188 * Enthalpy(N2,T=T2) "kJ/kmol fuel"$ 

W = (1000/0.25) \* 114.23 "kJ/kmol, since by data, for 0.25 kg/s of fuel, there is 1000 kW of work output"



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"Therefore:"

 $Q + H_R = W + H_P$  "...finds Q, kJ/kmol of fuel"

# **Results:**

# Unit Settings: SI K kPa kJ molar deg $h_{f0,C8H18,liq} = -249950 [kJ/kmol]$ $H_P = -752641 [kJ/kmol]$ $H_R = -250989 [kJ/kmol]$ Q = -44732 [kJ/kmol]T1 = 298 [K]T2 = 900 [K]W = 456920 [kJ/kmol]T2 = 900 [K]

# Thus:

Heat transfer, Q = -44732 kJ/kmol of fuel .... Ans. (-ve sign indicates heat being rejected)

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# 8.4 Problems solved with TEST:

It is very easy and convenient to make combustion calculations with TEST.

The combustion TEST Calc (or 'daemon' as it was called in earlier versions of TEST) is slightly different to operate compared to other daemons.

# Following are the important points to remember:

1. As with some other daemons, there are two types of combustion daemons: one for Closed systems and the other for Open systems, as shown below:



2. Hovering the mouse pointer over Closed 'Combustion and Chemical Equilibrium' daemon gives following explanatory pop-up:



3. Similarly, hovering the mouse pointer over Open 'Combustion and Chemical Equilibrium' daemon gives following explanatory pop-up:

| Node Specific Help   |                               |                             |                            |                            |                            |
|--|-------------------------------|-----------------------------|----------------------------|----------------------------|----------------------------|
| Steady-State Reactors<br>Analyze open steady reacting systems such as a combustion chamber. Select from premixed   | Species                       | kg<br>0.8918                | kmol<br>0.0318             | Mass Fra<br>0.0030         | Mole Frac<br>0.0030        |
| or non-premixed combustors for fundamental combustion analysis. Use the equilibrium<br>TESTcalcto study emissions. For simulating a combustion chamber, check out the Combustion<br>RIA. | CO2     H     H     H2     H2 | 42.6082<br>0.0006<br>0.0286 | 0.9681<br>0.0006<br>0.0142 | 0.1465<br>0.0000<br>0.0000 | 0.0917<br>0.0000<br>0.0013 |
| Chapters 13 and 14 cover combustion and equilibrium analysis.  |                               | 35.6795                     | 1.9805                     | 0.1226                     | 0.1877                     |
|  |                               |                             |                            |                            |                            |

4. Clicking on Closed Process 'Combustion and Chemical Equilibrium' gives the following Material selection window:



5. Clicking on Open system 'Combustion and Chemical Equilibrium' gives the following Material selection window:



6. Combustion daemon is built on the basic panel called the **'Reaction panel'**. It has 3 sections or blocks as shown below: Fuel block, Oxidizer block and Products block:

| thermofluids.net • TESTo       | calcs (Java A   | pplets) · Syst     | ems · Open       | <ul> <li>Steady St</li> </ul> | tate • S   | Specific · C    | ombustion/0                                  | ChemEqulib    | rium • uno   | defined • n-IG   | 6 Mode |
|--------------------------------|-----------------|--------------------|------------------|-------------------------------|------------|-----------------|--|---------------|--------------|------------------|--------|
| Look for accurate values of va | ariables on thi | s panel. For addit | tional messages, | enable the Ti                 | urn Help C | )n checkbox b   | elow.  |               |              |                  |        |
| • SI C English                 | C Mass          | Mole               | 🔽 Help Mes       | sages On                      |            | Super-Calcu     | late   | Load          |              | Super-Initialize |        |
| Reaction Par                   | nel             |                    | State Panel      |                               |            | Device          | Panel  |               | 1/           | O Panel          |        |
| Select an Action After Cho     | osing Fuel(s)   | Perfe              | orm Action       | <b>▲</b> /                    | (% Theor   | . Air)<br>ion 💌 | <ul> <li>(Eqv. Ratio</li> <li>1.0</li> </ul> | )<br>fraction | ✓ <b>1.0</b> | Scaling Factor   | ~      |
| Fuel Block:                    |                 | Select Fuel(s)     |                  |                               | <b>·</b>   | xidizer Block   | (try default):                               |               | Select Ox    | idizer           | ~      |
| kmol                           |                 | kmol               |                  | kmol                          |            | Air             | kmol   | ~             |              | kmol             |        |
| kmol                           | ~               | kmol               | <b></b>          | kmol                          |            |                 | kmol   | ~             |              | kmol             | ~      |
| Products Block (try default    | selections fir  |                    |                  |                               |            | Select Produc   | ts   |               |              |                  | ~      |
| C02                            |                 |                    | H20              |                               |            | N2              |  |               | 02           |                  |        |
| kmol                           | ×               |                    | kmol             | × .                           |            | km              | ol   | ×             |              | kmol             | ×      |
| kmol                           | ×               |                    | kmol             | ~                             |            | km              | ol   |               |              | kmol             | ×      |

7. We can select any one or more of fuels from the 'Select Fuel(s)' widget. Similarly, any of the oxidizers and Products can be selected from Oxidizer or Products widgets.

8. After selecting a fuel, choose the required action from the 'Select an action...' widget, and then perform that action by clicking on 'Perform Action':



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231

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# 9. State panel calculates the States of Fuel, oxidizer or Products, as per the selection:

| No  | on-Premixed Open-Stead                       | y Compustion TES              | Sicalc: n-1G Model       |                              |  |  |  |
|---|--|-------------------------------|--------------------------|------------------------------|--|--|--|
| thermofluids.net + TESTcalcs (Java App  | olets) · Systems · Open · Si                 | eady State 🔸 Specific         | Combustion/ChemEquilibri | ium 🔸 undefined 🔸 n-IG Model |  |  |  |
| Move mouse over a variable to display its valu  | e with more precision.                       |                               |                          |                              |  |  |  |
| • SI C English C Mass   | • Mole 🔽 Help Message                        | s On Super-                   | Calculate                | Super-Initialize             |  |  |  |
| Reaction Panel  | State Panel                                  |                               | evice Panel              | I/O Panel                    |  |  |  |
|   | otato i ano                                  |                               |                          | and and                      |  |  |  |
| < State-1 		 > <-Select To  | ogether> <mark>Fuel </mark> ♥<br>Fuel        | Calculate                     | No-Plots 💌               | Initialize                   |  |  |  |
| p1  | T1 Oxidizer v1                               |                               | u1                       | h1                           |  |  |  |
| kPa 💙   | AProducts                                    | m^3/kg 💉                      | kJ/kg 🚩                  | kJ/kg 💙                      |  |  |  |
|   | <u>۲</u> ۱                                   | el1                           | ✓ z1                     | e1                           |  |  |  |
| kJ/kg.K 👻   | kJ/kg ⊻ 0.0                                  | m/s 🗡                         | 0.0 m 🗠                  | kJ/kg 🗙                      |  |  |  |
| j1 mdo  | t1 V   | oldot1                        | A1                       | MM1                          |  |  |  |
| ∫ kJ/kg ♥   | kg/s 🖌                                       | m^3/s 💙                       | m^2 💉                    | kg/kmol 💉                    |  |  |  |
| c_p1 Mod  | el1  |                               |                          |                              |  |  |  |
| kJ/kg.K ⊻ 1.0   | UnitLess                                     |                               |                          |                              |  |  |  |
| A Note on State Evaluation  |  |                               | Fuel Composition         | on (Mass)                    |  |  |  |
| Set up the reaction in the reaction panel before evaluating states of the reactants and products in this panelMass Fractions, x |  |                               |                          |                              |  |  |  |
| The mass and compositions of fuel, oxidizer and   | products are deduced from the reaction.      | f you need to                 | Mole Fractions, y        |                              |  |  |  |
| change the mass flow rate, go back to the reacti<br>scaling factor.   | on panel and multiply (from the action mer   | u) the reaction by a suitable |                          |                              |  |  |  |
| In evaluating a state, select the state number first  | t and then the type of the mixture - Fuel, 0 | xidizer, or Products          | ✓                        |                              |  |  |  |

10. Device panel: Here, we enter Q and W values. One thing to remember is that values calculated here are not automatically transported to States panel, but we have to manually copy and paste them in to the States panel, if required, to complete the States calculations.

| thermofluids.net • TE   | STcalcs (Java Ap | plets) · System          | is · Open · Stea | dy State • Spe    | cific • Combustic | on/ChemEqulibrium | • undefined • n- | IG Mode |
|---|------------------|--------------------------|------------------|-------------------|-------------------|-------------------|------------------|---------|
| • SI C English  | C Mass           | <ul> <li>Mole</li> </ul> | Fion.            | m St              | per-Calculate     | Load              | Super-Initializ  | .e      |
| Reaction  | Panel            |                          | State Panel      |                   | Device Panel      | 1                 | I/O Panel        |         |
| Initi   | alize            |                          | < Device-A       | <b>*</b> >        |                   | C                 | alculate         |         |
| i1-State: State-Null  | *                |                          | i2-State:        | State-Null 💌      |                   | e-State: S        | State-Null 💌     |         |
| Qdot k  | W 💙              | Wdot_ext                 | ĸW               | ✓ T_B<br>✓ 298.15 | к                 | Sdot_g            | en<br>kW/K       | ~       |
| Jdot_net  | w 🗸              | Sdot_net                 | KW/K             | ~                 |                   |                   |                  |         |
| KW       KWK         Steady Mixing Reacting Device - A         Mass, Energy, and Entropy Equations:       State-Null: $0 = (\dot{m}_{i1} + \dot{m}_{i2}) - \dot{m}_{e}$ $I = X$ $0 = (\dot{m}_{i1}j_{i1} + \dot{m}_{i2}j_{i2}) - \dot{m}_{e}j_{e} + \dot{Q} - \dot{W}_{ext}$ $I = X$ $0 = (\dot{m}_{i1}g_{i1} + \dot{m}_{i2}g_{i2}) - \dot{m}_{e}g_{e} + \dot{Q} - \dot{W}_{ext}$ $I = X$ $0 = (\dot{m}_{i1}g_{i1} + \dot{m}_{i2}g_{i2}) - \dot{m}_{e}g_{e} + \dot{Q} - \dot{W}_{ext}$ $I = X$ $0 = (\dot{m}_{i1}g_{i1} + \dot{m}_{i2}g_{i2}) - \dot{m}_{e}g_{e} + \dot{Q} + \dot{R}_{gan}$ $I = X$ $0 = (\dot{m}_{i1}g_{i1} + \dot{m}_{i2}g_{i2}) - \dot{m}_{e}g_{e} + \dot{Q} + \dot{R}_{gan}$ $V$ $0 = (\dot{m}_{i1}g_{i1} + \dot{m}_{i2}g_{i2}) - \dot{m}_{e}g_{e} + \dot{Q} + \dot{R}_{gan}$ $V$ $0 = (\dot{m}_{i1}g_{i1} + \dot{m}_{i2}g_{i2}) - \dot{m}_{e}g_{e} + \dot{Q} + \dot{R}_{gan}$ $V$ $0 = (\dot{m}_{i1}g_{i1} + \dot{m}_{i2}g_{i2}) - \dot{m}_{e}g_{e} + \dot{Q} + \dot{R}_{gan}$ $V$ $0 = (\dot{m}_{i1}g_{i1} + \dot{m}_{i2}g_{i2}) - \dot{m}_{e}g_{e} + \dot{Q} + \dot{R}_{gan}$ $V$ $0 = (\dot{m}_{i1}g_{i1} + \dot{m}_{i2}g_{i2}) - \dot{m}_{e}g_{e} + \dot{Q} + \dot{R}_{gan}$ $V$ |                  |                          |                  |                   |                   |                   |                  |         |

#### With this short introduction, now let us solve a few standard types of combustion problems:

Prob. 8.4.1 Methane(gas) burns with theoretical air. Find out the AF ratio by moles and by mass.

(b) If 50% excess air is supplied, find the composition of products on mole basis, and also the Dew point temp.

# **TEST Solution:**

Following are the steps:

1. Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Various actions that are possible after choosing the fuel are shown below:

| Non   | -Premixed Open-Ste  | eady Com  | bustion TEST     | calc: n-IG Mode    | e/               |                  |       |
|---|---------------------|-----------|------------------|--------------------|------------------|------------------|-------|
| thermofluids.net • TESTcalcs (Java Apple                              | s) • Systems • Open | Steady St | ate • Specific • | Combustion/Chem    | Equlibrium • und | defined • n-IG   | Model |
| Qdot = kW [Net heat transfer rate]                                    |                     |           |                  |                    |                  |                  |       |
| 🖲 SI C English C Mass 🕞 I   | Mole 🔽 Help Mess    | sages On  | Super-Ca         | Iculate            | Load             | Super-Initialize |       |
| Reaction Panel  | State Panel         |           | Devi             | ce Panel           | U.               | O Panel          |       |
|   |                     |           |                  |                    |                  |                  |       |
| Theoretical Combustion with Air                                       | Y Perform Action    | 1.0       | (% Theor. Air)   | C (Eqv. Ratio)     | on 🗸 1.0         | Scaling Factor   | ~     |
| Select an Action After Choosing Fuel(s)                               | ^                   | 1         |                  |                    |                  |                  |       |
| Initialize the Reaction Panel   | el(s)               |           | V Oxidizer Blo   | ick (try default): | Select Ox        | idizer           | ~     |
| Theoretical Combustion with Air<br>Theoretical Combustion with Oxygen |                     | kmol      |                  | Air                | ~                | kmol             | ~     |
| Excess/Deficient Air (set by lambda)                                  | ·                   |           |                  |                    |                  |                  | -     |
| kmol 🗸  | kmol 🛛              | kmol      |                  | kmol               | ~                | kmol             | ~     |
| Products Block (try default selections first):                        |                     |           | Select Pro       | ducts              |                  |                  | ~     |
| C02   | H20                 |           | N2               |                    | 02               |                  |       |
| kmol 💙  | kmol                |           |                  | kmol 💙             |                  | kmol             | ×     |
| kmol  | kmol                | ~         |                  | kmol 🗸             |                  | kmol             | ~     |

2. Select Methane (CH4) as fuel, 'Theoretical combustion with Air' from Action widget, and click on 'Perform Action'. We get:

| Note: You   | Note: You can remove a default species by clicking its checkbox twice! |                   |                |                         |      |          |                 |               |      |                  |   |
|---|--|-------------------|----------------|-------------------------|------|----------|-----------------|---------------|------|------------------|---|
| @ SI  | C English  | C Mass            | Mole           | Mole 🔽 Help Messages On |      | S        | Super-Calculate |               | Load | Super-Initialize |   |
|   | Reaction Pa  | anel              |                | State Panel             | 1    |          | Device F        | 'anel         |      | I/O Panel        |   |
| Theoretical Combustion with Air Perform Action Perform Action (Eqv. Ratio) Scaling Factor 1.0 fraction (I.0 fraction) 1.0 fraction (I.0 No Unit |  |                   |                |                         |      |          |                 |               |      |                  |   |
| Fuel Bloc   | sk:  |                   | Select Fuel(s) |                         |      | V Oxio   | lizer Block (   | try default): |      | Select Oxidizer  | ~ |
| <b>_</b>  | Methane(CH4)   |                   |                |                         |      |          | Air             |               |      |                  |   |
| 1.0   | kmol   |                   | kmol           |                         | kmol | 9.52     | 3809            | kmol          | ~    | kmol             | × |
|   | kmol   |                   | kmol           |                         | kmol | × -      |                 | kmol          | V    | kmol             | × |
| Products  | Block (try defau   | It selections fir |                |                         |      | Se       | lect Product    | s             |      |                  | ~ |
| 1.0   | CO2  | 1                 | 2.0            | H2O<br>kmol             | ~ 7  | .5238094 | N2<br>kmc       | 1             | ¥    | kmol             | × |
|   |  |                   |                |                         |      |          |                 |               |      |                  |   |

Note that in the above, **Moles** radio button was chosen by default; also ,**Air** as oxidizer was chosen by default. And, products compositions of CO2, H2O and N2, are shown. We find that:

