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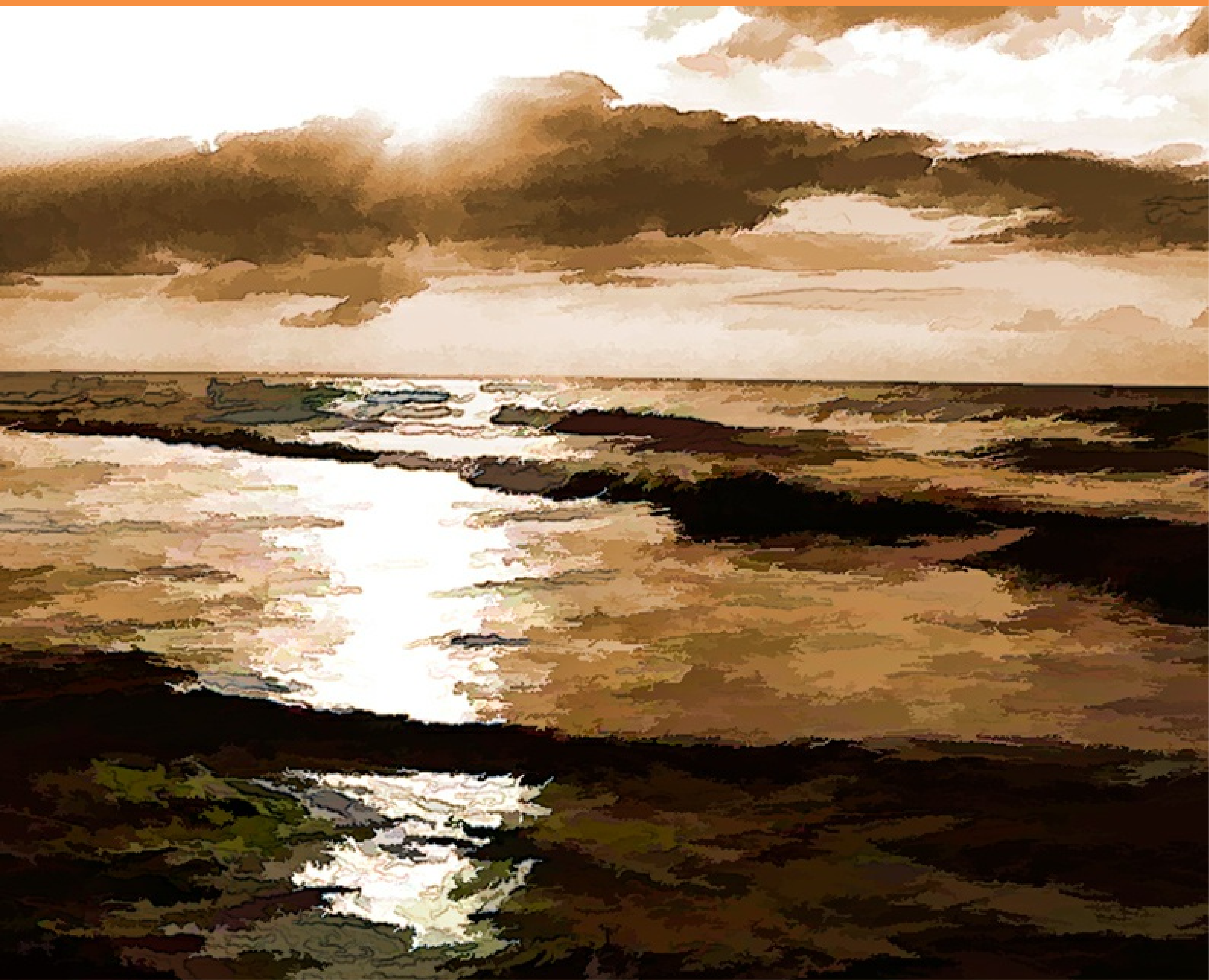
Applied Thermodynamics: Software Solutions

Part-IV

Dr. M. Thirumaleshwar



Dr. M. Thirumaleshwar

Applied Thermodynamics: Software Solutions

Part-IV (Psychrometrics, Reactive systems)

Applied Thermodynamics: Software Solutions: Part-IV (Psychrometrics, Reactive systems)
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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
Temp.	Sat. press.
T ^{0}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]:**

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

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:

$$w = \frac{m_w}{m_a} \quad \text{kg water vap/kg dry air}$$

i.e. $$w = \frac{\frac{p_w \cdot V}{R_w \cdot T}}{\frac{p_a \cdot V}{R_a \cdot T}} \quad \text{...using Ideal Gas relation}$$

i.e. $$w = 0.62198\cdot\frac{p_w}{p_a}$$

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

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

Relative humidity (RH or φ): 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.

$$\phi = \frac{m_w}{m_g} = \frac{\frac{p_w \cdot V}{R_w \cdot T}}{\frac{p_g \cdot V}{R_w \cdot T}} = \frac{p_w}{p_g} \quad \text{where } p_g = \text{psat at T}$$

Also: $$\phi = \frac{w \cdot p}{(0.62198 + w)\cdot p_g}$$

and $$w = \frac{0.62198\cdot\phi\cdot p_g}{p - \phi\cdot p_g}$$

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

$$\mu = \frac{w}{w_s} = \frac{0.622\cdot\dfrac{p_w}{p - p_w}}{0.622\cdot\dfrac{p_s}{p - p_s}}$$

i.e. $$\mu = \frac{p_w}{p_s}\cdot\frac{p - p_s}{p - p_w}$$

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

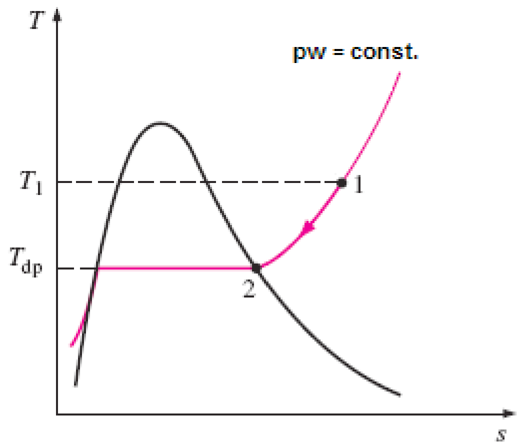
For dry air, i.e. when φ = 0, we have: μ = 0, and

For sat. air, i.e. when φ = 100%, we have: μ = 1, i.e φ 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:

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

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.

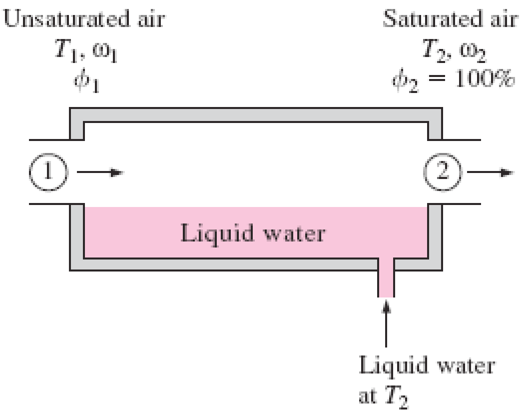
Dry bulb temperature (dbt): It is the temp measured with an ordinary thermometer placed in air.