# AF ratio on mole basis: 9.5238 .... Ans.

3. To get AF ratio on Mass basis: Click Mass radio button: immediately, screen changes to:

|              | English (              | • Mass C         | Mole        | Help Messages On | Sup              | er-Calculate          | Load     | Super-Initialize | e |
|--------------|------------------------|------------------|-------------|------------------|------------------|-----------------------|----------|------------------|---|
|              | Reaction Panel         |                  | 5           | itate Panel      |                  | Device Panel          |          | I/O Panel        |   |
| heoretica    | al Combustion with     | Air              | Perform     | Action           | λ (% Theor. Air) | C (Eqv. Rati          | 0)       | Scaling Factor   | r |
| iel Block:   |                        | Sel              | ect Fuel(s) |                  | Oxidiz           | er Block (try default | ):       | Select Oxidizer  |   |
| ✓ Me<br>5.04 | ethane(CH4)            |                  | kg 💙        | kg               | 275.90           | Air<br>0475 kg        | <b>v</b> | kg               |   |
|              | kg 🗸                   |                  | kg 💙        | kg               |                  | kg                    |          | kg               |   |
| aducts B     | llock (try default sei | lections first): |             |                  | Sele             | ct Products           |          |                  |   |
|              |                        |                  |             |                  |                  | 2                     |          |                  |   |



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234

# Now, **normalize reaction** to get mass of air for 1 kg of fuel:

| Note: You | i can remove | e a default speci | es by clicking its | checkbox twice! |                 |                 |                     |                    |                  |                                       |
|-----------|--------------|-------------------|--------------------|-----------------|-----------------|-----------------|---------------------|--------------------|------------------|---------------------------------------|
|           | C Englis     | sh 🔍 Ma           | iss C Mole         | 🔽 Help          | Messages On     | Su              | per-Calculate       | Load               | Super-Initialize | •                                     |
|           | React        | ion Panel         |                    | State Pan       | el              | [               | Device Panel        |                    | I/O Panel        |                                       |
| Normali   | ize Reaction | ) (by mass or m   | ole of fuel) 👻     | Perform Action  | <b>√</b><br>1.0 | \ (% Theor. Air | ) 🗆 (Eqv. R         | tatio)<br>fraction | Scaling Factor   | · · · · · · · · · · · · · · · · · · · |
| Fuel Blo  | ck:          |                   | Select Fue         | (s)             |                 | V Oxidi         | zer Block (try defa | ult):              | Select Oxidizer  | ~                                     |
| -         | Methane(Cl   | 14)               |                    |                 | J               |                 | Air                 |                    |                  |                                       |
| 1.0       | kg           | ×                 | kg                 | ×               | kg              | 17.20           | )1044 kg            | ×                  | kg               | X                                     |
|           | kg           | ~                 | kg                 | ×               | kg              | ~               | kg                  | ~                  | kg               | ×                                     |
| Products  | s Block (try | default selectio  | ns first):         |                 |                 | Sel             | ect Products        |                    |                  | ~                                     |
|           | CO2          |                   |                    | H2O             |                 |                 | N2                  |                    |                  |                                       |
| 2.74376   | 56           | kg                | × 2.246882         | 27 kg           | × [             | 13.133832       | kg                  | ~                  | kg               | ~                                     |
|           |              |                   |                    |                 |                 |                 |                     |                    |                  |                                       |

Therefore: AF ratio = 17.2 on mass basis ... Ans.

# 4. If 50% excess air is supplied:

Choose  $\lambda$  as 150%, and, from Action widget, select Excess/Deficient Air as shown below:

| Note: You can remove a default species by clic  | king its checkbox twice! |                     |                           |                     |                      |    |  |
|---|--------------------------|---------------------|---------------------------|---------------------|----------------------|----|--|
|   | Mole 🔽 Help Mess         | ages On             | Super-Calculate           | Load                | oad Super-Initialize |    |  |
| Reaction Panel  | State Panel              |                     | Device Panel              |                     | I/O Panel            |    |  |
| Excess/Deficient Air (set by lambda)<br>Excess/Deficient Air (set by lambda)                            | Perform Action           | ✓ λ (% The<br>150 9 | eor. Air) 🛛 (Eqv. Ra      | atio)<br>fraction 💌 | Scaling Factor       | ~  |  |
| Convert Air to O2 and N2<br>Balance Reaction (by atom balance)<br>Read As Is (all coefficients are set) | el(s)                    |                     | Oxidizer Block (try defau | ilt):               | Select Oxidizer      | ~  |  |
| Normalize Reaction (by mass or mole of fue<br>Multiply by the Scaling Factor                            |                          | kg 💉                | 17.201044 kg              | <b>v</b>            | kg                   | ×  |  |
| kg 🗸  | kg 🗸                     | kg 🗸                | kg                        | ×                   | kg                   | ×  |  |
| Products Block (try default selections first):  |                          |                     | Select Products           |                     |                      | ~  |  |
| CO2   | H2O                      |                     | N2                        |                     |                      |    |  |
| 2.7437656 kg 🗸 2  | .2468827 kg              | ✓ 13.1338           | 332 kg                    | *                   | kg                   | ×. |  |

# And, Click on 'Perform action'. We get:

| Error: This sp | oecies has bee                  | n already chos   | en.            |              |               |          |               |                 |                 |                |                |   |
|----------------|---------------------------------|------------------|----------------|--------------|---------------|----------|---------------|-----------------|-----------------|----------------|----------------|---|
| ⊂ SI ⊂         | English                         | Mass             | C Mole         | 🔽 Help Mess  | sages On      |          | Super-Cal     | culate          | Load            | Sup            | oer-Initialize |   |
|                | Reaction Pa                     | nel              |                | State Panel  |               |          | Devid         | e Panel         |                 | I/O Pa         | nel            |   |
| Excess/Det     | ficient Air (set <mark>l</mark> | by lambda)       | Y Pe           | rform Action | <b>1</b> 50.0 | λ (% The | or. Air)      | C (Eqv. Rat     | i0)<br>fraction | ✓ Sca          | ling Factor    | - |
| Fuel Block:    |                                 |                  | Select Fuel(s) |              |               | ~        | Oxidizer Bloc | k (try default: | ):              | Select Oxidize | r              | ~ |
| ✓ Met          | thane(CH4)                      |                  |                |              |               |          | 🖌 🖌           | ir              |                 |                |                |   |
| 1.0            | kg                              | ×                | kg             |              | kg            | ~        | 25.801567     | kg              | ~               |                | kg             | ~ |
| <b></b>        | kg                              | ~                | kg             |              | kg            |          |               | kg              | <u>⊻</u>        |                | kg             | ~ |
| Products Bl    | ock (try defaul                 | t selections fir | st):           |              |               |          | Select Prod   | ucts            |                 |                |                | * |
| 2.7437656      | CO2 kg                          | ~                | 2.2468827      | H2O<br>kg    | ~             | 19.70074 | N2            | g               | ✓ 1.995         | 02<br>50124 kg |                | ~ |

Note that now, extra O2 and N2 show up in products.

5. **If we desire results on mole basis,** select Mole radio button and Normalize, click Perform Action. We get:

| Error: This species has been already chosen.   |                         |  |                       |
|--|-------------------------|--|-----------------------|
| ● SI C English C Mass ● I                      | Mole 🔽 Help Messages On | Super-Calculate                            | Load Super-Initialize |
| Reaction Panel                                 | State Panel             | Device Panel                               | I/O Panel             |
| Normalize Reaction (by mass or mole of fuel    | Perform Action 150.0    | λ (% Theor. Air)<br>%<br>0.6666667 fractio | Scaling Factor        |
| Fuel Block: Sele                               | ect Fuel(s)             | • Oxidizer Block (try default):            | Select Oxidizer 💌     |
| Methane(CH4)                                   |                         | Air  |                       |
| 1.0 kmol 🗸                                     | kmol 🖌 kmol             | 14.285714 kmol                             | ▼ kmol ♥              |
| kmol   | kmol V                  | V kmol                                     | V kmol V              |
| Products Block (try default selections first): |                         | Select Products                            | <b>v</b>              |
| C02  | H2O                     | N2   | 02                    |
| 1.0 kmol 2.0                                   | 0 kmol 👻                | 11.285714 kmol 💌                           | 0.99999994 kmol 👻     |

Then, we observe:

Total no. of moles in products = 1 + 2 + 11.286 + 1 = 15.286

Mole fraction of water vapor in products = 2 / (15.286) = 0.131

Therefore, partial pressure of water vapor = 0.131 \* P = 0.131 bar = 13.1 kPa (where P = total pressure of mixture = 1 bar)

And, corresponding dew point temp = sat. temp at this partial pressure = 50.87 C ..... Ans.

**Prob. 8.4.2** 4.4 kg propane gas is burnt completely with 3 kmol of air. Find excess air and molar analysis of dry combustion products. [VTU]

\_\_\_\_\_\_



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\* Figures taken from London Business School's Masters in Management 2010 employment report



# **TEST Solution:**

Following are the steps:

 Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Select Propane for fuel, and for oxidizer, Air is chosen by default. Fill up 4.4 kg and 3 mol respectively for Propane and Air. Select 'Balance Reaction (by atom balance)' from Action widget, and click on 'Perform Action'. We get:

|   | Non-Premixed Open-St      | eady Combus                      | tion TESTcalc: n-IG   | Model            |                      |          |
|---|---------------------------|----------------------------------|---|------------------|----------------------|----------|
| thermofluids.net • TESTcalcs (Java /      | Applets) · Systems · Open | <ul> <li>Steady State</li> </ul> | Specific · Combustion   | n/ChemEqulibrium | • undefined • n-IG M | lodel    |
| Wdot_ext = kW [External work tran         | sfer rate]                |                                  |   |                  |                      |          |
| • SI C English C Mass                     | 🏵 Mole 🛛 🔽 Help Mes       | ssages On                        | Super-Calculate   | Load             | Super-Initialize     |          |
| Reaction Panel                            | State Panel               |                                  | Device Panel  |                  | I/O Panel            |          |
| Balance Reaction (by atom balance)        | Perform Action            | _ ∧ (% TI                        | neor. Air)  Graction  Control | io)<br>fraction  | Scaling Factor       | <b>•</b> |
| Fuel Block:                               | Select Fuel(s)            | ¥                                | Oxidizer Block (try defaul  | l): Se           | lect Oxidizer        | ~        |
| Propane(C3H8)                             |                           |                                  | Air   |                  |                      |          |
| 4.4 kg 💌                                  | kmol 🗸                    | kmol 🗸                           | 3.0 kmol  | ¥                | kmol                 | ×        |
| kmol 🗸                                    | kmol 💙                    | kmol 💙                           | kmol  | ~                | kmol                 | ×        |
| Products Block (try default selections fi |                           |                                  | Select Products   |                  |                      | *        |
| CO2                                       | H2O                       |                                  | N2  |                  | 02                   |          |
| 0 2993197 kmpl                            | 0 20000007                | 2.27                             | Concernence of the second second second second second second second second second second second second second s   | 0 40440070       |                      |          |

Note that composition of products is calculated.

# Molar analysis of dry combustion products (i.e. ignoring H2O):

Total no. of moles of CO2 + N2 + O2 = 0.2993 + 2.37 + 0.1311 = 2.8004 kmol

Therefore,

mole% of CO2 = 0.2993 \* 100 / 2.8 = 10.689% ... Ans.

mole% of N2 = 2.37 \* 100 / 2.8 = 84.643% .... Ans.

mole% of O2 = 0.1311 \* 100 / 2.8 = 4.682% ... Ans.

2. To get results on mass basis for this reaction, we select Mass radio button, and we get:

| Wdot_ext =    | kW [Extern       | al work trans | fer rate]     |               |                 |                 |            |                   |                 |          |                  |   |
|---------------|------------------|---------------|---------------|---------------|-----------------|-----------------|------------|-------------------|-----------------|----------|------------------|---|
| ⊂ SI ⊂ E      | Inglish          | • Mass        | C Mole        | 🔽 Help        | Messages On     |                 | Super-C    | alculate          | Load            | 1        | Super-Initialize |   |
|               | Reaction Pan     | el            |               | State Par     | nel             | 1               | De         | vice Panel        |                 |          | I/O Panel        |   |
| Balance Read  | ction (by atom   | balance)      | P             | erform Action | <b>√</b><br>1.0 | ∧ (% The<br>fra | or. Air)   | C (Eqv. Rat       | i0)<br>fraction | × 1.0    | Scaling Factor   | ~ |
| Fuel Block:   |                  | [             | Select Fuel(s | )             |                 | ~               | Oxidizer B | lock (try default | i):             | Select O | xidizer          | ~ |
| Propa         | ane(C3H8)        |               | kg            |               | kg              | ~               | ✓<br>86.91 | Air kg            | ~               |          | kg               | ~ |
|               | kg               |               | kg            |               | kg              | ~               |            | kg                | ×               |          | kg               | ~ |
| Products Bloc | k (try default s | elections fir | st):          |               |                 |                 | Select Pr  | oducts            |                 |          |                  | ~ |
|               | CO2              |               |               | H2O           |                 |                 | N2         |                   |                 | 02       |                  |   |
| 13.173061     | kg               | ~             | 7.191655      | kg            | ×               | 66.36           |            | kg                | ✓ 4.196         | 5281     | kg               | * |

Therefore, actual AF ratio = 86.91 / 4.4 = 19.752 on mass basis.

3. To get stoichiometric AF ratio: select 'Theoretical combustion with Air' from Action widget, and click on 'Perform Action'. We get:

| Note: You  | can remove a d  | efault species t | y clicking its che | ckbox twice! |                 |          |                     |                |                 |               |                |   |
|--|-----------------|------------------|--------------------|--------------|-----------------|----------|---------------------|----------------|-----------------|---------------|----------------|---|
| 🔍 SI   | C English       | Mass             | C Mole             | 🔽 Help Me    | ssages On       |          | Super-Calo          | culate         | Load            | Su            | per-Initialize |   |
|  | Reaction I      | Panel            |                    | State Panel  |                 |          | Devic               | e Panel        |                 | I/O P         | anel           |   |
| Theoret  | ical Combustior | n with Air       | Per                | form Action  | <b>✓</b><br>1.0 | λ (% The | eor. Air)<br>action | C (Eqv. Rati   | iO)<br>fraction | ✓ Sc          | aling Factor   |   |
| Fuel Bloc  | ck:             |                  | Select Fuel(s)     |              |                 | ~        | Oxidizer Bloc       | k (try default | ):              | Select Oxidiz | er             | ~ |
| <ul> <li>Image: A second s</li></ul> | Propane(C3H8)   |                  |                    |              |                 |          | A                   | ir             |                 |               |                |   |
| 1.0  | kg              | ×                | kg                 |              | kg              |          | 15.64086            | kg             | ~               |               | kg             | × |
|  | kg              |                  | kg                 |              | kg              | ~        |                     | kg             | ~               |               | kġ             | ~ |
| Products   | Block (try defa | ult selections f |                    |              |                 |          | Select Prod         | ucts           |                 |               |                | ~ |
| 2 99387  | CO2             |                  | 1 6344671          | H2O          |                 | 11 9425  | N2                  |                |                 |               |                |   |
| 2.33307  | Kg              |                  | 1.0344071          | ĸg           |                 | 11.3425  |                     | g              |                 | K             | y.             |   |

We see that: Stoichio. AF ratio = 15.6409 on mass basis.

Therefore, (Actual AF / Stoichio. AF) = 1.263 = 126.3%

i.e. Excess air = 26.3% ... Ans.

**Prob. 8.4.3** A hydrocarbon fuel  $C_{12}H_{26}$  is burnt with 50% excess air. Determine the volumetric (molal) analysis of products of combustion and also the dew point temp of products, if the pressure is 101 kPa. [VTU]

# **TEST Solution:**

Following are the steps:

Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Select C12H26 for fuel, and for oxidizer, Air is chosen by default. Change λ to 150% (since 50% excess air). Select 'Excess/Deficient Air' from Action widget, and click on 'Perform Action'. We get:

|               |                   | 1                | Non-Premi      | xed Open-St  | eady Con     | nbust    | ion TESTca     | lc: n-IG M                | 1odel      |             |                  |      |
|---------------|-------------------|------------------|----------------|--------------|--------------|----------|----------------|---------------------------|------------|-------------|------------------|------|
| thermofluid   | ds.net • TEST     | īcalcs (Java Aj  | pplets) · Sy   | stems · Open | • Steady S   | tate •   | Specific • C   | ombustion/C               | hemEqulibr | ium • unde  | fined • n-IG     | Mode |
| Error: This s | species has bee   | n aiready chos   | en.            |              |              |          |                |                           |            |             |                  |      |
| (€ SI (       | C English         | C Mass           | • Mole         | 🔽 Help Me    | ssages On    |          | Super-Calcu    | ulate                     | Load       | 5           | Super-Initialize | 1    |
| _             | Reaction Pa       | inel             |                | State Panel  |              |          | Device         | Panel                     |            | 1/0         | Panel            |      |
| Excess/De     | eficient Air (set | by lambda)       | Pe             | rform Action | <b>150.0</b> | λ (% The | or. Air)       | (Eqv. Ratio)<br>0.6666667 | fraction   | ✓ 1.0       | Scaling Factor   | ~    |
| Fuel Block    |                   |                  | Select Fuel(s) |              |              | ~        | Oxidizer Block |                           |            | Select Oxid | izer             | ~    |
| ✓ Do          | Decane(C12H2      | 6)               |                |              |              |          | Air            | t.                        |            |             |                  |      |
| 1.0           | kmol              | ×                | kmol           |              | kmol         | ~        | 132.14285      | kmol                      | ~          |             | kmol             | ×.   |
|               | kmol              |                  | kmol           |              | kmol         | ×        |                | kmol                      |            |             | kmol             | ~    |
| Products B    | Block (try defaul | t selections fir | st):           |              |              |          | Select Produ   | cts                       |            |             |                  | ~    |
|               | CO2               |                  |                | H2O          |              |          | N2             |                           |            | 02          |                  |      |
|               |                   |                  | 42.0           |              |              | 104 302  | 85             | a al                      | 9 2499     | 98          | Innal            | ~    |
| 12.0          | kmol              | ~                | 13.0           | kmol         |              | 104.552  | KII            | nor                       | 0.2400     | 50          | KINOI            |      |

# Thus, mole fraction of products:

Total no. of moles in products = 138.643

Mole% of CO2 = 12 \* 100 / 138.643 = 8.655% ... Ans.

Mole% of H2O = 13 \* 100 / 138.643 = 9.377% .... Ans.

Mole% of N2 = 104.393 \* 100 / 138.643 = 75.296% ... Ans.

Mole% of O2 = 9.25 \* 100 / 138.643 = 6.672% .... Ans.

**Reactive Systems** 

# 2. Dew point temp:

Knowing that mole fraction of H2O is 0.09377, we get the partial pressure of water vapor in products =  $101 \times 0.09377 = 9.471$  kPa (where P = 101 kPa = total pressure).

Dew point temp is the sat. temp corresponding to this partial pressure:

We get: Dew point temp = 44.642 C .... Ans.



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# 3. In addition, to get the Stoichio. AF ratio:

Select Mass radio button, and also select 'Theoretical combustion with Air' as Action item, and click on 'Perform Action'. Immediately, we get:



Thus: Theoretical or Stoichiometric AF ratio (by mass) = 15.012 ... Ans.

**Prob. 8.4.4** A sample of fuel has following percentage composition by weight: C = 84%, O2 = 3.5%, H2 = 10%, Ash = 1%, N2 = 1.5%. Determine: (i) stoichiometric AF ratio by mass (ii) if 20% excess air is supplied, find the percentage composition of dry flue gases by volume. [VTU]

Note: This is the same as Prob.8.2.2, solved with Mathcad.

# Now, let us solve it with TEST:

Following are the steps:

Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose Mass radio button. Select fuels: C, H2, Ash, O2 and N2 and fill in the fractions as shown. Air is chosen as oxidizer, by default. Select 'Read As Is' from Action widget, and click on 'Perform Action'. Then, select 'Theoretical Combustion with Air' from Action widget, and click on 'Perform Action'. We get:

|  |                                      | No   | on-Premixed                      | Open-Stead       | ly Combust   | tion TESTcalc                                 | : n-IG Model             |               |                  |      |
|--|--------------------------------------|--|----------------------------------|------------------|--------------|---|--------------------------|---------------|------------------|------|
| thermofluids                                     | s.net • TESTca                       | alcs (Java App   | lets) · System                   | ns • Open • S    | teady State  | Specific • Con                                | nbustion/ChemE           | qulibrium • u | ndefined • n-IG  | Mode |
| Note: You can                                    | n remove a defau                     | It species by cli  | cking its checkbo                | (twice!          |              |   |                          |               |                  |      |
| ି SI ୍   | English                              | • Mass   | <sup>°</sup> Mole                | 🔽 Help Message   | es On        | Super-Calcula                                 | te 🚺                     | oad           | Super-Initialize |      |
|  | Reaction Pan                         | el   |                                  | State Panel      |              | Device Pa                                     | anel                     |               | I/O Panel        |      |
| Theoretical                                      | Combustion wit                       | h Air  | Y Perform                        | Action           | λ (% Th      | eor. Air)                                     | (Eqv. Ratio)<br>fraction | ~             | Scaling Factor   | ×    |
| Fuel Block:                                      |                                      | Se   | elect Fuel(s)                    | -                | ×            | Oxidizer Block (t                             | ry default):             | Select (      | Dxidizer         | ~    |
| 🖌 C(s)   | )                                    | 1110   |                                  | ( Aph/p)         |              |   |                          |               |                  |      |
|  |                                      | ✓ HZ   |                                  | ✓ Ash(s)         |              | Air   |                          |               |                  |      |
| 0.84   | kg 1                                 | <ul> <li>✓ H2</li> <li>Ø.1</li> </ul>  | kg 🗸                             | • 0.01           | kg 💌         | Air<br>12.918715                              | kg                       | ·             | kg               | ~    |
| 0.84<br>✓ 02                                     | kg 1                                 | <ul> <li>✓ H2</li> <li>✓ 0.1</li> <li>✓ N2</li> </ul>  | kg 💌                             | • Ash(s)<br>0.01 | kg 💌         | Air<br>12.918715                              | kg                       |               | kg               | ~    |
| 0.84<br>✓ O2<br>0.035                            | kg f                                 | <ul> <li>H2</li> <li>0.1</li> <li>N2</li> <li>0.015</li> </ul>                                 | kg 🗸                             | ASII(5)<br>0.01  | kg 💌         | Air<br>12.918715                              | kg 1                     |               | kg<br>kg         | ×    |
| 0.84<br>02<br>0.035<br>Products Blo              | kg f                                 | <ul> <li>H2</li> <li>0.1</li> <li>0.015</li> <li>elections first)</li> </ul>                   | kg 🗸                             | Asii(s)     O.01 | kg 💌         | Air<br>12.918715<br>Select Products           | kg (*                    | <pre></pre>   | kg<br>kg         | ~    |
| 0.84<br>CO2<br>0.035<br>Products Blo             | kg f                                 | <ul> <li>✓ H2</li> <li>0.1</li> <li>✓ N2</li> <li>✓ 0.015</li> <li>elections first)</li> </ul> | kg 🔮                             | Asin(s)          | kg 💌         | Air<br>12.918715<br>Select Products<br>Ash(s) | kg P                     | v             | kg               |      |
| 0.84<br>02<br>0.035<br>Products Bio<br>3.0778787 | kg (kg )<br>kg (try default s<br>CO2 | <ul> <li>0.1</li> <li>0.1</li> <li>0.015</li> <li>elections first)</li> </ul>                  | kg ¥<br>kg ¥<br>H24<br>0.8939379 | Asir(s)          | kg 💙<br>kg 💙 | Air<br>12.918715<br>Select Products<br>Ash(s) | kg kg                    | ×             | kg<br>kg<br>kg   | ~    |

Therefore, we read: Stoichiometric AF ratio = 12.92, by mass.... Ans.

1. With 20% Excess air: Change  $\lambda$  to 1.2 (i.e. 20% excess air). From Action widget, select 'Excess/Deficient Air (set by Lambda)' and click on 'Perform Action'. Immediately, we get:







2. Then, to get Products by volume, choose the Mole radio button. Immediately, we get:

| Error: This species has been already chosen.                            |                                     |                                 |                      |
|---|-------------------------------------|---------------------------------|----------------------|
| 🕫 SI C English C Mass 🕫   | Mole Verse Help Messages On         | Super-Calculate                 | oad Super-Initialize |
| Reaction Panel  | State Panel                         | Device Panel                    | I/O Panel            |
| Excess/Deficient Air (set by lambda)                                    | Perform Action                      | A (% Theor. Air)                | Scaling Factor       |
| Fuel Block: Sel   | lect Fuel(s)                        | • Oxidizer Block (try default): | Select Oxidizer 👻    |
| ✓ C(s) 0.069935896 kmol ✓ H2  | Ash(s)<br>kmol V 1.66666666E-4 kmol | ✓ Air<br>0.5351211 kmol         | kmol 🗸               |
| ✓ 02         ✓ N2           0.00109375         kmol         ≶.3571427E- | 4 kmol kmol                         | kmol                            | V kmol V             |
| Products Block (try default selections first):                          |                                     | Select Products                 | <b>v</b>             |
| CO2   | H2O                                 | Ash(s)                          | N2                   |
| 0.069935896 kmol 🗸 0  | 1.049608096 kmol ⊻                  | 1.6666666E-4 kmol ✓ 0           | .42328137 kmol 👻     |
| 02<br>0.01872924 kmol 🗸   | kmol 👻                              | kmol 😪                          | kmol 🗸               |

Then, we observe:

# Percentage of dry products by volume:

Total no. of kmol for products (excluding ash and H2O): 0.5119 kmol

% CO2 = 0.0699 \* 100 / 0.5119 = 13.658% .... Ans.

% N2 = 0.4328 \* 100 / 0.5119 = 84.564% .... Ans.

% O2 = 0.0187 \* 100 / 0.5119 = 3.517% .... Ans.

\_\_\_\_\_

**Prob. 8.4.5** Methane (CH4) is burnt with atm. air. The analysis of products of combustion on a dry basis is as follows: CO2 = 10%, O2 = 2.37%, CO = 0.53%, N2 = 87.1%. Calculate the AF ratio and the percent theoretical air and determine the combustion equation. [VTU]

# **TEST Solution:**

Following are the steps:

2. Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose **Mole** radio button. Select fuel: CH4, and in the Products block fill in the fractions as shown. Air is chosen as oxidizer, by default.

| Look for accurate values of variables on this p                             | anel. For additional messages, enable the  | Turn Help On checkbox below.     |                       |
|---|--|----------------------------------|-----------------------|
| • SI C English C Mass •   | Mole 🔽 Help Messages On  | Super-Calculate                  | Load Super-Initialize |
| Reaction Panel  | State Panel  | Device Panel                     | I/O Panel             |
|   |  | \\ (% Theor, Air) □ (Eqv. Ratio) | Scaling Factor        |
| Read As Is (all coefficients are set)                                       | Perform Action   | fraction 🕥 1 fraction            | n 💌 1 No Unit 💌       |
| Excess/Deficient Air (set by lambda)<br>Convert Air to O2 and N2            | el(s)  | Oxidizer Block (try default):    | Select Oxidizer 💌     |
| Balance Reaction (by atom balance)<br>Read As Is (all coefficients are set) |  | Air                              | V kmol V              |
| Normalize Reaction (by mass or mole of fue                                  | H) V   |                                  |                       |
| kmol 💙  | kmol 🗸   | kmol                             | V kmol V              |
| Products Block (try default selections first):                              | Sector Contraction of the sector of the sect | Select Products                  | ~                     |
| ✓ CO2   | H20  | ✓ N2                             | ✓ co                  |
| 10 kmol 💌   | kmol 🕑   | 87.1 kmol 💌 🕻                    | 0.53 kmol 🗸           |
| ✓ 02  |  |                                  |                       |
| 2.37 kmol 💌   | kmol 🗸   | kmol 💌                           | kmol 💙                |



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3. Select 'Read As Is' from Action widget, and click on 'Perform Action'. We get:

| Look for accurate values of variables on this panel. For additional messages, enable the Turn Help On checkbox below. |                 |                  |                               |                       |  |  |  |  |
|---|-----------------|------------------|-------------------------------|-----------------------|--|--|--|--|
| 🔍 SI C English C Mass 🤆   | Mole 🔽 Help Mes | ssages On        | Super-Calculate               | Load Super-Initialize |  |  |  |  |
| Reaction Panel  | State Panel     |                  | Device Panel                  | I/O Panel             |  |  |  |  |
| Read As Is (all coefficients are set)   | Perform Action  | ۸ (% Theo<br>fra | or. Air)  Ction               | Scaling Factor        |  |  |  |  |
| Fuel Block:   | elect Fuel(s)   | ~                | Oxidizer Block (try default): | Select Oxidizer 🗸     |  |  |  |  |
| Methane(CH4)  |                 | _                | Air                           |                       |  |  |  |  |
| kmol 😽  | kmol 🗸          | kmol 👻           | kmol                          | Memol Memol           |  |  |  |  |
| kmol Y  | kmol 👻          | kmol 👻           | kmol                          | w kmol w              |  |  |  |  |
| Products Block (try default selections first)   |                 |                  | Select Products               | <b>•</b>              |  |  |  |  |
| ✓ C02   | H2O             |                  | ✓ N2                          | ✓ co                  |  |  |  |  |
| 10.0 kmol 🛩   | kmol            | 87.1             | kmol 💉                        | 0.53 kmol ¥           |  |  |  |  |
| <ul> <li>✓ 02</li> <li>2.37</li> <li>kmol</li> </ul>  | kmol            | ×                | kmol 💙                        | kmol 👻                |  |  |  |  |

4. Select 'Balance Reaction (by atom balance)' from the Action widget:

| Look for accurate values of variables on this pa                            | nel. For additional messages, enabl | the Turn Help On checkbox below.                     |                       |  |  |
|---|-------------------------------------|--|-----------------------|--|--|
| ଙ୍ଗ SI C English C Mass ଙ   | Mole 🔽 Help Messages                | On Super-Calculate                                   | Load Super-Initialize |  |  |
| Reaction Panel  | State Panel                         | Device Panel   | I/O Panel             |  |  |
| Balance Reaction (by atom balance)<br>Excess/Deficient Air (set by lambda)  | Perform Action                      | Λ (% Theor. Air)<br>fraction<br>fraction<br>fraction | Scaling Factor        |  |  |
| Convert Air to O2 and N2  | el(s)                               | • Oxidizer Block (try default):                      | Select Oxidizer 🗸 🗸   |  |  |
| Balance Reaction (by atom balance)<br>Read As Is (all coefficients are set) |                                     | Air  |                       |  |  |
| Normalize Reaction (by mass or mole of fuel                                 | of 🗸 kn                             | kmol   | ✓ kmol ✓              |  |  |
|   | kmol V kn                           | ol Y   | v kmol v              |  |  |
| Products Block (try default selections first):                              |                                     | Select Products                                      | ▼                     |  |  |
| ✓ C02   | H20                                 | ✓ N2   | ✓ co                  |  |  |
| 10.0 kmol 🕑   | kmol                                |  | 0.53 kmol 👻           |  |  |
| ₹ 02<br>2.37 kmol ♥   | kmol                                | kmol 🗸   | kmol 🗸                |  |  |

# 5. And, click on 'Perform Action'. We get:

| thermoflu  | uids.net • TEST  | calcs (Java A   | oplets) • Sys    | tems · Open ·       | Steady State    | e · Specific · | Combustion/ | ChemEqulibri | um • undefined • I | n-IG Model |
|------------|--|-----------------|------------------|---------------------|-----------------|----------------|-------------|--------------|--------------------|------------|
| Look for a | occurate values of v   | ariables on thi | s panel. For add | itional messages, e | enable the Turn | Help On checkb | ox below.   |              |                    |            |
| • si       | C English  | C Mass          | • Mole           | 🔽 Help Mess         | ages On         | Super-C        | alculate    | Load         | Super-Initia       | lize       |
|            | Reaction Pa  | nel             |                  | State Panel         |                 | De             | vice Panel  |              | I/O Panel          |            |
| Balance    | Balance Reaction (by atom balance) Perform Action Fraction (by atom balance) Perform Action Reaction (by atom balance) Perform Action (by atom balance) P |                 |                  |                     |                 |                |             |              |                    |            |
| Fuel Bloc  |  |                 | Select Fuel(s)   |                     |                 | Oxidizer Bl    |             |              | Select Oxidizer    | *          |
|            | Methane(CH4)   |                 |                  |                     |                 |                | Air         |              |                    |            |
| 10.53      | kmol   | ×               | kmol             |                     | kmol            | 110.25317      | kmol        | ×            | kmol               | ×          |
|            | kmol   |                 | kmol             |                     | kmol            | -              | kmol        | I.Y.         | kmol               | ~          |
| Products   | Block (try default   | selections fir  |                  |                     |                 | Select Pr      | oducts      |              |                    | ~          |
|            | ✓ CO2  |                 |                  | H2O                 |                 | 🖌 N2           |             |              | ✓ co               |            |
| 10.0       | kmol   | ~               | 21.06            | kmol                | ▶ 87.1          |                | kmol        | ✓ 0.53       | kmol               | ~          |
| 2.358164   | 02<br>45 kmol  | ~               |                  | kmol                | ~               |                | kmol        | ~            | kmol               | ~          |