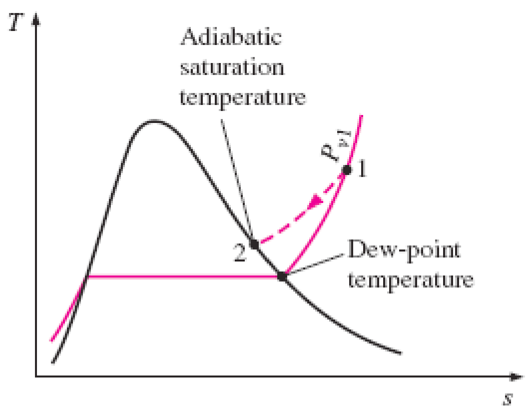
Wet bulb temperature (wbt): It is the temp measured by a thermometer when its bulb is enveloped with a cotton wick saturated with water and held in a flowing stream of air.

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:

$$w_1 = \frac{cp \cdot (T_2 - T_1) + w_2 \cdot h_{fg2}}{h_{g1} - h_{f2}} \quad \text{...kg H2O/kg dry air}$$

and,

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

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:

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

Ex: $\text{phi}(20, 15.7) = 0.647 = 64.7\%$

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:

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

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

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

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

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

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

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

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

Difference Between Dry Bulb and Wet Bulb Temperatures $T_{db} - T_{wb}$ (^oC)	Relative Humidity - *RH* (%) Dry Bulb Temperature - T_{db} (^oC)							
	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

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:

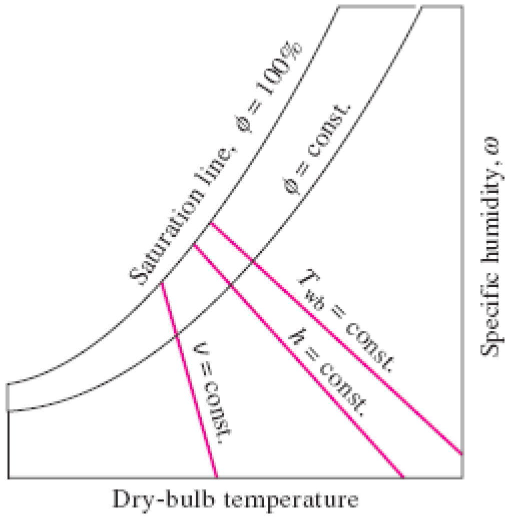
$$v = \frac{\left(\frac{1}{P}\right)\cdot 287.055\cdot(dbt + 273.15)\cdot(1 + 1.6078\cdot w)}{1 + w} \quad \text{m^3/kg of moist air}$$

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

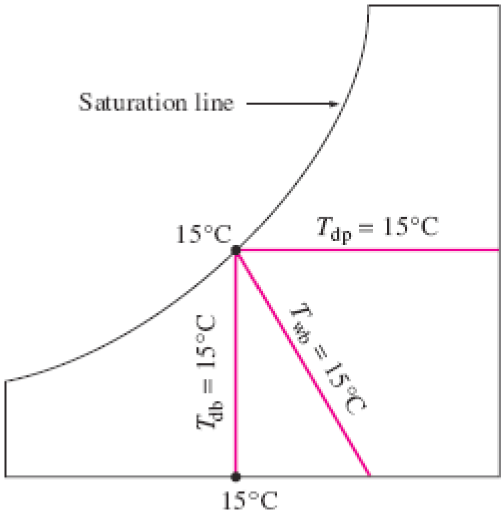
7.1.3 Psychrometric chart:

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).

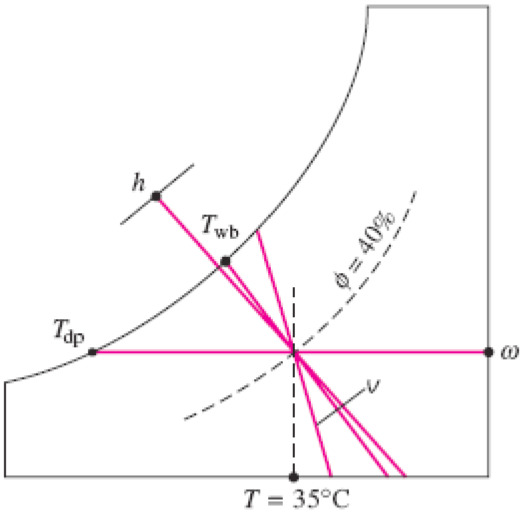
Following schematic from Ref. 1 shows various lines:



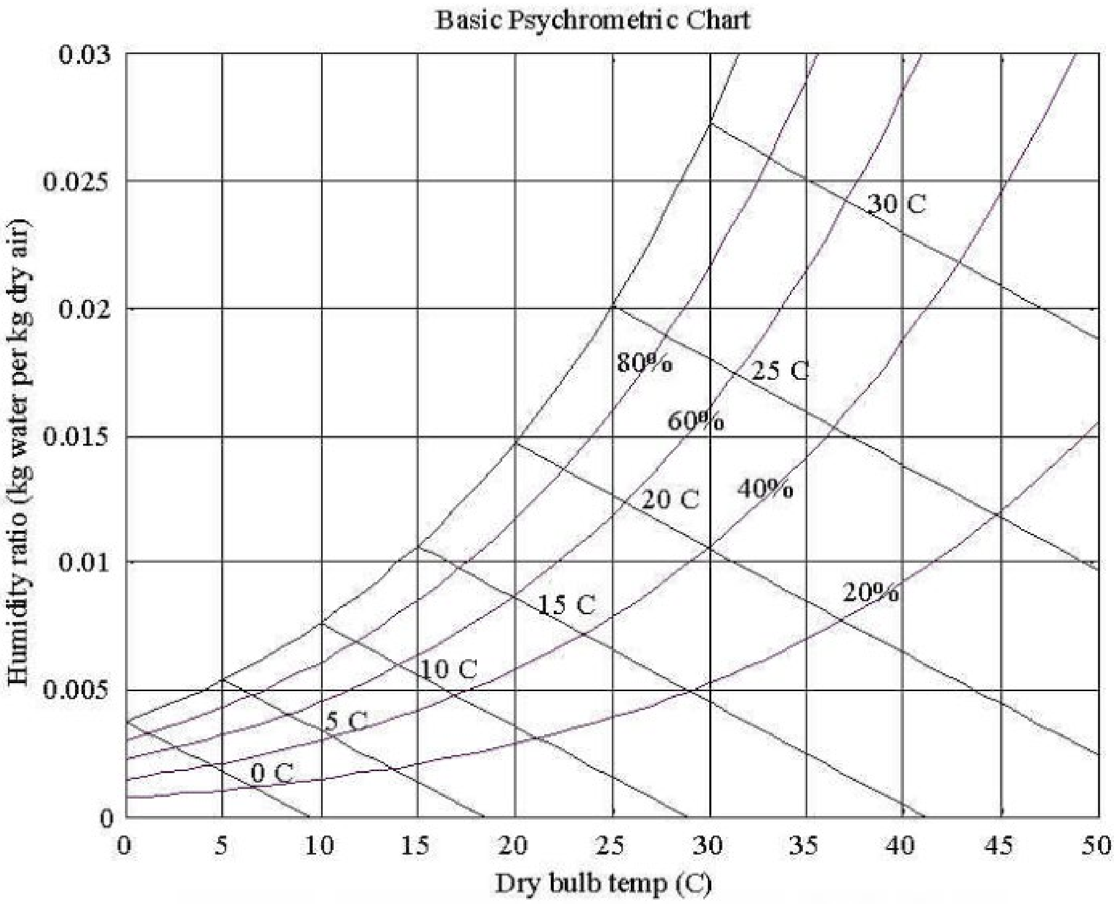
In the Psychrometric chart, for sat. air, DBT, WBT and DPT coincide as shown below:



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

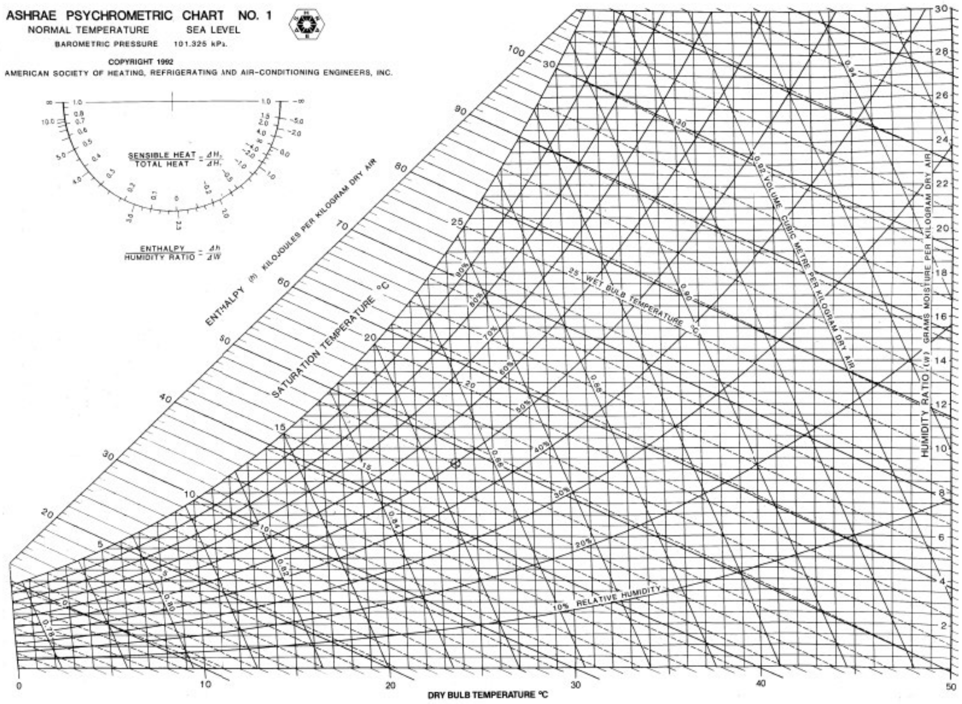


A Basic Psychrometric chart is shown below:



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)

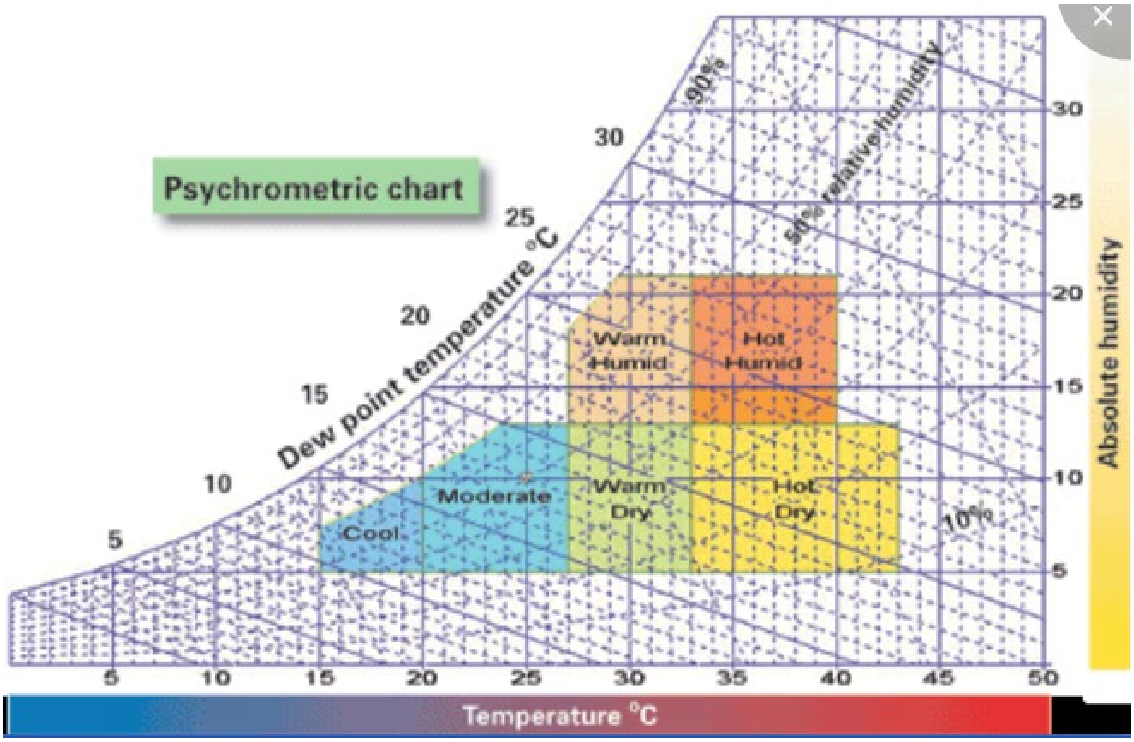


And, different zones of temp and humidity are shown in the following fig.:

Comfort zone for humans is generally in the following range:

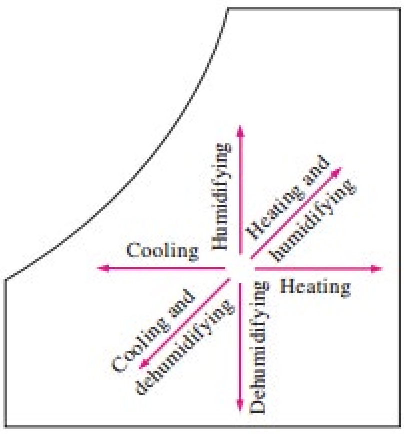
DBT: between 22 C and 27 C

RH: between 40% and 60%



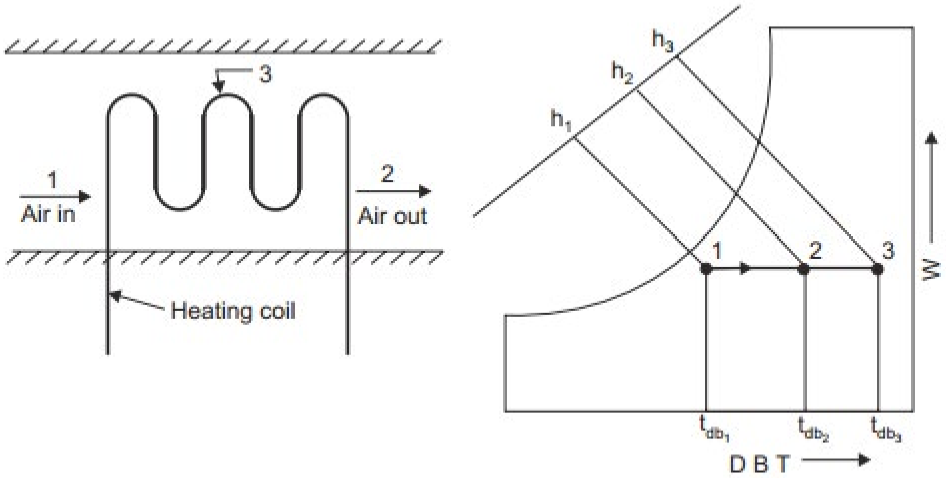
7.1.4 Air-conditioning processes:

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

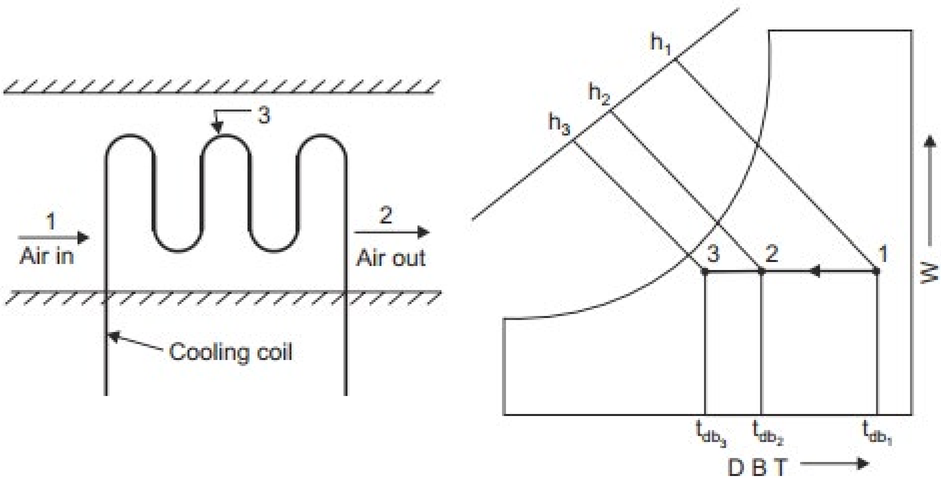
Bypass Factor (BF) is defined as:

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

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.

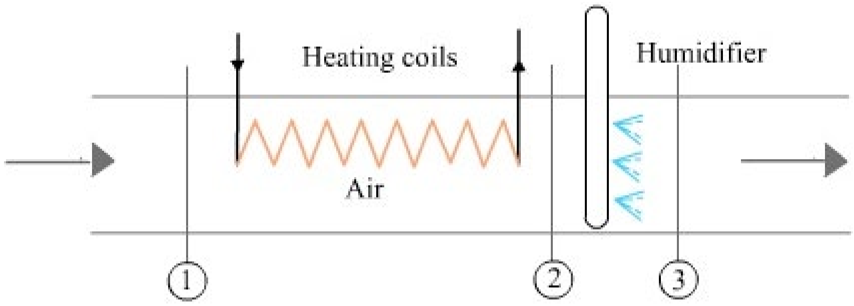
Heat transferred, Q = m_a * (h1 – h2), kJ/s

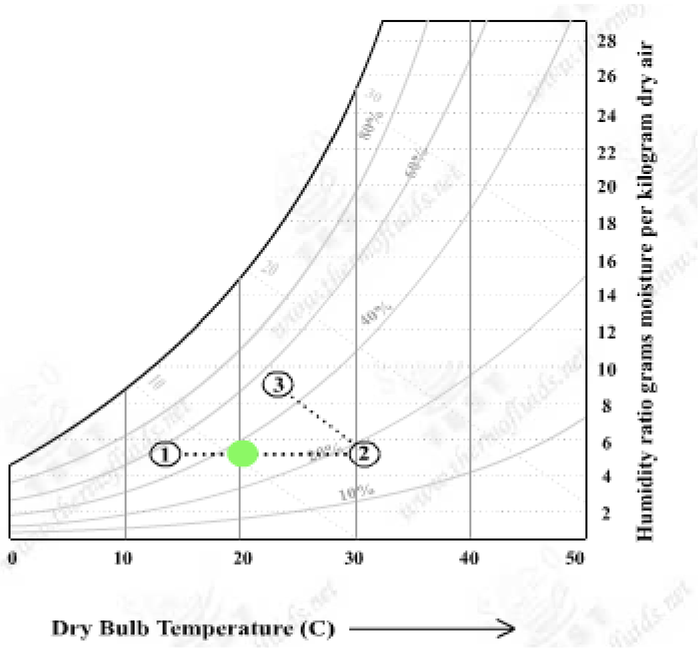
Bypass Factor (BF) is defined as:

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

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:





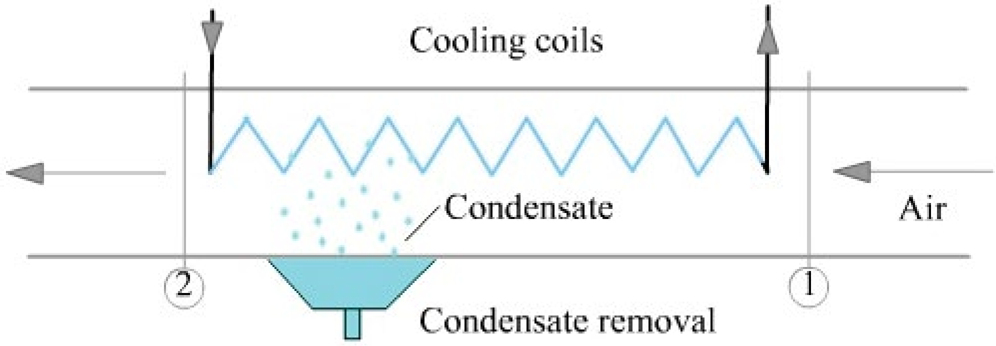
For the above case, we have:

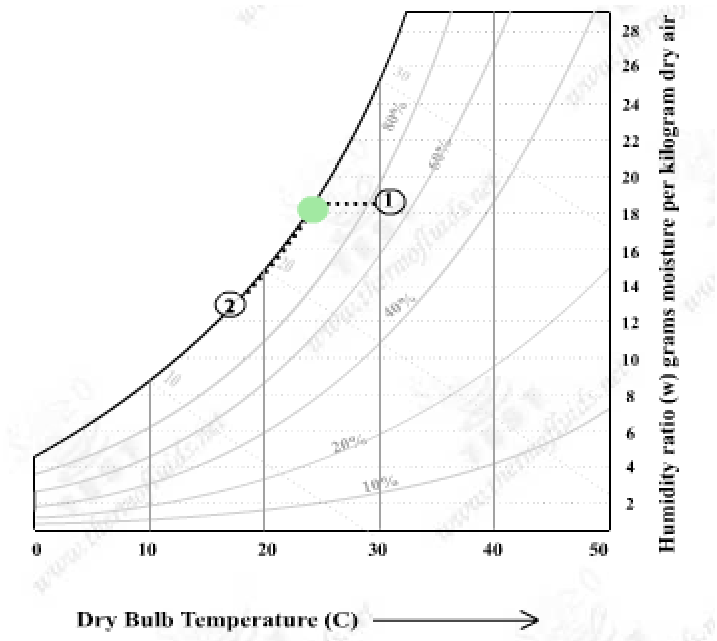
Dry air mass balance: $m_{a1} = m_{a2} = m_a$

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. $Q_{in} = m_a \cdot (h_2 - h_1)$

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





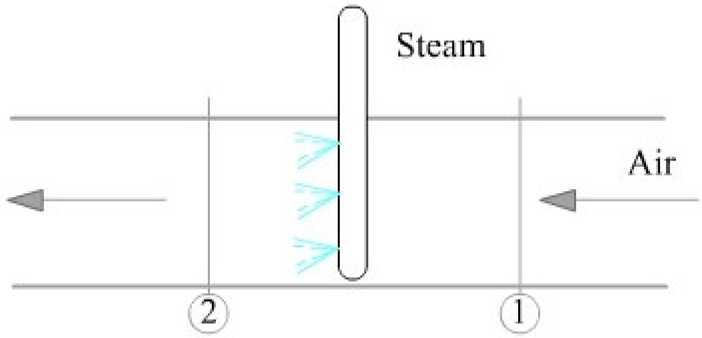
For the above case:

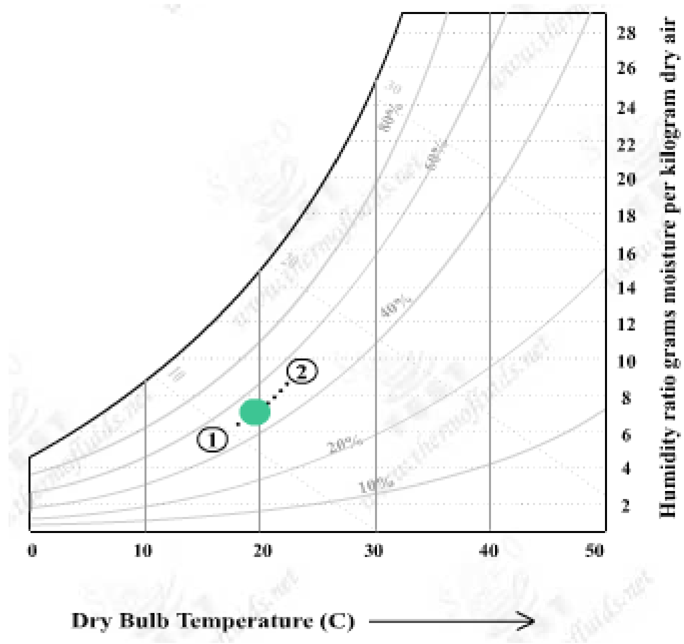
Dry air mass balance: $m_{a1} = m_{a2} = m_a$

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.

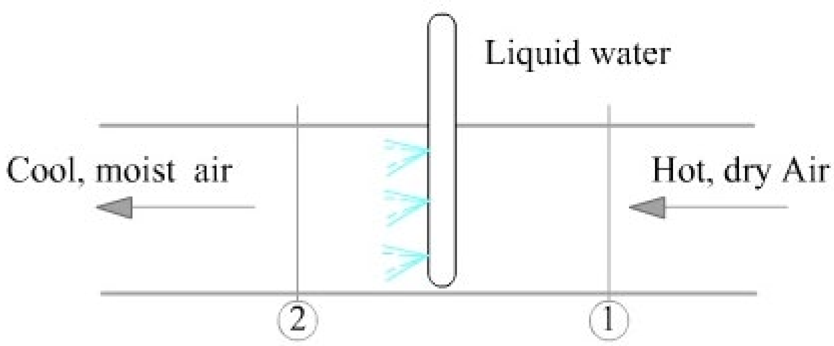
f) **Evaporative cooling:[12]**

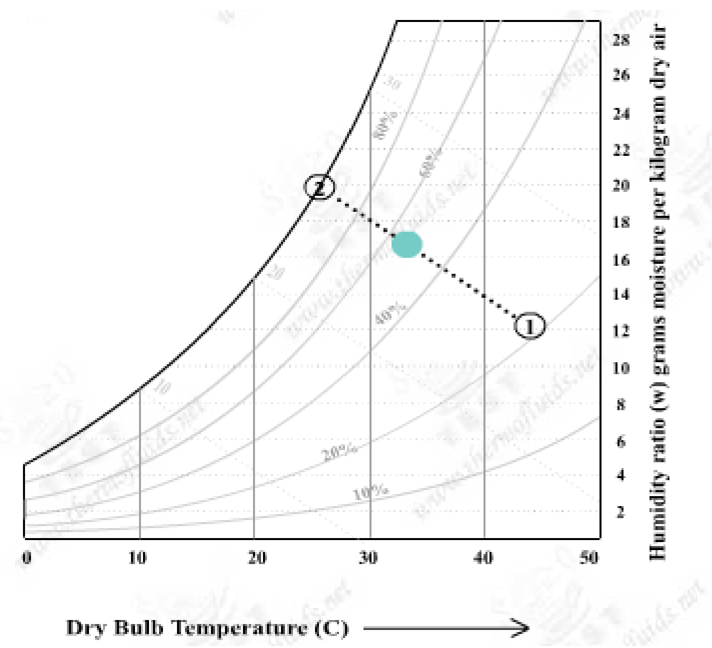
Evaporative coolers or swamp coolers are used in hot and dry (i.e. desert) climates.

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.



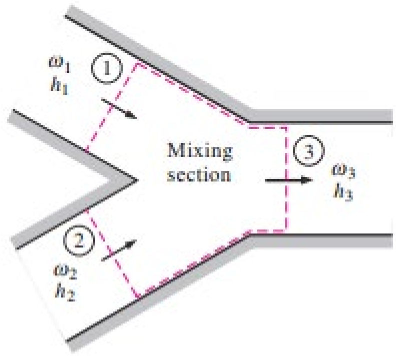


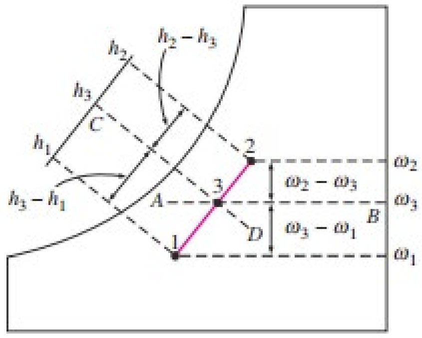
For the above process (1–2), we can write:

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

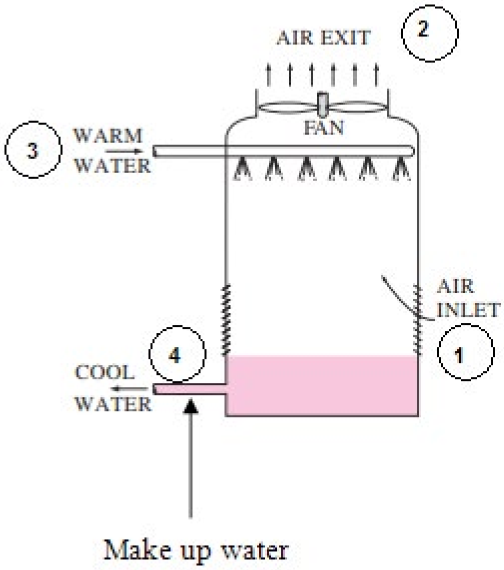
Then, we get:

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

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}.

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.



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 m_a:

$$m_a = \frac{m_3 \cdot (h_3 - h_4)}{(h_2 - h_1) - (w_2 - w_1) \cdot h_4} \quad \text{kg/s}$$

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:

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

7.1.5 Two free calculators for Psychrometric properties:

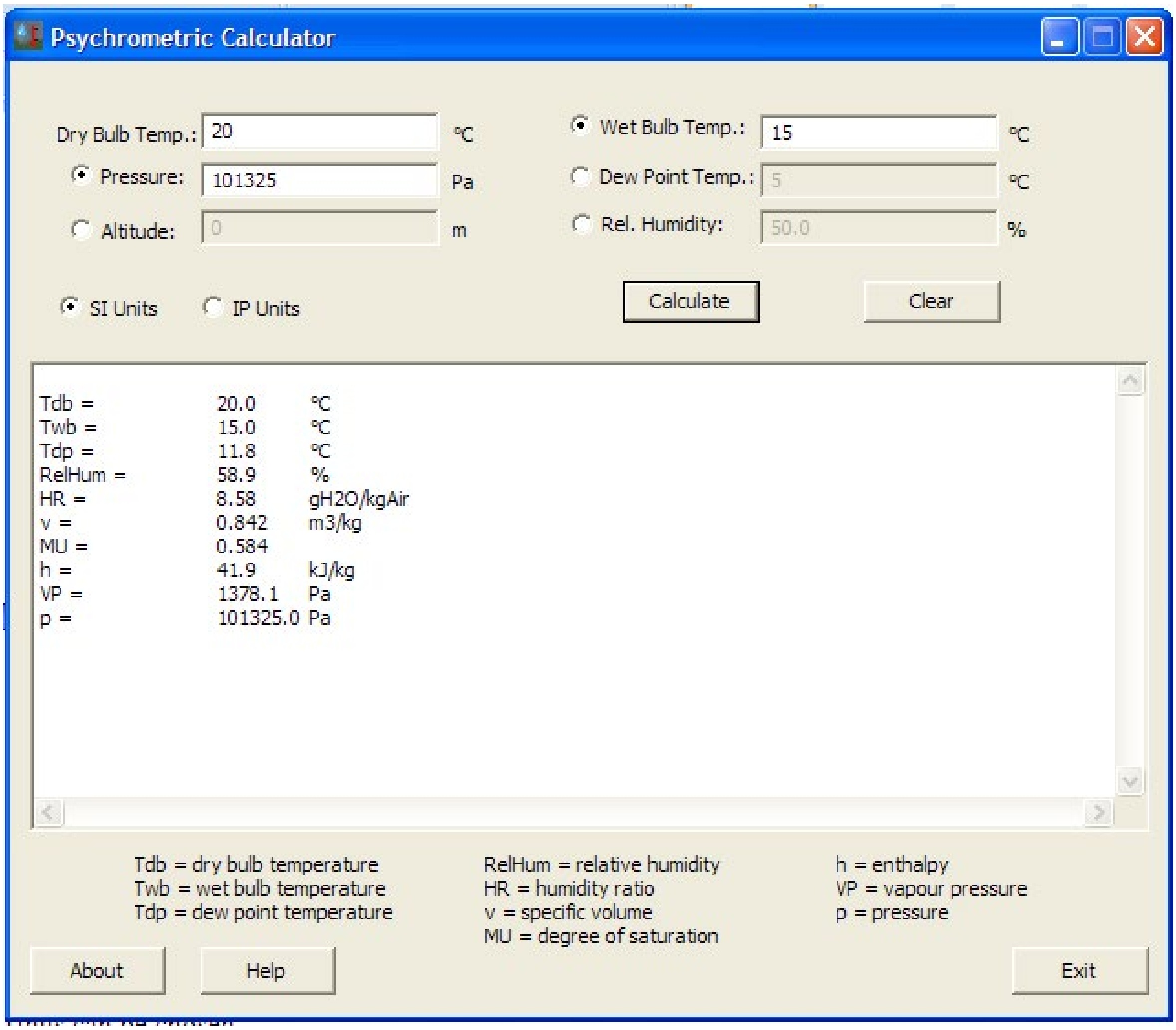
Quite a large number of calculators are available for calculation of Psychrometric properties.

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** www.numlog.ca:

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.

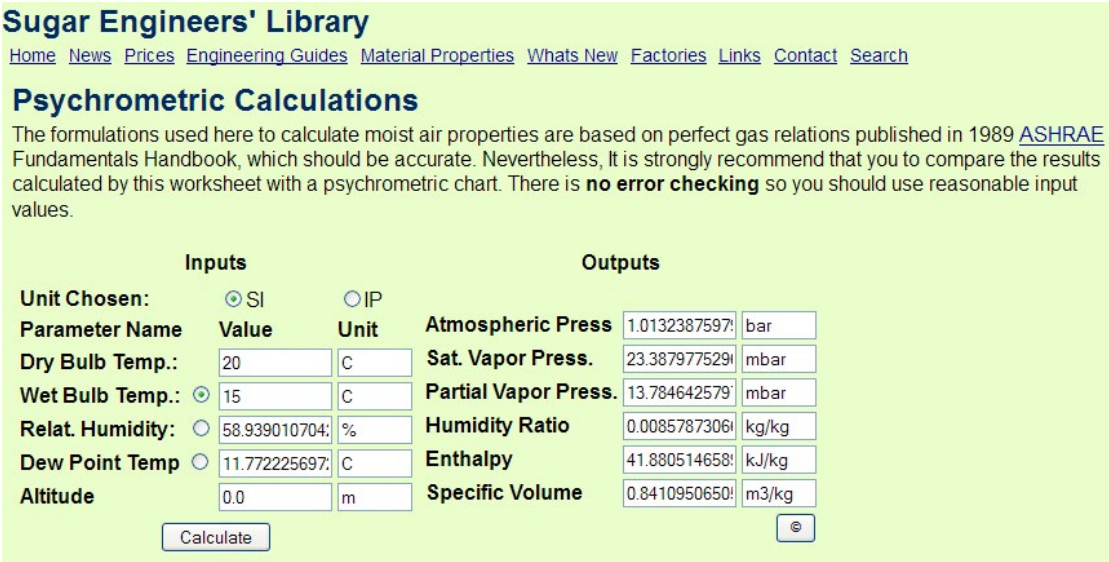
As an example, following screen shot shows the properties when DBT = 20 C and WBT = 15 C are input and Calculate button is pressed:



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 (http://www.sugartech.com/engrdata/index.php) 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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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

tsat := (deg.C)	psat := (kPa)	hf := (kJ/kg)	hg := (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
30	4.246	125.79	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

$PSATT(T) := \text{linterp}(tsat, psat, T) \cdot 1000$ Ex: $PSATT(25) = 3.169 \times 10^{3}$ Pa

$TSATP(P) := \text{linterp}\left(psat, tsat, \frac{P}{1000}\right)$ Ex: $TSATP(1754) = 15.386$ C

$HFSATT(T) := \text{linterp}(tsat, hf, T)$ Ex: $HFSATT(30) = 125.79$ kJ/kg

$HGSATT(T) := \text{linterp}(tsat, hg, T)$ Ex: $HGSATT(30) = 2.556 \times 10^{3}$ kJ/kg

$HFGSATT(T) := HGSATT(T) - HFSATT(T)$ Ex: $HFGSATT(15) = 2.466 \times 10^{3}$ kJ/kg

Other Functions:

Sat. pressure over water: Range: 0 to 200 C:

T in deg.C, pressure in Pa.

1. Sat. pressure:

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

Ex: $psatt(20) = 2.339\times 10^{3}$ 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 ϕ:

$\phi(pw, dbt) := \dfrac{pw}{psatt(dbt)}$ ...pw is the prtial pressure of water at dry bulb temp, dbt

3. Partial pressure of water, pw:

$Pw(dbt, RH) := RH\cdot psatt(dbt)$ Pa

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

4. Humidity ratio, w:

$$w(P,pw) := \frac{0.622 \cdot pw}{P - pw}$$ kg H2O/kg dry air P is total pressure = atmosph. pr.

$$W(dbt,RH,P) := \frac{0.622 \cdot RH \cdot psatt(dbt)}{(P - RH \cdot psatt(dbt))}$$ kg H2O/kg dry air .... P...in Pa

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

$$ws(P,dbt) := \frac{0.622 \cdot psatt(dbt)}{P - psatt(dbt)}$$ ... 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: $mu(20,0.5,101325) = 0.494$

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

$$dpt(pw) := -35.957 - 1.8726 \cdot \ln(pw) + 1.1689 \cdot (\ln(pw))^2$$ ....deg. C, pw in Pa

Ex: $dpt(1169.4) = 9.147$ 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 :

$$rho(dbt, RH, P) := \frac{1}{v(dbt, RH, P)}$$ ...density of moist air ...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)

$$h_{dryair}(T) := 1.005 \cdot T$$ kJ/kg

Ex: $h_{dryair}(25) = 25.125$ kJ/kg

11. Enthalpy of moist air :

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

Ex: $h_{moist}(20, 0.5, 101325) = 38.527$ 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 :