Therefore, combustion eqn is:

# 10.53 CH4 + (110.253/4.76). (O2 + 3.76 N2) = 10 CO2 + 21.06 H2O + 87.1 N2 + 0.53 CO + 2.358 O2

6. To convert by mass, simply choose Mass radio button. Immediately, we get:

| Look for accurate values of variables on this panel. For additional messages, enable the Turn Help On checkbox below. |                 |                    |                |              |           |          |                  |               |         |                  |   |
|---|-----------------|--------------------|----------------|--------------|-----------|----------|------------------|---------------|---------|------------------|---|
| ⊛ si  | C English       | Mass               | C Mole         | 🔽 Help Me    | ssages On |          | Super-Calcula    | ate           | Load    | Super-Initialize | l |
|   | Reaction I      | Panel              |                | State Panel  |           | 1        | Device P         | anel          |         | I/O Panel        |   |
| Balance   | Reaction (by at | tom balance)       | Pe             | rform Action | J P       | λ (% The | or. Air)         | (Eqv. Ratio)  | ion 💌   | Scaling Factor   | v |
| Fuel Bloc   | ska             |                    | Select Fuel(s) |              |           | ~        | Oxidizer Block ( | try default): |         | Select Oxidizer  | ~ |
|   | Methane(CH4)    |                    |                |              |           |          | Air              |               |         |                  |   |
| 168.901   | 2 kg            | ×                  | kg             |              | kg        | M        | 3194.0342        | kg            | ×       | kg               | ~ |
|   | kg              |                    | kg             | V            | kg        | ~        |                  | kg            |         | kg               |   |
| Products  | Block (try defa | ult selections fir |                |              |           |          | Select Products  | 5             |         |                  | * |
|   | ✓ CO2           |                    |                | H2O          |           |          | ✓ N2             |               |         | СО               |   |
| 440.1   | kg              | ~                  | 379.5012       | kg           | ¥ 2       | 2438.8   | kg               | *             | 14.8453 | kg               | ~ |
| 75.4612   | 02<br>66 kg     | ~                  |                | kg           |           |          | kg               | Y             |         | kg               | * |

7. **To get the eqn on unit mass of fuel basis:** choose 'Normalize Reaction' in Action widget, and click on 'Perform Action'. We get:



We read from the above: AF = 18.91 by mass basis. ... Ans.



8. **To get Theoretical Air required:** Choose 'Theoretical Combustion with Air' from Action widget, and click on 'Perform Action'. We get:



# We see that: Theoretical AF ratio = 17.2 by mass.

Therefore, percent theoretical air = 18.91 \* 100 / 17.2 = 109.942%

i.e. 9.942 % excess air ... Ans.

\_\_\_\_\_\_

**Prob. 8.4.6** The products of combustion of an unknown hydrocarbon CxHy have the following composition as measured by an Orsat apparatus: CO2 = 8%, CO = 0.9%, O2 = 8.8%, N2 = 82.3%. Determine: (i) the composition of fuel (ii) AF ratio (iii) The percent excess air used. [VTU]

# **TEST Solution:**

Following are the steps:

Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose Mole radio button. Select fuels: C and H2, and in the Products block fill in the fractions as shown. Air is chosen as oxidizer, by default. Select 'Read As Is' from Action widget, and click on 'Perform Action' to register the entered values:

|  | Non-Premixed Open-Steady Combustion TESTcalc: n-IG Model |                |                   |                |               |                 |                       |       |  |  |
|--|--|----------------|-------------------|----------------|---------------|-----------------|-----------------------|-------|--|--|
| thermofluids.net • TESTcalcs (Jav      | va Applets) • Sys  | stems · Open · | Steady St         | ate • Specific | Combustion/   | ChemEquiibriu   | um • undefined • n-IG | Model |  |  |
| Error: This species has been already c | hosen.   |                |                   |                |               |                 |                       |       |  |  |
| GSI CEnglish CMas                      | ss 🕫 Mole  | 🔽 Help Mess    | ages On           | Super-         | Calculate     | Load            | Super-Initialize      | ĺ.    |  |  |
| Reaction Panel                         |  | State Panel    |                   | De             | evice Panel   |                 | I/O Panel             |       |  |  |
| Read As Is (all coefficients are set)  | Per  | form Action    | <u>√</u> ∧<br>1.0 | (% Theor. Air) | C (Eqv. Ratio | )<br>fraction 💙 | Scaling Factor        | ~     |  |  |
| Fuel Block:                            | Select Fuel(s)   |                |                   | Oxidizer E     |               |                 | Select Oxidizer       | ~     |  |  |
| H2                                     | C(s)   |                |                   |                | Air           |                 |                       |       |  |  |
| kmol 🗸                                 | kmol   | ~              | kmol              |                | kmol          | ×               | kmol                  | ~     |  |  |
| kmol 💙                                 | kmol   |                | kmol              | ~              | kmol          | ×               | kmol                  | ~     |  |  |
| Products Block (try default selection  | s first):  |                |                   | Select P       | roducts       | 1499 C          |                       | ~     |  |  |
| ✓ CO2                                  |  | H2O            |                   | 🖌 N2           |               |                 | ✓ 02                  |       |  |  |
| 8.0 kmol                               | ~  | kmol           | 8                 | 2.3            | kmol          | ✓ 8.8           | kmol                  | ~     |  |  |
| ✓ co                                   |  |                | _                 |                | - Constant    | _               |                       |       |  |  |
| 0.9 kmol                               | ~  | kmol           | ×                 |                | kmol          | × .             | kmol                  | Y     |  |  |

 Next, select 'Balance Reaction (by atom balance)' and click on 'Perform Action'. Immediately, the eqn is balanced and we get:

| Error: This species has been already ch | osen.          |                    |                                |  |
|---|----------------|--------------------|--------------------------------|--|
| G SI C English C Mass                   | s 🔍 Mole       | 🔽 Help Messages On | Super-Calculate                | Load Super-Initialize                        |
| Reaction Panel                          | 1              | State Panel        | Device Panel                   | I/O Panel                                    |
| Balance Reaction (by atom balance)      | ✓ Perfo        | rm Action          | λ (% Theor. Air) fraction      | o)<br>fraction V Scaling Factor<br>No Unit V |
| Fuel Block:                             | Select Fuel(s) |                    | • Oxidizer Block (try default) | Select Oxidizer 💌                            |
| H2                                      | C(s)           |                    | Air                            |  |
| 9.254431 kmol 💌 8.9                     | kmol           | kmol               | 104.177216 kmol                | Kmol 🗸                                       |
| kmol V                                  | kmol           | V kmol             | kmol                           | kmol V                                       |
| Products Block (try default selections  | first):        |                    | Select Products                |  |
| ✓ C02                                   | ŀ              | H2O                | ✓ N2                           | ✓ 02   |
| 8.0 kmol                                | ♥ 9.254431     | kmol 💌             | 82.3 kmol                      | 8.8 kmol 🗸                                   |
| ✓ co                                    |                |                    |                                |  |
| 0.9 kmol                                | ~              | kmol 🗠             | kmol                           | × kmol ×                                     |

3. To convert on mass basis: click on Mass radio button. Immediately, we get:

| Error: This species has been already chosen. |                    |               |                     |                  |   |               |                  |   |  |
|--|--------------------|---------------|---------------------|------------------|---|---------------|------------------|---|--|
| 🖲 SI 🔿 English                               | • Mass             | Mole 🔽 He     | elp Messages On     | Super-           | Calculate                                     | Load          | Super-Initialize |   |  |
| Reaction Pa                                  | nel                | State         | Panel               | D                | evice Panel                                   |               | I/O Panel        |   |  |
| Balance Reaction (by ator                    | n balance)         | Perform Actio | yn <mark>1.0</mark> | \ (% Theor. Air) | <ul> <li>(Eqv. Ratio)</li> <li>1.0</li> </ul> | )<br>fraction | Scaling Factor   | ~ |  |
| Fuel Block:                                  | Se                 | lect Fuel(s)  |                     | V Oxidizer       |   |               | Select Oxidizer  | * |  |
| H2   | C(s)               |               |                     |                  | Air   |               |                  |   |  |
| 18.65508 kg                                  | ✓ 106.8979         | kg 💌          | kg                  | 3018.014         | kg  | ~             | kg               | ~ |  |
| kg   |                    | kg 🗸          | kg                  |                  | kg  | ~             | kg               | ~ |  |
| Products Block (try defaul                   | selections first): |               |                     | Select F         | roducts                                       |               |                  | ~ |  |
| ✓ CO2  |                    | H2O           |                     | 🖌 N2             | _   |               | ✓ 02             |   |  |
| 352.08 kg                                    | × 1                | 166.76483 kg  | g 💉 2               | 304.4            | kg  | ✓ 281.6       | kg               | ~ |  |
| ✓ co   |                    |               |                     |                  |   | _             |                  |   |  |
| 25.209 kg                                    | ~                  | k             |                     |                  | kg  | ~             | kg               | ~ |  |

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252

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4. **To get on unit mass of fuel basis:** select 'Normalize Reaction' from Action widget, and click on 'Perform Action'. We get:

| Error: This species has been already  | rchosen.            |             |            |                     |            |                     |                          |   |  |
|---------------------------------------|---------------------|-------------|------------|---------------------|------------|---------------------|--------------------------|---|--|
| 🖲 SI C English 💮 M                    | ass C Mole          | 🔽 Help Mess | ages On    | Super-C             | alculate   | Load                | Super-Initialize         |   |  |
| Reaction Panel                        |                     | State Panel |            | De                  | vice Panel |                     | I/O Panel                |   |  |
| Normalize Reaction (by mass or m      | nole of fuel) 💌 Per | form Action | ✓ ∧<br>1.0 | (% Theor. Air)      | ction 💌    | Scaling Factor      |                          |   |  |
| Fuel Block:                           | Select Fuel(s)      |             |            | V Oxidizer B        | S          | Select Oxidizer 🗸 🗸 |                          |   |  |
| H2<br>0.14858334 kg 🗸 0.8             | C(s)<br>5141665 kg  | kg 🗸        |            | Air<br>24.037771 kg |            | ~                   | kg                       | ~ |  |
| kg M                                  | kg                  |             | kg         | v                   | kg         | ~                   | kg                       | ~ |  |
| Products Block (try default selection | ons first):         |             |            | Select Pr           | oducts     |                     |                          | * |  |
| ✓ C02                                 |                     | H2O         |            | 🖌 N2                |            |                     | <ul> <li>✓ 02</li> </ul> |   |  |
| 2.8042345 kg                          | 1.3282428           | kg          | ✓ 18       | 3.354004            | kg 😽       | 2.242878            | kg                       | ~ |  |
| CO<br>0.20078376 kg                   | ×                   | kg          | ~          |                     | kg 🗸       |                     | kg                       | ~ |  |

Thus, Fuel contains: 14.86% by mass of H2 and 85.14% by mass of C..... Ans.

#### And, actual AF ratio, by mass = 24.04 .... Ans.

5. **To find 'Theoretical air':** select 'Theoretical combustion with Air' from Action widget, and click on 'Perform Action'. We get:

| Note: You can remove  | a default species by clic | king its checkbox twice! |                   |                           |                      |                   |
|-----------------------|---------------------------|--------------------------|-------------------|---------------------------|----------------------|-------------------|
| • SI C Englisi        | h 🔍 Mass G                | Mole 🔽 Help Me           | essages On        | Super-Calculate           | Load                 | Super-Initialize  |
| Reaction              | on Panel                  | State Panel              |                   | Device Panel              |                      | I/O Panel         |
| Theoretical Combus    | tion with Air             | Perform Action           | <mark>✓</mark> (% | 6 Theor. Air)             | Ratio)<br>fraction 💌 | Scaling Factor    |
| Fuel Block:           | Sel                       | ect Fuel(s)              |                   | • Oxidizer Block (try def | ault):               | Select Oxidizer 🗸 |
| ✓ H2                  | ✓ C(s)                    |                          |                   | Air                       |                      |                   |
| 0.14858334 kg         | ✓ 0.85141665              | kg 💉                     | kg                | v 14.86314 kg             | ×                    | kg 🗸              |
| kg                    |                           | kg V                     | kg                | ✓ kg                      | ×.                   | kg V              |
| Products Block (try d | efault selections first): |                          |                   | Select Products           |                      | ×                 |
| CO2                   |                           | H2O                      |                   | N2                        |                      |                   |
| 3.119711              | kg 💙 🚺                    | .3282428 kg              | ✓ 11.3            | 348728 kg                 | ~                    | kg 🗸              |
|                       | kg 💌                      | kg                       | ~                 | kg                        | ×                    | kg. 🗡             |

And, Theoretical (or stoichiometric) AF ratio, by mass = 14.86 .... Ans.

#### 6. Excess air: (Actual AF ratio) / (Theoeretical AF ratio) = 24.04/14.86 = 1.618 = 161.8%

#### Therefore, Excess air = 61.8% .... Ans.

#### Note: See the ease with which these calculations are made in TEST.

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**Prob. 8.4.7** The analysis of dry exhaust gas from an internal combustion engine gave 12% CO2, 2% CO, 4% CH4, 1% H2, 4.5% O2, 76.5% N2. Calculate the proportions by mass of carbon to hydrogen in the fuel, assuming it to be a pure hydrocarbon fuel, and the AF ratio used. [VTU]

#### **TEST Solution:**

Following are the steps:

 Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose Mole radio button. Select fuels: C and H2, and in the Products block, fill in the fractions as shown. Air is chosen as oxidizer, by default. Select 'Read As Is' from Action widget, and click on 'Perform Action' to register the entered values. Then, select 'Balance Reaction' from the Action widget, and click on 'Perform Action'. We get:

|                          | N                      | lon-Premixed C         | pen-Steady Co    | mbusti    | on TEST      | alc: n-IG M        | lodel      |   |               |
|--------------------------|------------------------|------------------------|------------------|-----------|--------------|--------------------|------------|---|---------------|
| thermofluids.net • T     | ESTcalcs (Java Ap      | plets) • Systems       | • Open • Steady  | State •   | Specific •   | Combustion/C       | hemEqulibr | ium • undefine                            | ed • n-IG Mod |
| Error: You must select a | I fuel before using ar | iy of the reaction com | mands.           |           |              |                    |            |   |               |
| G SI C English           | C Mass                 | • Mole 🖓               | Help Messages On |           | Super-Cal    | culate             | Load       | Sup                                       | er-Initialize |
| Reaction                 | n Panel                | Sta                    | ate Panel        |           | Devi         | ce Panel           |            | I/O Par                                   | rel           |
|                          |                        |                        |                  | A W The   | a Airo       | D (Em) Datia       |            |   | in Footon     |
| Balance Reaction (by     | atom balance)          | Perform Ad             | tion 1.0         | ∧ (% Theo | or. Alr)     | 1.0                | fraction   | <ul> <li>✓ Scal</li> <li>✓ 1.0</li> </ul> | No Unit       |
| Fuel Block:              |                        | Select Fuel(s)         |                  | ~         | Oxidizer Blo | ock (try default): |            | Select Oxidizer                           | ~             |
| C(s)                     | н                      | 2                      |                  |           |              | Air                |            |   |               |
| 18.0 kmol                | ₩ 14.670886            | kmol 💌                 | kmol             | $\sim$    | 96.83544     | kmol               | ~          | 1   | kmol 🗸        |
| kmol                     |                        | kmol 💌                 | kmol             | ~         |              | kmol               | ×          |   | amol 💌        |
| Products Block (try de   | fault selections firs  | t):                    |                  |           | Select Proc  | lucts              |            |   | ~             |
| ✓ CO2                    |                        | H2O                    |                  |           | ✓ N2         |                    |            | ✓ 02                                      |               |
| 12.0                     | kmol 💙                 | 5.670886               | kmol 💌           | 76.5      |              | kmol               | ✓ 4.5      | km  | ol 🗸          |
| ✓ CO                     |                        | ✓ Metha                | ine(CH4)         |           | ✓ H2         |                    |            |   |               |
| 2.0                      | kmol 💉                 | 4.0                    | kmol 💌           | 1.0       |              | kmol               | ~          | km  | ol 🗸          |

\_\_\_\_\_

#### 2. To convert it on mass basis, simply select the Mass radio button. Immediately, we get:

|                      |                   | (                  | Non-Premi  | xed Open-Ste  | eady Cor        | nbusti           | on TEST     | calc: n-IG  | Model            |             |                  |       |
|----------------------|-------------------|--------------------|--|---------------|-----------------|------------------|-------------|-------------|------------------|-------------|------------------|-------|
| thermoflu            | uids.net • TE     | STcalcs (Java A    | Applets) · Sy  | stems · Open  | Steady 9        | State ·          | Specific •  | Combustion  | n/ChemEqu        | librium • u | ndefined • n-IG  | Model |
| Error: You           | ı must select a f | uel before using   | any of the react   | ion commands. |                 |                  |             |             |                  |             |                  |       |
| • si                 | C English         | Mass               | C Mole   | 🔽 Help Mes    | sages On        |                  | Super-Ca    | Iculate     | Loa              | 1           | Super-Initialize | 1     |
|                      | Reaction          | Panel              |  | State Panel   |                 |                  | Devi        | ce Panel    |                  |             | I/O Panel        |       |
| Balance              | Reaction (by a    | tom balance)       | ✓ Performed and the second | rform Action  | <b>√</b><br>1.0 | λ (% Theo<br>fra | or. Air)    | C (Eqv. Rat | iio)<br>fraction | ✓ 1.0       | Scaling Factor   | ~     |
| Fuel Bloc            |                   |                    | Select Fuel(s)   |               |                 | ~                | Oxidizer Bl |             | uit):            | Select      | Oxidizer         | ~     |
|                      | C(s)              |                    | H2   |               |                 |                  |             | Air         |                  |             |                  |       |
| <mark>216.198</mark> | kg                | 29.5735            | 72 kg  | ×             | kg              | ×                | 2805.3228   | kg          | ~                |             | kg               | ×     |
|                      | kg                | M                  | kg   |               | kg              | ~                |             | kg          | ¥                |             | kg               | ×     |
| Products             | s Block (try defa | ault selections fi |  |               |                 |                  | Select Pro  | ducts       |                  |             |                  | ~     |
|                      | ✓ CO2             |                    |  | H2O           |                 |                  | ✓ N2        |             |                  | ✓ 02        |                  |       |
| 528.12               | kg                | 1                  | 102.18937  | kg            | ~               | 2142.0           |             | kg          | ✓ 144.           | 0           | kg               | ~     |
|                      | ✓ со              |                    | -  | Methane(CH4)  |                 |                  | ✓ H2        |             |                  |             |                  |       |
| 56.02                | kg                |                    | 64.16  | kg            | ×               | 2.0158           |             | kg          | ~                |             | kg               | ×.    |

3. Now, to get it for unit mass of fuel, select 'Normalize Reaction' from ction widget, and click on 'Perform Action'. We get:

| Error: You must select a fuel before using any | of the reaction commands. |                                 |                          |
|--|---------------------------|---------------------------------|--------------------------|
| ଙ୍ଗ SI ି English ଙ୍କ Mass ି                    | Mole 🔽 Help Messages On   | Super-Calculate                 | Load Super-Initialize    |
| Reaction Panel                                 | State Panel               | Device Panel                    | I/O Panel                |
| Normalize Reaction (by mass or mole of fue     | el) V Perform Action 1.0  | A (% Theor. Air)<br>Fraction    | scaling Factor           |
| Fuel Block: Se                                 | elect Fuel(s)             | • Oxidizer Block (try default): | Select Oxidizer 👻        |
| C(s) H2  |                           | Air                             |                          |
| 0.8796705 kg 🕑 0.12032951                      | kg 💉                      | V 11.4143505 kg                 | 🖌 kg 👻                   |
| kg V   | kg V                      | kg                              | v kg v                   |
| Products Block (try default selections first): |                           | Select Products                 | <b>v</b>                 |
| ✓ C02  | H2O                       | ✓ N2                            | <ul> <li>✓ 02</li> </ul> |
| 2.1488247 kg 😪 C                               | 0.41579002 kg 💙           | 8.71541 kg 🗸                    | 0.5859099 kg 😪           |
| ✓ CO   | Methane(CH4)              | ✓ H2                            |                          |
| 0.22793522 kg 💉 0                              | 0.2610554 kg 💉            | 0.008201925 kg 💙                | kg 🗸 🗸                   |

4. Thus, we see that:

\_\_\_\_\_

Fuel contains: 87.97% of Carbon by mass, and 12.03% by mass of H2 .... Ans.

AF ratio used = 11.414, by mass.... Ans.

**Prob. 8.4.8** Liquid Octane ( $C_8H_{18}$ ) at 25 C is burnt with 400 % theoretical air at 101 kPa, 25 C in a steady flow process. Determine the adiabatic flame temp.

(b) Plot adiabatic flame temp vs percent excess air.

#### **TEST Solution:**

Following are the steps:

Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose Mole radio button. Select Octane (L) for fuel, and select λ as 4 (fraction) i.e. 400%. Air is chosen as oxidizer, by default. Select 'Excess/Deficient Air' from Action widget, and click on 'Perform Action'. We get:

Non-Premixed Open-Steady Combustion TESTcalc: n-IG Model

| thermofluids.net + TESTcalcs (Java A      | Applets) · Systems · Open | • Steady State •        | Specific · Combustion                 | n/ChemEqulibrium | • • undefined • n-IG Mo | odel |
|---|---------------------------|-------------------------|---------------------------------------|------------------|-------------------------|------|
| Error: This species has been already chos | sen.                      |                         |                                       |                  |                         |      |
|   | ତ Mole 🔽 Help Mes         | ssages On               | Super-Calculate                       | Load             | Super-Initialize        |      |
| Reaction Panel                            | State Panel               |                         | Device Panel                          |                  | I/O Panel               |      |
| Excess/Deficient Air (set by lambda)      | Perform Action            | <mark>√</mark> ∧ (% The | eor. Air) 🛛 (Eqv. Ra<br>action 💙 0.25 | tio)<br>fraction | Scaling Factor          |      |
| Fuel Block:                               | Select Fuel(s)            | <b>~</b>                | Oxidizer Block (try defau             | lit):            | Select Oxidizer         | ~    |
| ✓ Octane(L)                               |                           |                         | Air                                   |                  |                         |      |
| 1.0 kmol 💌                                | kmol 🔍                    | kmol 🔍                  | 238.09525 kmol                        | ×                | kmol                    | ~    |
| kmol                                      | kmol 🗸                    | kmol 🗸                  | kmol                                  | ×                | kmol                    | ~    |
| Products Block (try default selections fi |                           |                         | Select Products                       |                  |                         | ~    |
| CO2                                       | H2O                       |                         | N2                                    |                  | 02                      |      |
| 8.0 kmol                                  | 9.0 kmol                  | ✓ 188.095               | 25 kmol                               | 37.500004        | kmol                    | ~    |
|   |                           |                         |                                       |                  |                         |      |

 Now, go to States panel. For State 1, Fuel is chosen by default. Fill in P and T as 101 kPa and 25 C respectively. Click on Calculate. Immediately, State 1 is calculated:







3. State 2: this is for Oxidizer. Again, fill in P and T as shown, and press Enter or click on Calculate. Now, State 2 is calculated:



4. State 3 is for Products. Here temp is the unknown. Fill in the known value of P as shown, press Enter. We get:



Of course, State 3 is not completely calculated since data is not enough. We will revisit this State after completing the Device panel.

5. Now, go to Device panel. Fill in State 1 and State 2 for i10-state and i2-state, and State 3 for e-state. Also, enter Wdot\_ext = 0 and Qdot = 0. Click on 'Calculate':







6. Now, go back to State 3. Observe that j3 is posted (with a grey background) there:

| Vel = 0.0 m/s [V   | 'elocity]   |  |          |              |              |      |            |              |       |            |         |      |          |         |             |   |
|--|---|--|----------|--------------|--------------|------|------------|--------------|-------|------------|---------|------|----------|---------|-------------|---|
| I SI C Er  | nglish  | C Mas  | s 🖲 N    | loie 🔽       | Help I       | Aess | ages On    |              | Super | -Calculate |         | Load |          | Super   | -Initialize |   |
| F  | Reaction Panel  |  |          | Sta          | State Panel  |      |            | Device Panel |       |            |         |      | 1        | /O Pane | 1           |   |
| < 0  | State-3 🗸 >   | <se< td=""><td></td><td>ther&gt; Produc</td><td colspan="3">&gt; Products 🗸</td><td>Calculate</td><td></td><td></td><td>No-Plot</td><td>s 💌</td><td></td><td>Init</td><td>ialize</td><td></td></se<> |          | ther> Produc | > Products 🗸 |      |            | Calculate    |       |            | No-Plot | s 💌  |          | Init    | ialize      |   |
| 🖌 рЗ   |   |  | T3       |              |              |      | <i>v</i> 3 |              |       | u3         |         |      | h3       |         |             |   |
| 101.0  | kPa   | ×  |          | deg-C        | ~            |      |            | m^3/kg       | *     | ]          | kJ/k    | g 🎽  |          |         | kJ/kg       | ~ |
| s3   |   |  | g3       |              |              | ✓    | Vel3       |              |       | ✓ z3       |         |      | e3       |         | (           |   |
|  | kJ/kg.K   | ×  |          | kJ/kg        | ×            | 0.0  |            | m/s          | *     | 0.0        | m       | ~    |          |         | kJ/kg       | ~ |
| 🗾 j3   |   |  | mdot3    |              |              |      | Voldot3    |              |       | A3         |         |      | MM3      |         |             |   |
| -35.786556   | kJ/kg   | ✓ 6  | 980.9272 | kg/s         | ~            |      |            | m^3/s        | *     |            | m^2     | 2    | 28.77603 | )       | kg/kmol     | ~ |
| c_p3   |   |  | Mode/3   |              |              |      |            |              |       |            |         |      |          |         |             |   |
|  | kJ/kg.K   | × 3  | .0       | UnitLess     | ~            |      |            |              |       |            |         |      |          |         |             |   |
| A Note<br>Set up the reacting<br>The mass and co<br>change the mass<br>scaling factor. | kJ/kg.K       3.0       UnitLess         A Note on State Evaluation       CO2: 352.0800000000003 kg;         Set up the reaction in the reaction panel before evaluating states of the reactants and products in this panel.       CO2: 352.080000000000 kg;         The mass and compositions of fuel, oxidizer and products are deduced from the reaction. If you need to change the mass flow rate, go back to the reaction panel and multiply (from the action menu) the reaction by a suitable scaling factor.       CO2: 1200.000799999988 kg;         In evaluating a state, select the state number first and then the type of the mixture - Fuel Oxidizer, or Products       Mass Fractions, x |  |          |              |              |      |            |              |       |            |         |      |          |         |             |   |

7. Now, click on 'Calculate', and, immediately calculations of State 3 are completed as shown below:

| Move mouse over a variable  | to display its value with m  | ore precision. |            |                    |              |       |              |              |  |  |
|---|--|----------------|------------|--------------------|--------------|-------|--------------|--------------|--|--|
| • SI C English  | C Mass 🔆 Mole  | 🔽 Help Me      | essages On | Supe               | r-Calculate  | Load  | Super        | r-Initialize |  |  |
| Reaction Pa   | inel   | State Panel    |            |                    | Device Panel |       | I/O Pane     | el           |  |  |
| < <mark>©State-3</mark> ¥   | <select th="" together<=""><th>Products 🗸</th><th></th><th colspan="3">Calculate No-Plots</th><th colspan="3">✓ Initialize</th></select>   | Products 🗸     |            | Calculate No-Plots |              |       | ✓ Initialize |              |  |  |
| 🖌 рЗ  | T3   |                | v3         |                    | u3           |       | h3           |              |  |  |
| 101.0 kPa   | ♥ 959.5006   | К 💙 2.         | 74475      | m^3/kg 💙           | -313.00653   | kJ/kg | ✓ -35.78656  | kJ/kg 🛩      |  |  |
| s3  | g3   |                | Vel3       |                    | 🖌 z3         |       | e3           |              |  |  |
| 8.22897 kJ/kg.K   | ✓ -7931.4893   | kJ/kg 💉 0.     | 0          | m/s 💙              | 0.0          | m     | ✓ -313.00653 | kJ/kg 💌      |  |  |
| ✓ j3  | mdot3  |                | Voldot3    |                    | A3           |       | ММЗ          |              |  |  |
| -35.786556 kJ/kg  | ✓ 6980.9272  | kg/s 💉 🚺       | 9160.914   | m^3/s 💙            | 1.91609126E  | 9 m^2 | ✓ 28.77603   | kg/kmol 💉    |  |  |
| c_p3  | Mode/3   |                |            |                    |              |       |              |              |  |  |
| 1.16986 kJ/kg.K   | 3.0  | UnitLess 💉     |            |                    |              |       |              |              |  |  |
| A Note on State Ev.<br>Set up the reaction in the rea<br>The mass and compositions (<br>change the mass flow rate, g<br>scaling factor. | 1.16996       kJ/kg.K       3.0       UnitLess         Set up the reaction in the reaction panel before evaluating states of the reactants and products in this panel.       CO2: 352.0800000000003 kg;<br>H20: 162.180000000001 kg;<br>U20: 162.180000000001 kg;<br>U20: 162.180000000001 kg;<br>U20: 100.00007999999898 kg;<br>CO2: 352.66693000001 kg;<br>U20: 100.0000799999998 kg;<br>CO2: 352.66693000001 kg;<br>U20: 100.000799999998 kg;<br>CO2: 352.666930000000000000000000000000000000000 |                |            |                    |              |       |              |              |  |  |

We observe from the above that T3 = 959.5 K = Adiabatic Flame temp .... Ans.

8. Now that the State 3 is completely known, go back to Device panel, and click on Calculate. Immediately, **Second Law analysis** is completed, and we get:



We observe that: **entropy generated in the reaction = Sdot\_net = 9606.593 kW/K**, and the **Irreversibility** (or, exergy loss) can be calculated as  $T_0 * Sdot_gen$ , kW where  $T_0$  is the surroundings temp in K.