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

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

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

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

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

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

Ex: $RH(20, 15.7, 101325) = 0.641$ = 64.1%

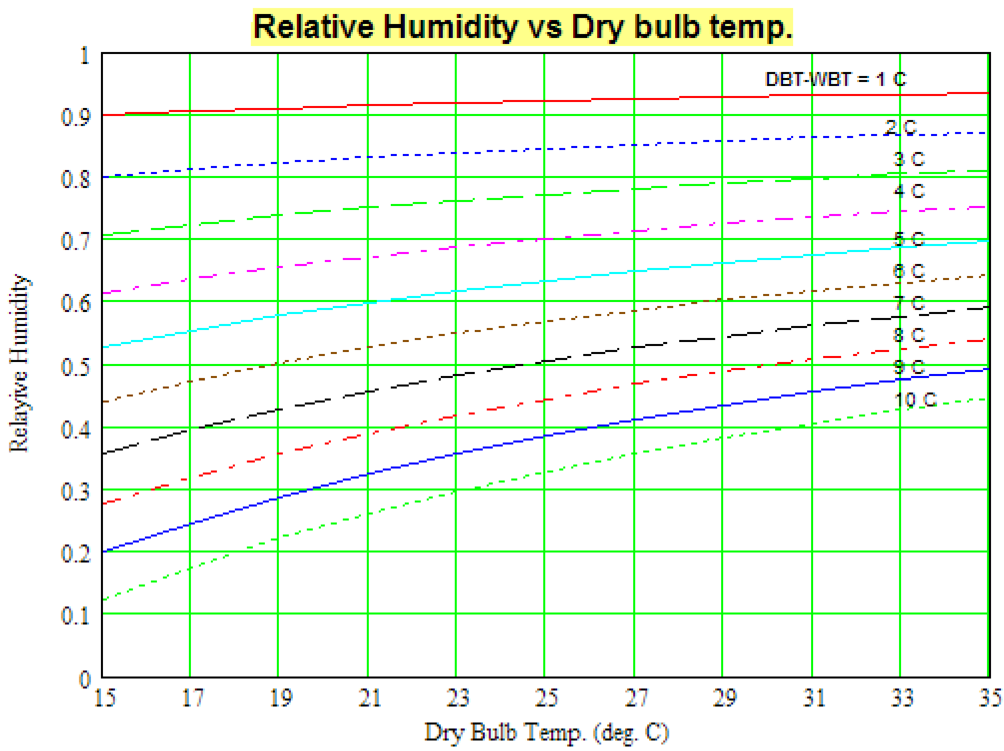
Plot RH vs DBT for different "wet bulb depression (DBT-WBT)" values:

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

DBT =	RH(DBT, DBT − 4, 101325)	RH(DBT, DBT − 5, 101325)	RH(DBT, DBT − 6, 101325)
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



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: $W1(20, 15, 101325) = 8.558 \times 10^{-3}$ kg H2O/kg. dry air

14. Humidity from DBT & RH:

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

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

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:

$$p\_w(dbt, wbt, P) := \frac{\omega 1(dbt, wbt, P) \cdot P}{\omega 1(dbt, wbt, P) + 0.622}$$ Pa ... dbt, wbt in C, P is atm. pressure in Pa

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

18. pw from DBT, RH & P:

$$P\_w(DBT, RH, P) := \frac{\omega 1(DBT, RH, P) \cdot P}{\omega 1(DBT, RH, P) + 0.622}$$ Pa ... DBT in C, P is atm. pressure in Pa

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

Summary of Mathcad Functions to determine various Psychrometric properties:

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 a function of temp (C), data from Steam Tables	$HFSATT(30) = 125.79$
HGSATT(T)	enthalpy of sat. vapor (kJ/kg) as a function of temp (C), data from Steam Tables	$HGSATT(30) = 2.556 \times 10^3$
HFGSATT(T)	enthalpy vaporization of water (kJ/kg) as a function of temp (C), data from Steam 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.	$tsatp(7384) = 40.001$
$\phi(pw, dbt)$	Relative humidity from pw(Pa) and dbt (C)	$\phi(2380, 25) = 0.751$

Pw(dbt, RH)	Pw (Pa) from dbt (C) and RH, 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 dry air)	$W(20, 0.5, 101325) = 7.262 \times 10^{-3}$
ws(P, dbt)	ws … sp. humidity at saturation, P is atm. 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 and RH	dewpt(20, 0.75) = 15.276
v(dbt, RH, P)	sp.vol. (m^3/kg of moist air), given in Psychrometric chart	v(20, 0.5, 101325) = 0.834
rho(dbt, RH, P)	density (kg/m^3 moist air), given in Psychrometric chart	rho(20, 0.5, 101325) = 1.199
$h_g(T)$	Enthalpy (kJ/kg) of water vapor	$h_g(25) = 2.5464 \times 10^3$
$h_{dryair}(T)$	Enthalpy (kJ/kg) of dry air	$h_{dryair}(25) = 25.125$
$h_{moist}(dbt, RH, P)$	Enthalpy (kJ/kg) of moist air	$h_{moist}(20, 0.5, 101325) = 38.527$
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 atm. pr in Pa**	RH(20, 15.7, 101325) = 0.641
W1(dbt, wbt, P)	**Sp. humidity (kg H2O/kg dry air) when dbt and wbt are known, P is atm. pr in Pa**	$W1(20, 15, 101325) = 8.558 \times 10^{-3}$
ω1(DBT, RH, P)	**Sp. humidity (kg H2O/kg dry air) when dbt and RH are known, P is atm. pr in Pa**	$\omega1(20, 0.64, 101325) = 9.326 \times 10^{-3}$
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, P (Pa)	$p_w(0.0152, 101325) = 2.417 \times 10^3$
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 $\quad wbt := 25$ C $\quad P := 101325$ 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: $pw := pw(dbt, wbt, P)$ $\quad pw = 2.513 \times 10^{3}$ Pa

Therefore: $pa := P - pw$ $\quad pa = 9.881 \times 10^{4}$ 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. $rho_w = 0.018$ **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.**

$\text{dewpt}(\text{dbt}, \text{RH}(\text{dbt}, \text{wbt}, P)) = 23.821$ **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:

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

Therefore, water condensed:

$W1(\text{dbt}, \text{wbt}, P) - W1(10, 10, P) = 0.01116$ **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:

$\text{dbt} := 30$ C .... dry bulb temp $P := 101325$ Pa ..... atm. pressure

$\text{dpt} := 15$ C ... dew point temp

Calculations:

Recollect the following Mathcad Function we wrote earlier:

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

$$\text{dpt}(pw) := \left[-35.957 - 1.8726 \cdot \ln(pw) + 1.1689 \cdot (\ln(pw))^2\right]$$ ....deg. C,   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. $pw = 1.723 \times 10^{3}$ **Pa.... partial pressure of water vapor .... Ans.**

Therefore, partial pressure of dry air:

$pa := P - pw$

i.e. $pa = 9.96 \times 10^{4}$ **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.**

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 × 4m × 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]

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. $pw = 2.535 \times 10^{3}$ Pa....partial pressure of water ... Ans.

Therefore, partial pressure of air at 25 C:

$$pa := P - pw$$

i.e. $pa = 9.879 \times 10^{4}$ 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.

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

$$h_{moist}(dbt, RH, P) = 65.774$$ **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:

$R_a := 287$ 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:

$m_a := \frac{pa \cdot V}{R_a \cdot T}$ i.e. $m_a = 110.832$ **kg....mass of dry air .... Ans.**

$m_w := \frac{pw \cdot V}{R_w \cdot T}$ i.e. $m_w = 1.767$ **kg....mass of water vapor .... Ans.**

==

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.