- 9. To plot Adiabatic Flame temp vs Excess air is now very easy:
  - i. Go to Reaction panel, change  $\lambda$  to 3.5 (i.e. 350% theor. Air or 250% excess air), Select 'Excess/Deficient Air' from Action widget, and click on 'Perform Action'. And, click on SuperCalculate. Immediately, all calculations are updated. Go to State 3, and read T3, the adiabatic Flame temp.
  - ii. Repeat this procedure for desired values of  $\lambda$ , and tabulate the results as shown below:

#### Adiabatic flame temp vs excess air:

| % Theoretical air, | % Excess air     | Adiab. Flame temp (K) |
|--------------------|------------------|-----------------------|
| ۸.                 |                  |                       |
| 400                | <u>300</u>       | <u>959.5</u>          |
| 350                | <mark>250</mark> | <mark>1043.63</mark>  |
| 300                | <mark>200</mark> | <mark>1152.54</mark>  |
| 250                | <mark>150</mark> | 1299.25               |
| 200                | <mark>100</mark> | 1507.97               |
| 150                | <mark>50</mark>  | <mark>1829.43</mark>  |
| 100                | Stoichio.        | <b>2396.17</b>        |

#### Now, plot the results in EXCEL:



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262

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#### 10. To see the TEST code etc. go to I/O panel:

#~~~~OUTPUT OF SUPER-CALCULATE :

#### # TESTcalc Path: ..Open>Steady>Specific>UnMixedCombustion>IG-Mixture; v-10.ce02

#-----Start of TEST-Codes -----

States {

State-1: Fuel;

Given: { p1= 101.0 kPa; T1= 25.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 114.231 kg/s; Model1= 1.0 UnitLess; }

State-2: Oxidizer;

```
Given: { p2= 101.0 kPa; T2= 25.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= 6897.6196 kg/s; Model2= 2.0 UnitLess; }
```

State-3: Products;

Given: { p3= 101.0 kPa; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= 6980.9272 kg/s; Model3= 3.0 UnitLess; }

}

Analysis {

Device-A: i-State = State-1, State-2; e-State = State-3; Mixing: true;

Given: { Qdot= 0.0 kW; Wdot\_ext= 0.0 kW; T\_B= 298.15 K; }

}

#-----End of TEST-Code: Reaction Block Starts -----

# Reaction (Note: To reproduce the TEST solution from the TEST-codes, **this reaction has to be manually set up** after the loading the TEST-codes.):

# (1.0 kmol) Octane(L) + (238.09525 kmol) Air = (8.0 kmol) CO2 + (9.0 kmol) H2O + (188.09525 kmol) N2 + (37.500004 kmol) O2

#-----End of Reaction Block -----

#### #\*\*\*\*\*DETAILED OUTPUT:

#### **#** Evaluated States:

| #       | State-1: Fuel > IG-Mixture;  |
|---------|--|
| #       | Given: p1= 101.0 kPa; T1= 25.0 deg-C; Vel1= 0.0 m/s;                       |
| #       | z1= 0.0 m; mdot1= 114.231 kg/s; Model1= 1.0 UnitLess;                      |
| #       | Calculated: v1= 0.00142 m^3/kg; u1= -2188.2542 kJ/kg; h1= -2188.11 kJ/kg;  |
| #       | s1= 3.15754 kJ/kg.K; g1= -3129.532 kJ/kg; e1= -2188.2542 kJ/kg;            |
| #       | j1= -2188.11 kJ/kg; Voldot1= 0.0 m^3/s; A1= 0.0 m^2;                       |
| #       | MM1= 114.231 kg/kmol; c_p1= 1.71127 kJ/kg.K;                               |
| #       | State-2: Oxidizer > IG-Mixture;  |
| #       | Given: p2= 101.0 kPa; T2= 25.0 deg-C; Vel2= 0.0 m/s;                       |
| #       | z2= 0.0 m; mdot2= 6897.6196 kg/s; Model2= 2.0 UnitLess;                    |
| #       | Calculated: v2= 0.84718 m^3/kg; u2= -85.54667 kJ/kg; h2= 0.01836 kJ/kg;    |
| #       | s2= 6.88333 kJ/kg.K; g2= -2052.2454 kJ/kg; e2= -85.54667 kJ/kg;            |
| #       | j2= 0.01836 kJ/kg; Voldot2= 5843.5156 m^3/s; A2= 5.8435155E8 m^2;          |
| #       | MM2= 28.97 kg/kmol; c_p2= 1.00416 kJ/kg.K;                                 |
| #       | State-3: Products > IG-Mixture;  |
| #       | Given: p3= 101.0 kPa; Vel3= 0.0 m/s; z3= 0.0 m;                            |
| #       | mdot3= 6980.9272 kg/s; Model3= 3.0 UnitLess;                               |
| #       | Calculated: T3= 959.5006 K; v3= 2.74475 m^3/kg; u3= -313.00653 kJ/kg;      |
| #       | h3= -35.78656 kJ/kg; s3= 8.22897 kJ/kg.K; g3= -7931.4893 kJ/kg;            |
| #       | e3= -313.00653 kJ/kg; j3= -35.78656 kJ/kg; Voldot3= 19160.914 m^3/s;       |
| #       | A3= 1.91609126E9 m^2; MM3= 28.77603 kg/kmol; c_p3= 1.16986 kJ/kg.K;        |
| # Mass  | , Energy, and Entropy Analysis Results:                                    |
| #       | Device-A: i-State = State-1, State-2; e-State = State-3; Mixing: true;     |
| #       | Given: Qdot= 0.0 kW; Wdot_ext= 0.0 kW; T_B= 298.15 K;                      |
| #       | Calculated: Sdot_gen= 9606.593 kW/K; Jdot_net= -0.0076252595 kW; Sdot_net= |
| -9606.5 | 93 kW/K;   |
|         |  |

\_\_\_\_\_

**Reactive Systems** 

**Prob. 8.4.9** Liquid propane (C3H8) enters a steady flow combustion chamber at 25 C and 1 atm at a rate of 0.4 kg/min where it is mixed and burned with 150% excess air that enters the combustion chamber at 12 C. If the combustion products leave at 1200 K and 1 atm, determine: (i) mass flow rate of air, (ii) rate of heat transfer from the combustion chamber, and (iii) the rate of entropy generation during this process. Assume T0 = 25 C.

(b) Plot the rate of exergy destruction for the surrounding temp varying from 0 to 38 C. [Ref: 1]



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#### **TEST Solution:**

Following are the steps:

Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose Mole radio button. Select Propane (L) for fuel, and select λ as 250% i.e. 150% excess air. Air is chosen as oxidizer, by default. Select 'Excess/Deficient Air' from Action widget, and click on 'Perform Action'. We get:

|               |                   | Ν                  | Ion-Premi:     | ked Open-St  | teady Cor  | nbusti                  | on TESTc     | alc: n-IG      | Model      |            |                  |        |
|---------------|-------------------|--------------------|----------------|--------------|------------|-------------------------|--------------|----------------|------------|------------|------------------|--------|
| hermofluid:   | ls.net • TES      | Tcalcs (Java Ap    | plets) · Sy    | stems · Open | • Steady S | tate •                  | Specific •   | Combustion     | /ChemEquli | brium • un | defined • n-I    | G Mode |
| Error: This s | pecies has bee    | n already chose    |                |              |            |                         |              |                |            |            |                  |        |
| ⊙ si (        | C English         | C Mass             | Mole           | 🔽 Help Me    | ssages On  |                         | Super-Cale   | culate         | Load       |            | Super-Initialize |        |
|               | Reaction Pa       | anel               |                | State Panel  |            |                         | Devic        | e Panel        |            | ĺ.         | /O Panel         |        |
|               |                   |                    |                |              |            |                         |              |                |            |            |                  |        |
| Excess/De     | aficient Air (set | by lambda)         | Dor            | form Action  | -          | ۸ <mark>(% The</mark> o | or. Air)     | 🗆 (Eqv. Rat    | io)        |            | Scaling Factor   |        |
| Excessibe     | encient All (Set  | by lambda)         |                | IOTHI ACUOIT | 250.0      | %                       | ×            | 0.4            | fraction   | ✓ 1.0      | No Unit          | ~      |
| Fuel Block:   | t.                |                    | Select Fuel(s) |              |            | ~                       | Oxidizer Blo | ck (try defaul | i):        | Select O   | kidizer          | *      |
| 🖌 Pi          | ropane(L)         |                    |                |              |            |                         | × .          | Air            |            |            |                  |        |
| 1.0           | kmol              | ~                  | kmol           | × .          | kmol       | $\sim$                  | 59.52381     | kmol           | ~          |            | kmol             | $\sim$ |
|               |                   |                    |                |              |            |                         |              |                |            |            |                  |        |
|               | kmol              |                    | kmol           | × .          | kmol       | 1                       |              | kmol           | ×          |            | kmol             | 1      |
| Products B    | lock (try defau   | It selections firs | it):           |              |            |                         | Select Prod  | ucts           |            |            |                  | ~      |
|               |                   |                    |                |              |            |                         |              |                |            |            |                  |        |
|               | CO2               |                    |                | H2O          |            |                         | N2           |                |            | 02         | <i>6</i> .       |        |

#### Therefore: Flow rate of air for a flow rate of 0.4 kg/min of fuel:

 $\frac{59.5238 \cdot 29}{44.1} \cdot 0.4 = 15.657$  kg/min air for 0.4 kg/min of fuel ...Ans.

2. Go to State 1, i.e. Fuel: enter p1 = 1 atm, T1 = 25 C, hit Enter. We get:

| Move mouse over a variable to display its   | s value with more precision.    |                  |                        |            |            |            |              |  |  |  |
|---|---------------------------------|------------------|------------------------|------------|------------|------------|--------------|--|--|--|
|   | s 🕫 Mole 🔽 H                    | lelp Messages On | Super                  | -Calculate | Load       | Supe       | r-Initialize |  |  |  |
| Reaction Panel  | State                           | Panel            | Device Panel I/O Panel |            |            |            |              |  |  |  |
| < <mark>©State-1 v</mark> > <sele< td=""><td>ect Together&gt; <mark>Fuel</mark></td><td>~</td><td>Calculate</td><td></td><td>No-Plots 🔽</td><td>Init</td><td>tialize</td></sele<>   | ect Together> <mark>Fuel</mark> | ~                | Calculate              |            | No-Plots 🔽 | Init       | tialize      |  |  |  |
| 🖌 p1 🗹  | T1                              | v1               |                        | u1         |            | h1         |              |  |  |  |
| 1.0 atm 💉 25  | 5.0 deg-C                       | ♥ 0.002          | m^3/kg 💌               | -2782.9692 | kJ/kg 🗸 🗸  | -2782.7666 | kJ/kg 💉      |  |  |  |
| s1  | g1                              | ✓ Vel1           |                        | ¥ z1       |            | e1         |              |  |  |  |
| 4.29291 kJ/kg.K ❤ -40   | 062.6968 kJ/kg                  | ▶ 0.0            | m/s 💙                  | 0.0        | m 🗸        | -2782.969  | kJ/kg 💊      |  |  |  |
| jt  | mdot1                           | Voldot1          |                        | A1         |            | MM1        |              |  |  |  |
| -2782.7666 kJ/kg 🗡 44   | kg/s                            | ♥ 0.0            | m^3/s 💌                | 0.0        | m^2 🗸      | 44.1       | kg/kmol 💉    |  |  |  |
| c_p1  | Model1                          |                  |                        |            |            |            |              |  |  |  |
| 2.77007 kJ/kg.K 🛛 1.0   | 0 UnitLess                      | ~                |                        |            |            |            |              |  |  |  |
| 2.77007       kUkg K       1.0       UnitLess         A Note on State Evaluation       Fropane(L): 44.1 kg:         Set up the reaction in the reaction panel before evaluating states of the reactants and products in this panel.       Propane(L): 44.1 kg:         The mass and compositions of fuel, oxidizer and products are deduced from the reaction. If you need to change the mass flow rate, go back to the reaction panel and multiply (from the action menu) the reaction by a suitable scaling factor.       Propane(L): 42.1 kg:         In evaluating a state select the state number first and then the two of the mixture - Firel Oxidizer or Products       Propane(L): y = 1.0 |                                 |                  |                        |            |            |            |              |  |  |  |

Note that mdot1 = 44.1 kg/s is automatically selected, since 1 kmol of fuel was entered in the Reaction panel.

3. State 2: Enter p2, T2 for oxidizer. Hit Enter. We get:

| Move mouse over a variable to disp | play its value with more prec        | ision.             |                          |                      |
|------------------------------------|--------------------------------------|--------------------|--------------------------|----------------------|
| • SI C English C I                 | Mass 🔍 Mole                          | 🔽 Help Messages On | Super-Calculate          | oad Super-Initialize |
| Reaction Panel                     |                                      | State Panel        | Device Panel             | I/O Panel            |
| < <mark>©State-2 v</mark> > <      | Select Together> <mark>Oxi</mark>    | dizer 🗸            | Calculate No-Plots       | Initialize           |
| 🖌 p2                               | 🖌 T2                                 | v2                 | u2                       | h2                   |
| 1.0 atm                            | 12.0 deg-1                           | 0.80764            | m^3/kg -94.86336 kJ/kg   | ✓ -13.02914 kJ/kg ✓  |
| s2                                 | g2                                   | ✓ Vel2             | ✓ z2                     | e2                   |
| 6.83816 kJ/kg.K 🔊                  | <ul> <li>-1962.9299 kJ/kg</li> </ul> | ✓ 0.0              | m/s 💉 0.0 m              | ✓ -94.86336 kJ/kg ✓  |
| j2                                 | mdot2                                | Voldot2            | A2                       | MM2                  |
| -13.02914 kJ/kg 💙                  | 1724.4048 kg/s                       | ✓ 1392.6998        | m^3/s ↔ 1.39269984E8 m^2 | ✓ 28.97 kg/kmol ✓    |
| c_p2                               | Mode/2                               |                    |                          |                      |
| 1.00348 kJ/kg.K 🚿                  | 2.0 UnitLet                          | s 🗸                |                          |                      |

4. State 3, for Products. Again, enter p3, T3 and hit Enter. We get:

| Nove mouse over a variable to display its value with more precision. |  |  |  |  |  |  |  |  |  |  |
|--|--|--|--|--|--|--|--|--|--|--|
| Load Super-Initialize  |  |  |  |  |  |  |  |  |  |  |
| I/O Panel  |  |  |  |  |  |  |  |  |  |  |
| v Initialize   |  |  |  |  |  |  |  |  |  |  |
| h3   |  |  |  |  |  |  |  |  |  |  |
| ✓ -187.51718 kJ/kg ✓   |  |  |  |  |  |  |  |  |  |  |
| e3   |  |  |  |  |  |  |  |  |  |  |
| ✓ -536.1194 kJ/kg ✓  |  |  |  |  |  |  |  |  |  |  |
| ММЗ  |  |  |  |  |  |  |  |  |  |  |
| ✓ 28.61943 kg/kmol ✓   |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |

5. Now, go to Device panel. Enter State 1, State 2 and State 3 for i1-state, i2-state and e-state. Also enter Wdot\_ext = 0. Hit Enter. Click on SuperCalculate. We get:



#### Therefore, Heat Transfer, Q = -184983.36 KJ/s for 1 kmol/s of fuel

#### And, Heat Transfer for 0.4 kg/min of fuel:

 $\frac{-184988.36}{44.1} = -4.195 \times 10^{3}$  kJ..per kg of propane -4195·0.4 = -1.678 × 10<sup>3</sup> kJ for 0.4 kg/min of propane .... Ans..

Entropy generation: Sdot\_gen = 3734.5896 kJ for 44.1 kg of fuel

Then, entropy gen. for 0.4 kg/min of fuel:

 $\frac{3734.59}{44.1} \cdot 0.4 = 33.874$  kJ/min.K for 0.4 kg/min of propane.... Ans.

And, Irreversibility (or, loss of exergy) =  $T_0 * S_{gen}$ :

298.15-33.874 = 1.01 × 10<sup>4</sup> kJ/min.... Ans.

6. I/O panel gives the TEST code etc:

#~~~~~OUTPUT OF SUPER-CALCULATE

# TESTcalc Path: ..Open>Steady>Specific>UnMixedCombustion>IG-Mixture; v-10.ce02

#-----Start of TEST-Codes -----

States {

State-1: Fuel;

Given: { p1= 1.0 atm; T1= 25.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 44.1 kg/s; Model1= 1.0 UnitLess; }

**Reactive Systems** 

#### State-2: Oxidizer;

Given: { p2= 1.0 atm; T2= 12.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= 1724.4048 kg/s; Model2= 2.0 UnitLess; }

State-3: Products;

Given: { p3= 1.0 atm; T3= 1200.0 K; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= 1760.7767 kg/s; Model3= 3.0 UnitLess; }

}

Analysis {

Device-A: i-State = State-1, State-2; e-State = State-3; Mixing: true;

Given: { Wdot\_ext= 0.0 kW; T\_B= 298.15 K; }

}

#-----End of TEST-Code: Reaction Block Starts -----



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# Reaction (Note: To reproduce the TEST solution from the TEST-codes, this reaction has to be manually set up after the loading the TEST-codes.):

# (1.0 kmol) Propane(L) + (59.52381 kmol) Air = (3.0 kmol) CO2 + (4.0 kmol) H2O + (47.02381 kmol) N2 + (7.5 kmol) O2

#-----End of Reaction Block -----

#### #\*\*\*\*\*DETAILED OUTPUT: #

#### # Evaluated States:

| #      | State-1: Fuel > IG-Mixture;  |
|--------|--|
| #      | Given: p1= 1.0 atm; T1= 25.0 deg-C; Vel1= 0.0 m/s;   |
| #      | z1= 0.0 m; mdot1= 44.1 kg/s; Model1= 1.0 UnitLess;   |
| #      | Calculated: v1= 0.002 m^3/kg; u1= -2782.9692 kJ/kg; h1= -2782.7666 kJ/kg;                                  |
| #      | s1= 4.29291 kJ/kg.K; g1= -4062.6968 kJ/kg; e1= -2782.969 kJ/kg;  |
| #      | $j1 = -2782.7666 \text{ kJ/kg}; \text{ Voldot}1 = 0.0 \text{ m}^3/\text{s}; \text{ A}1 = 0.0 \text{ m}^2;$ |
| #      | MM1= 44.1 kg/kmol; c_p1= 2.77007 kJ/kg.K;  |
| #      | State-2: Oxidizer > IG-Mixture;  |
| #      | Given: p2= 1.0 atm; T2= 12.0 deg-C; Vel2= 0.0 m/s;   |
| #      | z2= 0.0 m; mdot2= 1724.4048 kg/s; Model2= 2.0 UnitLess;  |
| #      | Calculated: v2= 0.80764 m^3/kg; u2= -94.86336 kJ/kg; h2= -13.02914 kJ/kg;                                  |
| #      | s2= 6.83816 kJ/kg.K; g2= -1962.9299 kJ/kg; e2= -94.86336 kJ/kg;  |
| #      | j2= -13.02914 kJ/kg; Voldot2= 1392.6998 m^3/s; A2= 1.39269984E8 m^2;                                       |
| #      | MM2= 28.97 kg/kmol; c_p2= 1.00348 kJ/kg.K;   |
| #      | State-3: Products > IG-Mixture;  |
| #      | Given: p3= 1.0 atm; T3= 1200.0 K; Vel3= 0.0 m/s;   |
| #      | z3= 0.0 m; mdot3= 1760.7767 kg/s; Model3= 3.0 UnitLess;  |
| #      | Calculated: v3= 3.44044 m^3/kg; u3= -536.1194 kJ/kg; h3= -187.51718 kJ/kg;                                 |
| #      | s3= 8.57304 kJ/kg.K; g3= -10475.163 kJ/kg; e3= -536.1194 kJ/kg;  |
| #      | j3= -187.51718 kJ/kg; Voldot3= 6057.8413 m^3/s; A3= 6.0578413E8 m^2;                                       |
| #      | MM3= 28.61943 kg/kmol; c_p3= 1.23771 kJ/kg.K;  |
| # Mass | , Energy, and Entropy Analysis Results:  |
| #      | Device-A: i-State = State-1, State-2; e-State = State-3; Mixing: true;                                     |
| #      | Given: Wdot_ext= 0.0 kW; T_B= 298.15 K;  |
| #      | Calculated: Qdot= -184988.36 kW; Sdot_gen= 3734.5896 kW/K; Jdot_net= 184988.36                             |
| kW; Sd | lot_net= -3114.1357 kW/K;  |
|        |  |

#### (b) Plot the rate of exergy destruction for the surrounding temp varying from 0 to 38 C:

#### Procedure is quite simple:

In the Analysis panel, change the T\_B to desired value, hit Enter, and click on SuperCalculate.

Tabulate Sdot\_gen against T\_B. Complete the Table as shown below, remembering that Exergy destroyed = Irreversibility = T\_B \* Sdot\_gen.

| Т_В (К) | Sdot_gen (kW/K) | Sdot_gen. for 0.4 kg/min of<br>fuel = Col. 2 * 0.4 / 44.1<br>(kJ/min.K) | Exergy destroyed =<br>T0 * Sdot_gen =<br>Col. 1 * Col. 3 (kJ/min) |
|---------|-----------------|---|---|
| 273.15  | 3791.38         | 34.389  | 9393.337  |
| 278.15  | 3779.2          | 34.278  | 9534.553  |
| 283.15  | 3767.46         | 34.172  | 9675.794  |
| 288.15  | 3756.12         | 34.069  | 9817.016  |
| 293.15  | 3745.17         | 33.970  | 9958.246  |
| 298.15  | 3734.59         | 33.874  | 10099.483   |
| 303.15  | 3714.45         | 33.691  | 10213.474   |
| 311.15  | 3708.67         | 33.639  | 10466.691   |



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#### Now, plot the Results:



**Prob. 8.4.10** A gasoline engine consumes 0.011 kg/s of Liquid Octane (C8H18) at 1 atm, 25 C, and delivers 150 kW. It uses 150% theoretical air, entering at 1 atm, 45 C. Products of combustion leave the engine at 750 K. Find out the heat transfer.

#### **TEST Solution:**

#### Following are the steps:

Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose Mass radio button. Select Octane(L) for fuel, and select λ as 150%. Air is chosen as oxidizer, by default. Select 'Excess/ Deficient Air' from Action widget, and click on 'Perform Action'. We get:

| ror: This species  | has been already chos | en.   |                   |       |   |   |                                 |            |                    |                          |  |
|--|-----------------------|---|-------------------|-------|---|---|---------------------------------|------------|--------------------|--------------------------|--|
| 🔍 SI O En  | glish 🖲 Mass 🔿 Mo     | le  | Free Help Message | es On | Su  | per-Calculate                               | I                               | Load       |                    | Super-Initialize         |  |
| Rea  | ction Panel           |   | State Panel       |       |   | Device P                                    | anel                            | 1          | 1                  | /O Panel                 |  |
| xcess/Deficient  | Air (set by lambda)   | Y Per                                       | form Action       | 150.0 | %   | <b>v</b>                                    | .6666667                        | fraction   | · 1.0              | No Unit                  |  |
| xcess/Deficient  | Air (set by lambda)   | Select Euel(s)                              | form Action       | 150.0 | %<br>%  | xidizer Block (                             | .6666667<br>trv default):       | fraction   | Select O           | No Unit                  |  |
| el Block:  | Air (set by lambda)   | Select Fuel(s)                              | form Action       | 150.0 | × 0   | xidizer Block                               | .6666667<br>try default):       | fraction   | Select O           | No Unit                  |  |
| el Block:  | Air (set by lambda)   | Select Fuel(s)                              | form Action       | 150.0 | <ul><li>%</li><li></li></ul> <li>%</li> <li>2:</li>   | xidizer Block<br>Air<br>2.643654            | .6666667<br>try default):<br>kg | fraction N | Select O           | No Unit<br>xidizer       |  |
| el Block:  | Air (set by lambda)   | Select Fuel(s)                              | form Action       | kg    | ♥ </td <td>xidizer Block<br/>Air<br/>2.643654</td> <td>.6666667<br/>try defauit):<br/>kg</td> <td>fraction 1</td> <td>Select O</td> <td>No Unit<br/>xidizer<br/>kg</td> <td></td> | xidizer Block<br>Air<br>2.643654            | .6666667<br>try defauit):<br>kg | fraction 1 | Select O           | No Unit<br>xidizer<br>kg |  |
| el Block:<br>Cotane(L<br>Cotane(L<br>Reconstruction)<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction<br>Reconstruction | Air (set by lambda)   | V Per<br>Select Fuel(s)<br>kg<br>kg<br>st): | torm Action       | kg    | %           %           √           2:           ×  | xidizer Block<br>2.643654<br>Select Product | 6666667<br>try default):<br>kg  | fraction   | v 1.0<br>Select 0. | No Unit<br>xidizer<br>kg |  |

2. To convert on basis of 0.011 kg/s of fuel: Select the scaling factor as 0.011 and from the Action widget, select 'Multiply by the Scaling factor' and click on 'Perform Action'. We get:

| Error: This species has been | already chosen.    |             |                  |            |                 |                     |               |                      |        |  |
|------------------------------|--------------------|-------------|------------------|------------|-----------------|---------------------|---------------|----------------------|--------|--|
| • SI • English •             | Mass 🤆 Mole        |             | Help Messages Or | 1          | Super-Calculate |                     |               | Super-Initialize     |        |  |
| Reaction Pan                 | iel                |             | State Panel      |            | Device          | Panel               |               | I/O Panel            |        |  |
| Multiply by the Scaling Fact | tor                | Perform     | Action           | ✓ A (% The | eor. Air)       | (Eqv. Ratio)<br>1.0 | )<br>fraction | ✓ Scaling<br>0.011 N | Factor |  |
| Fuel Block:                  | Sel                | ect Fuel(s) |                  | ~          | Oxidizer Bloc   | k (try default):    |               | Select Oxidizer      | ~      |  |
| ✓ Octane(L)                  |                    |             |                  |            | 🖌 🖌             | ir                  |               |                      |        |  |
| 0.011 kg                     | ~                  | kg N        | 2                | kg 🗸       | 0.2490802       | kg                  | ~             | kg                   | ×      |  |
| kg                           |                    | kg          |                  | kg 💙       |                 | kg                  | ×             | kg                   | ~      |  |
| Products Block (try default  | selections first): |             |                  |            | Select Produ    | icts                |               |                      | ~      |  |
| CO2                          | ✓ 0.               | .015617302  | )<br>kg          | ✓ 0.19018  | N2<br>48 kg     | 3                   | ✓ 0.01925     | 02<br>59222 kg       | ~      |  |

3. Now, go to States panel. Here, mass flow rates are chosen automatically, with reference to the Reaction panel. So, flow rate of fuel is 0.011 kg/s. For State 1 (i.e. fuel), enter p1, T1 as shown and hit Enter. We get:



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| Move mouse  | over a variable to   | display its   | value with mo  | re precision  |  |  |   |       |        |   |   |           |           |                |   |
|---|--|---|--|---|--|--|---|-------|--------|---|---|-----------|-----------|----------------|---|
| • SI  | C English 🔍 M  | lass 🤆 M  | lole   | 🔽 Help  | Mes                                    | sages On   | Sup   | er-Ca | alcula | ate   | Load  | 1         | Sup       | oer-Initialize |   |
|   | Reaction Panel   |   |  | Stat  | e Pan                                  | el   | 1   | I     | Devic  | e Panel                                       |   |           | I/O Pa    | anel           |   |
| <   | ©State-2 🗸 >   | <sele< th=""><th></th><th>Oxidizer</th><th>~</th><th></th><th>Calculate</th><th></th><th></th><th></th><th>No-Plots 💌</th><th></th><th></th><th>nitialize</th><th></th></sele<> |  | Oxidizer  | ~                                      |  | Calculate   |       |        |   | No-Plots 💌  |           |           | nitialize      |   |
| 🖌 p2  |  | <u> </u>  | T2   |   |  | v2   |   |       |        | u2  |   |           | h2        |                |   |
| 1.0   | atm  | ✓ 45.0  | 0  | deg-C   | ~                                      | 0.90111  | m^3/kg  | ~     | -71.   | 18205   | kJ/kg   | ~         | 20.12271  | kJ/kg          | ~ |
| s2  |  |   | g2   |   |  | ✓ Vel2   |   |       | 1      | z2  |   |           | e2        |                |   |
| 6.94773   | kJ/kg.K  | ✓ -21   | 90.2974  | kJ/kg   | ~                                      | 0.0  | m/s   | ~     | 0.0    |   | m   | *         | -71.18205 | kJ/kg          | ~ |
| j2  |  | n   | ndot2  |   |  | Voldot2  |   |       |        | A2  |   |           | MM2       |                |   |
| 20.12271  | kJ/kg  | ✓ 0.2   | 490802   | kg/s  | ~                                      | 0.22445  | m^3/s   | ۷     | 224    | 44.816  | m^2   | *         | 28.97     | kg/kmol        | * |
| c_p2  |  | h   | Model2   |   |  |  |   |       |        |   |   |           |           |                |   |
| 1.00652   | kJ/kg.K  | ✓ 2.0   |  | UnitLess  | ~                                      |  |   |       |        |   |   |           |           |                |   |
| A N<br>Set up the re<br>The mass an<br>change the m<br>scaling facto<br>In evaluating | lote on State Evalua<br>action in the reactior<br>d compositions of fu<br>lass flow rate, go b<br>r.<br>a state, select the si | tion<br>n panel befo<br>uel, oxidizer<br>ack to the re<br>tate number   | and products ar<br>eaction panel an<br>r first and then th | ates of the re<br>re deduced fro<br>d multiply (fro<br>ne type of the | actants<br>om the<br>m the a<br>mixtur | and products in th<br>reaction. If you nee<br>ction menu) the rea<br>e - Fuel, Oxidizer, o | is panel.<br>ed to<br>action by a suit<br>ir Products | able  |        | Air: 0.24<br>Mi<br>Air: x =<br>Mi<br>Air: y = | Oxidizer Co<br>9080194 kg;<br>ass Fractions, x<br>1.0<br>ole Fractions, y-<br>1.0 | ompo<br>( |           |                |   |

4. Similarly, for State 2, (i.e. Oxidizer) enter p2, T2 and hit Enter. We get:

5. And, for State 3: enter p3, T3 and hit Enter. We get:

| Move mouse ov   | ver a variable to o  | display  | its value wi  | th more precisio  | n.                                |   |   |         |  |  |   |                                     |               |   |
|---|--|--|---|---|-----------------------------------|---|---|---------|--|--|---|-------------------------------------|---------------|---|
| ା ମା  | English 🖲 M  | ass (  | Mole  | 🔽 He  | lp Mes                            | sages On  | Su  | per-Cal | iculate  | Loa  | d   | Sup                                 | er-Initialize |   |
|   | Reaction Panel   |  |   | St  | ate Par                           | el  |   | D       | evice Panel  |  |   | I/O Pa                              | nel           |   |
| < (   | DState-3 ♥ >   | <s< td=""><td>elect Toget</td><td>ner&gt; <mark>Produc</mark></td><td>ts 🗸</td><td></td><td>Calculat</td><td>e</td><td></td><td>No-Plots 💌</td><td></td><td>1</td><td>nitialize</td><td></td></s<> | elect Toget   | ner> <mark>Produc</mark>  | ts 🗸                              |   | Calculat  | e       |  | No-Plots 💌   |   | 1                                   | nitialize     |   |
| 🖌 рЗ  |  |  | 🖌 T3  |   |                                   | v3  |   |         | u3   |  |   | h3                                  |               |   |
| 1.0   | atm  | ~  | 750.0   | К   | ~                                 | 2.14614   | m^3/kg  | ~       | -1694.2028   | kJ/kg  | ~   | -1476.7448                          | kJ/kg         | ~ |
| s3  |  |  | g3  |   |                                   | ✓ Vel3  |   |         | 🖌 z3   |  |   | e3                                  |               |   |
| 8.02829   | kJ/kg.K  | ~  | -7497.963   | kJ/kg   | ~                                 | 0.0   | m/s   | ~       | 0.0  | m  | ~   | -1694.2026                          | kJ/kg         | ~ |
| j3  |  |  | mdot3   |   |                                   | Voldot3   |   |         | A3   |  |   | ММЗ                                 |               |   |
| -1476.7448  | kJ/kg  | ~  | 0.25896525  | kg/s  | ~                                 | 0.55578   | m^3/s   | ~       | 55577.64   | m^2  | *   | 28.67452                            | kg/kmol       | * |
| с_р3  |  |  | Model3  |   |                                   |   |   |         |  |  |   |                                     |               |   |
| 1.17584   | kJ/kg.K  | ~  | 3.0   | UnitLess  | ~                                 |   |   |         |  |  |   |                                     |               |   |
| A No<br>Set up the read<br>The mass and<br>change the ma<br>scaling factor. | te on State Evalua<br>ction in the reaction<br>compositions of fu<br>ss flow rate, go ba<br>state, select the st | tion<br>n panel<br>lel, oxid<br>ack to th<br>tate nur  | before evalua<br>izer and prodi<br>he reaction pa<br>nber first and | ting states of the r<br>ucts are deduced<br>nel and multiply (fi<br>then the type of th | reactant<br>from the<br>rom the a | a and products in th<br>reaction. If you new<br>action menu) the re-<br>e - Fuel, Oxidizer, c | nis panel.<br>ad to<br>action by a s<br>or Products | uitable | <ul> <li>CO2: 0.0<br/>H2O: 0.0<br/>N2: 0.19<br/>O2: 0.01</li> <li>CO2: x<br/>H2O: x</li> </ul> | Products C<br>13390393150720<br>1561730178322i<br>01848081215050<br>92592225232999<br>ass Fractions,<br>= 0.13092076903<br>= 0.06030655056 | Comp<br>908 kg<br>8722 k<br>94 kg;<br>54 kg;<br>x<br>328969<br>916769 | osition<br>g;<br>g;<br><br>38<br>19 |               | < |

 Now, go to Device panel. Enter State 1, State 2 and State 3 for i1-state, i2-state and e-state respectively. Also, enter for Wdot\_ext = 150 kW. Hit Enter. Also, click on SuperCalculate. We get:



Thus, heat transfer, Qdot = -213.37 kW for a fuel flow rate of 0.011 kg/s (-ve sign indicates heat flowing *out* of system).... Ans.

7. I/O panel gives the TEST code etc:

#~~~~~OUTPUT OF SUPER-CALCULATE:

#### # TESTcalc Path: ..Open>Steady>Specific>UnMixedCombustion>IG-Mixture; v-10.ce02

#### #\*\*\*\*\*TEST-CODES:

#-----Start of TEST-Codes -----

States {

State-1: Fuel;

Given: { p1= 1.0 atm; T1= 25.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 0.011 kg/s; Model1= 1.0 UnitLess; }

State-2: Oxidizer;

Given: { p2= 1.0 atm; T2= 45.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= 0.24908 kg/s; Model2= 2.0 UnitLess; }

**Reactive Systems** 

#### State-3: Products;

Given: { p3= 1.0 atm; T3= 750.0 K; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= 0.25897 kg/s; Model3= 3.0 UnitLess; }

}

Analysis {

Device-A: i-State = State-1, State-2; e-State = State-3; Mixing: true;

Given: { Wdot\_ext= 150.0 kW; T\_B= 298.15 K; }

}

#-----End of TEST-Code: Reaction Block Starts ------



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# Reaction (Note: To reproduce the TEST solution from the TEST-codes, this reaction has to be manually set up after the loading the TEST-codes.):

### # (0.011 kg) Octane(L) + (0.2490802 kg) Air = (0.03390393 kg) CO2 + (0.015617302 kg) H2O + (0.1901848 kg) N2 + (0.019259222 kg) O2

#-----End of Reaction Block -----

#### #\*\*\*\*\*DETAILED OUTPUT:

#### # Evaluated States:

| #      | State-1: Fuel > IG-Mixture;   |
|--------|---|
| #      | Given: p1= 1.0 atm; T1= 25.0 deg-C; Vel1= 0.0 m/s;  |
| #      | z1= 0.0 m; mdot1= 0.011 kg/s; Model1= 1.0 UnitLess;   |
| #      | Calculated: v1= 0.00142 m^3/kg; u1= -2188.2542 kJ/kg; h1= -2188.11 kJ/kg;                         |
| #      | s1= 3.15754 kJ/kg.K; g1= -3129.532 kJ/kg; e1= -2188.2542 kJ/kg;                                   |
| #      | $j1 = -2188.11 \text{ kJ/kg}$ ; Voldot $1 = 0.0 \text{ m}^3/\text{s}$ ; A $1 = 0.0 \text{ m}^2$ ; |
| #      | MM1= 114.231 kg/kmol; c_p1= 1.71127 kJ/kg.K;  |
| #      | State-2: Oxidizer > IG-Mixture;   |
| #      | Given: p2= 1.0 atm; T2= 45.0 deg-C; Vel2= 0.0 m/s;  |
| #      | z2= 0.0 m; mdot2= 0.24908 kg/s; Model2= 2.0 UnitLess;   |
| #      | Calculated: v2= 0.90111 m^3/kg; u2= -71.18205 kJ/kg; h2= 20.12271 kJ/kg;                          |
| #      | s2= 6.94773 kJ/kg.K; g2= -2190.2974 kJ/kg; e2= -71.18205 kJ/kg;                                   |
| #      | j2= 20.12271 kJ/kg; Voldot2= 0.22445 m^3/s; A2= 22444.816 m^2;                                    |
| #      | MM2= 28.97 kg/kmol; c_p2= 1.00652 kJ/kg.K;  |
| #      | State-3: Products > IG-Mixture;   |
| #      | Given: p3= 1.0 atm; T3= 750.0 K; Vel3= 0.0 m/s;   |
| #      | z3= 0.0 m; mdot3= 0.25897 kg/s; Model3= 3.0 UnitLess;   |
| #      | Calculated: v3= 2.14614 m^3/kg; u3= -1694.2028 kJ/kg; h3= -1476.7448 kJ/kg;                       |
| #      | s3= 8.02829 kJ/kg.K; g3= -7497.963 kJ/kg; e3= -1694.2026 kJ/kg;                                   |
| #      | j3= -1476.7448 kJ/kg; Voldot3= 0.55578 m^3/s; A3= 55577.64 m^2;                                   |
| #      | MM3= 28.67452 kg/kmol; c_p3= 1.17584 kJ/kg.K;   |
| # Mass | s, Energy, and Entropy Analysis Results:  |
| #      | Device-A: i-State = State-1, State-2; e-State = State-3; Mixing: true;                            |
| #      | Given: Wdot_ext= 150.0 kW; T_B= 298.15 K;   |
| #      | Calculated: <b>Qdot= -213.36855 kW;</b> Sdot_gen= 1.0294154 kW/K; Jdot_net= 363.36856             |
| kW; Sd | lot_net= -0.31377375 kW/K;  |

\_\_\_\_\_\_

**Prob. 8.4.11** One kmol of Methane (CH4) gas undergoes complete combustion with stoichiometric amount of air in a rigid container. Initially, the air and methane are at 100 kPa and 25 C. The products of combustion are at 567 C. How much heat is rejected from the container, in kJ/kmol fuel? Also, find the exergy lost and the final pressure.

(b) Plot final pressure, heat rejected and exergy lost as the final temp varies from 300 C to 650 C.[Ref: 1]

#### **TEST Solution:**

#### Following are the steps:

1. Select the Closed system, Combustion daemon, since the reaction occurs in a closed vessel, as shown below:



#### 2. Select Pre-mixed, Ideal Gas (IG) for Material selection:





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3. Clicking on IG mixture model gives the following window, where we have to choose the reactants, i.e. Methane and Air, in the present case:

| actants Bloc | k: Select reactant(s | ) and specify a  | mount(s) if known. | a · process · | Specific • Combust   | ion/Chemedulibhur         | m · Premixed · h-16 r | 100 |
|--------------|----------------------|--|--------------------|---------------|--|---------------------------|-----------------------|-----|
| •si ⊂e       | English C            | Mass 🔍 🕅   | lole 🔽 Help Mess   | ages On       | Super-Calculate  | Load                      | Super-Initialize      | I   |
|              | Reaction Panel       |  | State Panel        |               | Process Pane   |                           | I/O Panel             | _   |
| ect an Act   | ion After Choosing   | Reactant(s)  | Perform Action     | ✓ \ (% Th     | eor. Air) 🛛 (Eqv.  | Ratio)<br>fraction 💙      | Scaling Factor        |     |
|              |                      |  |                    |               | Methane  | (CH4)                     |                       |     |
|              |                      |  |                    |               | Select R   | eactants                  |                       |     |
|              | kmol                 | v  | kmol               | ×             | Select R<br>C(s)<br>S  | eactants                  |                       |     |
|              | kmol<br>kmol         | <ul> <li></li> <li></li> <li></li> <li></li> <li></li> </ul> | kmol               |               | C(s)<br>Select R<br>C(s)<br>H2<br>Ash(s)<br>Methane            | (CH4)                     |                       |     |
| ducts Bloc   | kmol<br>kmol         | IS, products ar  | e auto-seleted):   | ×<br>×        | Select R<br>C(s)<br>S<br>H2<br>Ash(s)<br>Methane<br>Select Pro | (CH4)<br>e(C2H2)<br>ducts |                       |     |

4. After choosing Methane and Air, choose 'Theoretical reaction with Air' from the Action widget, and click on 'Perform Action'. We get:

| • SI     | C English           | C Mass          | • Mole         | 🔽 Help Messa | iges On         | Sup              | per-Calculate | Lo                | ad    | Super-Initialize |        |
|----------|---------------------|-----------------|----------------|--------------|-----------------|------------------|---------------|-------------------|-------|------------------|--------|
|          | Reaction Pan        | iel             |                | State Panel  |                 |                  | Process Panel |                   |       | I/O Panel        |        |
| Select a | n Action After Cho  | osing Reactant  | t(s) ⊻ Perf    | orm Action   | <b>√</b><br>1.0 | λ (% Theor. Air) | ) 🛛 (Eqv. R   | atio)<br>fraction | ✓ 1.0 | Scaling Factor   | ~      |
|          |                     |                 |                |              |                 |                  | Select Re     | actants           |       |                  | ~      |
|          | Methane(CH4         | 4)              |                | Air          |                 |                  |               |                   |       |                  |        |
| 1.0      | kmol                | ~               | 9.523809       | kmol         | ~               | -                | kmol          |                   |       | kmol             | ×      |
|          | kmol                | ×               |                | kmol         | ×               |                  | kmol          | ×                 |       | kmol             | ×      |
| Products | s Block (for some a | actions, produc | ts are auto-se | eleted):     |                 |                  | Select Prod   | ucts              |       |                  | ~      |
|          | C02                 |                 |                | H20          |                 | N                | 12            |                   |       |                  |        |
| 1.0      | kmol                | ~               | 2.0            | kmol         | ×               | 7.5238094        | kmol          | ~                 |       | kmol             | $\sim$ |
|          |                     |                 |                |              |                 |                  |               |                   |       |                  |        |

5. Now, go to State panel. For State 1, enter p1 = 100 kPa, T1 = 25 C, as shown and hit Enter. We get:



6. For State 2, enter T2 = 567 C, Vol2 = Vol1 (since it is a rigid vessel). Hit Enter. We get:

| C SI C English C Mass C Mole   | 🔽 Help Messages On                      | Super-Calculate     | Load                          | Super-Initialize |
|--|---|---------------------|-------------------------------|------------------|
| Reaction Panel   | State Panel                             | Process Pan         | el 🛛                          | I/O Panel        |
| < OState-2 > <select td="" together-<=""><td>&gt; Products 💌</td><td>Calculate</td><td>No-Plots 💌</td><td>Initialize</td></select> | > Products 💌                            | Calculate           | No-Plots 💌                    | Initialize       |
| p2 🖌 T2  | v2                                      | u2                  |                               | h2               |
| 281.78775 kPa 😪 567.0  | deg-C 💉 0.89732                         | m^3/kg 💉 -2624.8916 | kJ/kg 💉 -23                   | 372.0378 kJ/kg 💙 |
| s2g2   | ✓ Vel2                                  | ✓ z2                |                               | e2               |
| 8.13791 kJ/kg.K 😪 -9209.101  | kJ/kg 🕑 0.0                             | m/s 💉 0.0           | m 🖌 -26                       | 624.8918 kJ/kg 💙 |
| j2 m2  | ✓ Vol2                                  | MM2                 |                               | c_p2             |
| -2372.0378 kJ/kg 🛛 290.71667   | kg 💙 =Vol1                              | m^3 ❤ 27.62466      | kg/kmol 💉 1.2                 | 27063 kJ/kg.K 💙  |
| Model2   |   |                     |                               |                  |
| 3.0 UnitLess   |   |                     |                               |                  |
|  |   |                     |                               |                  |
| A Note on State Evaluation   |   | CO2: 44.0           | Products Compositio<br>)1 kg: | )n               |
| Set up the reaction in the reaction panel first.   |   | H2O: 36.0           | )4 kg;                        |                  |
| The mass and compositions of reactants and products are  | picked up from the balanced reaction. T | o change            | 0000000000009 Kg;             |                  |
| the mass (or mass flow rate), use the Scaling Factor in the  | reaction panel.                         | Ma                  | ess Fractions, x              |                  |
| In evaluating a state, select the state number first and then  | the mixture type - reactans or products | H2O: x =            | 0.12396950065929024           |                  |

Note that p2 is 281.79 kPa ... Ans.

 Now, go to Process panel. Fill in State 1 for bA-state, Null-state for bB-state, and State 2 for f-state. Also, W\_ext = 0. Hit Enter. Click on SuperCalculate. We get:



Note that heat transfer ,  $Q = -662146.94 \text{ kJ} \dots$  Ans. (-ve sign indicates heat rejected from system). And, Entropy generated = S\_gen is also calculated, and exergy loss = T\_B \* S\_gen.



#### 8. I/O panel gives the TEST code etc:

#### #~~~~~OUTPUT OF SUPER-CALCULATE

#### # TESTcalc Path: ..Closed>Process>Specific>PreMixedCombustion>IG-Mixture; v-10.ce02

#-----Start of TEST-Codes -----

States {

State-1: Reactants;

Given: { p1= 100.0 kPa; T1= 25.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 291.94476 kg; Model1= 1.0 UnitLess; }

State-2: Products;

Given: { T2= 567.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; m2= 290.71667 kg; Vol2= "Vol1" m^3; Model2= 3.0 UnitLess; }

}

Analysis {

Process-A: b-State = State-1; f-State = State-2;

Given: { W\_ext= 0.0 kJ; T\_B= 298.15 K; }

}

#-----End of TEST-Code: Reaction Block Starts -----

# Reaction (Note: To reproduce the TEST solution from the TEST-codes, this reaction has to be manually set up after the loading the TEST-codes.):

# (1.0 kmol) Methane(CH4) + (9.523809 kmol) Air = (1.0 kmol) CO2 + (2.0 kmol) H2O + (7.5238094 kmol) N2

#-----End of Reaction Block -----

#### #\*\*\*\*\*DETAILED OUTPUT:

#### **#** Evaluated States:

| #       | State-1: Reactants > IG-Mixture;  |
|---------|---|
| #       | Given: p1= 100.0 kPa; T1= 25.0 deg-C; Vel1= 0.0 m/s;                                |
| #       | z1= 0.0 m; m1= 291.94476 kg; Model1= 1.0 UnitLess;                                  |
| #       | Calculated: v1= 0.89355 m^3/kg; u1= -345.79453 kJ/kg; h1= -256.43988 kJ/kg;         |
| #       | s1= 7.24025 kJ/kg.K; g1= -2415.1194 kJ/kg; e1= -345.79453 kJ/kg;                    |
| #       | j1= -256.43988 kJ/kg; Vol1= 260.8662 m^3; MM1= 27.74136 kg/kmol;                    |
| #       | c_p1= 1.07163 kJ/kg.K;  |
| #       | State-2: Products > IG-Mixture;   |
| #       | Given: T2= 567.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m;                                   |
| #       | m2= 290.71667 kg; Vol2= "Vol1" m^3; Model2= 3.0 UnitLess;                           |
| #       | Calculated: p2= 281.78775 kPa; v2= 0.89732 m^3/kg; u2= -2624.8916 kJ/kg;            |
| #       | h2= -2372.0378 kJ/kg; s2= 8.13791 kJ/kg.K; g2= -9209.101 kJ/kg;                     |
| #       | e2= -2624.8918 kJ/kg; j2= -2372.0378 kJ/kg; MM2= 27.62466 kg/kmol;                  |
| #       | c_p2= 1.27063 kJ/kg.K;  |
| # Mass, | , Energy, and Entropy Analysis Results:   |
| #       | Process-A: b-State = State-1; f-State = State-2;                                    |
| #       | Given: W_ext= 0.0 kJ; T_B= 298.15 K;  |
| #       | Calculated: Q= -662146.94 kJ; S_gen= 2472.9243 kJ/K; Delta_E= -662146.94 kJ; Delta_ |
| S= 252. | 07263 kJ/K;   |

(b) Plot final pressure (p2), heat rejected and exergy lost vs final temp:

#### Procedure as follows:

Go to State panel, and in State 2, change the T2 to desired value, hit Enter, observe new value of p2, and click on SuperCalculate. Then, go to Process panel, and note new values of Q and S\_gen.

Tabulate values of p2, Q, S\_gen against T2. Complete the Table as shown below, remembering that Exergy destroyed = T\_B \* Sdot\_gen:

| T_B = 298.15 K |             |          |               |          |
|----------------|-------------|----------|---------------|----------|
| T2 (C)         | Heat        | S_gen    | Exergy loss = | p2 (kPa) |
|                | rejected, Q | (kJ/K)   | T_B * S_gen   |          |
|                | (kJ)        |          | (kJ)          |          |
| 300            | 734490.94   | 2612.190 | 778824.36     | 192.24   |
| 350            | 721407.06   | 2590.225 | 772275.67     | 209.00   |
| 400            | 708099.44   | 2566.108 | 765085.10     | 225.78   |
| 450            | 694584.1    | 2540.169 | 757351.30     | 242.55   |
| 500            | 680855.6    | 2512.460 | 749090.07     | 259.32   |
| 550            | 666929.44   | 2483.224 | 740373.35     | 276.09   |
| 567            | 662146.94   | 2472.924 | 737302.38     | 281.79   |
| 600            | 652801.06   | 2452.484 | 731208.22     | 292.86   |
| 650            | 638485.5    | 2420.428 | 721650.61     | 309.63   |

Now, plot the results in EXCEL:







\_\_\_\_\_

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