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:

$T1 := 25$ C .... DBT $T2 := 15$ C .... WBT $cp := 1.005$ kJ/kg.C $P := 101325$ Pa

We have:

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

Therefore:

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

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

And:

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

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.**

==

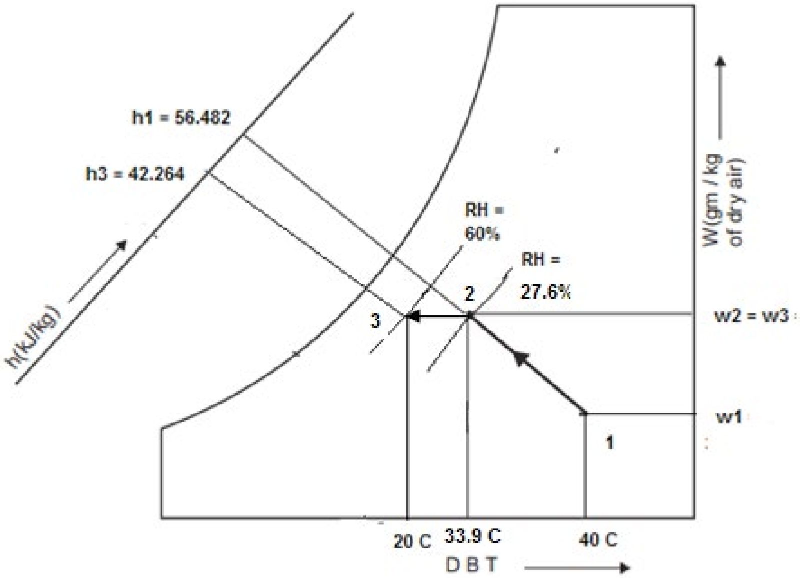
Prob.7.2.7 For a hall to be air conditioned, following conditions are given:

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 $R_a := 287$ J/kg.C

Calculations:

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

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

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:

$$p_a := P - p_{w1} \quad \text{i.e.} \quad p_a = 1.003 \times 10^5 \quad \text{Pa....partial pressure of air}$$

Therefore, mass flow rate of air:

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

Sp. humidity at 1:

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

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. $RH1 = 0.138$ **= 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.

$$\omega1(DBT, RH, P) := RH \cdot \frac{0.622 \cdot psatt(DBT)}{P - psatt(DBT) \cdot RH}$$ **..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. $h2 = 1.005 \cdot DBT2 + w2 \cdot (2500.9 + 1.82 \cdot DBT2)$

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:

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

i.e. $Q_{ton} = 33.859$ **tons of refrigeration ... Ans.**

==

Prob.7.2.8 We have one stream, 30 m^3/min of air at 15 C DBT and 13 C WBT mixed with 12 m^3/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]

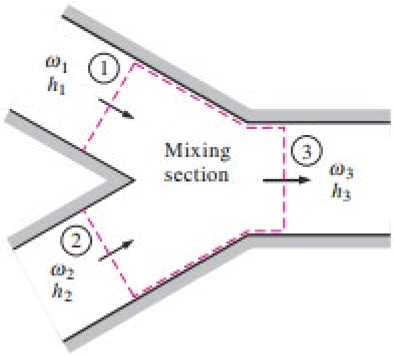


Fig.Prob.7.2.8 Adiabatic mixing of two streams

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 $R_a := 287$ J/kg.C

Calculations:

For stream 1:

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

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

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:

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

Sp. humidity at 1:

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

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:

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

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

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:

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

Sp. humidity at 2:

$w2 := \dfrac{0.622 \cdot p_{w2}}{P - p_{w2}}$ i.e. $w2 = 9.994 \times 10^{-3}$ 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:

$RH2 := \phi\left(p_{w2}, DBT2\right)$ 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: $m_{a1} \cdot h_1 + m_{a2} \cdot h_2 = m_{a3} \cdot h_3$

Then, we get:

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

Therefore: $$w3 := \frac{m_{a1} \cdot w1 + m_{a2} \cdot w2}{m_{a1} + m_{a2}}$$

i.e. $w3 = 8.914 \times 10^{-3}$ **kg/kg... sp. humidity of mixture....Ans.**

And, enthalpy of mixture is given by::

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

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

To find T3, the DBT of the mixture stream:

We have: $pw3 := p_w(w3, P)$ ...partial pressure of vapor at 3

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

Now, enthalpy of mixture is also given by:

$$h3 = 1.005 \cdot T3 + w3 \cdot (2500.9 + 1.82 \cdot T3) \quad \text{kJ/kg dry air}$$

Therefore:

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

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

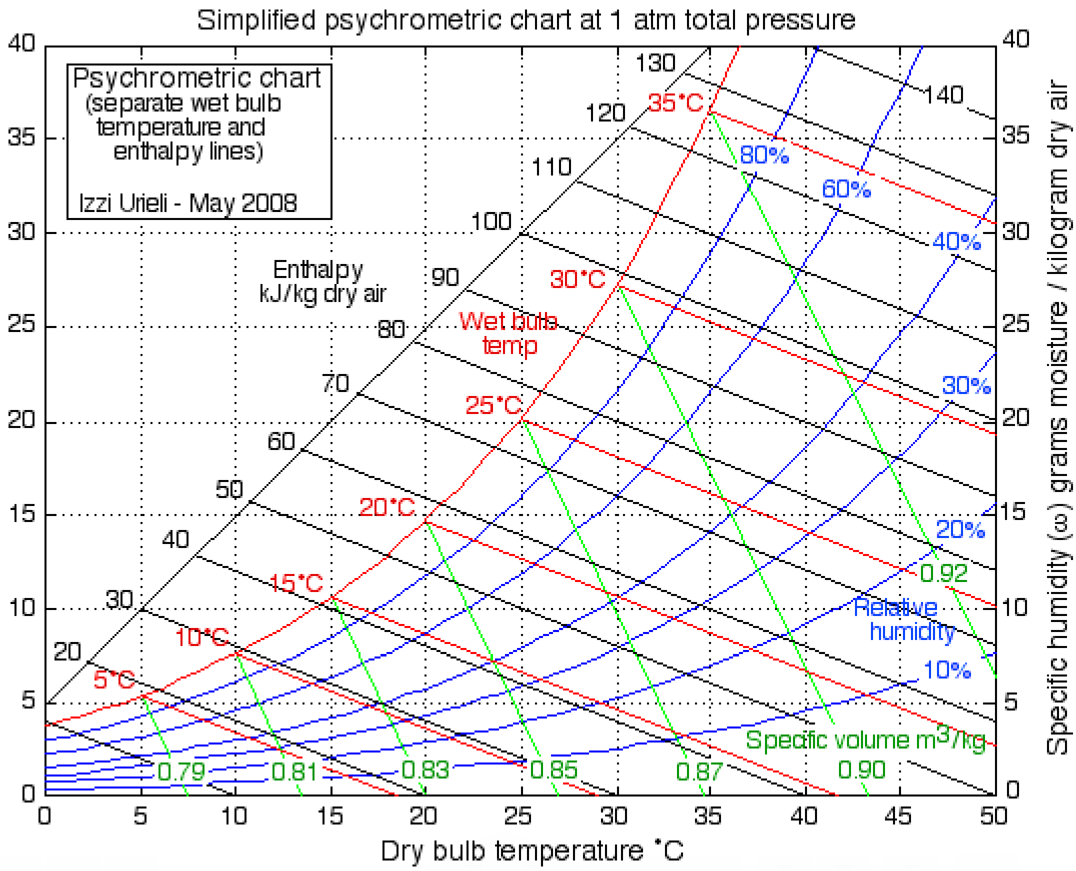
==

7.3 Problems solved with Psychrometric chart:

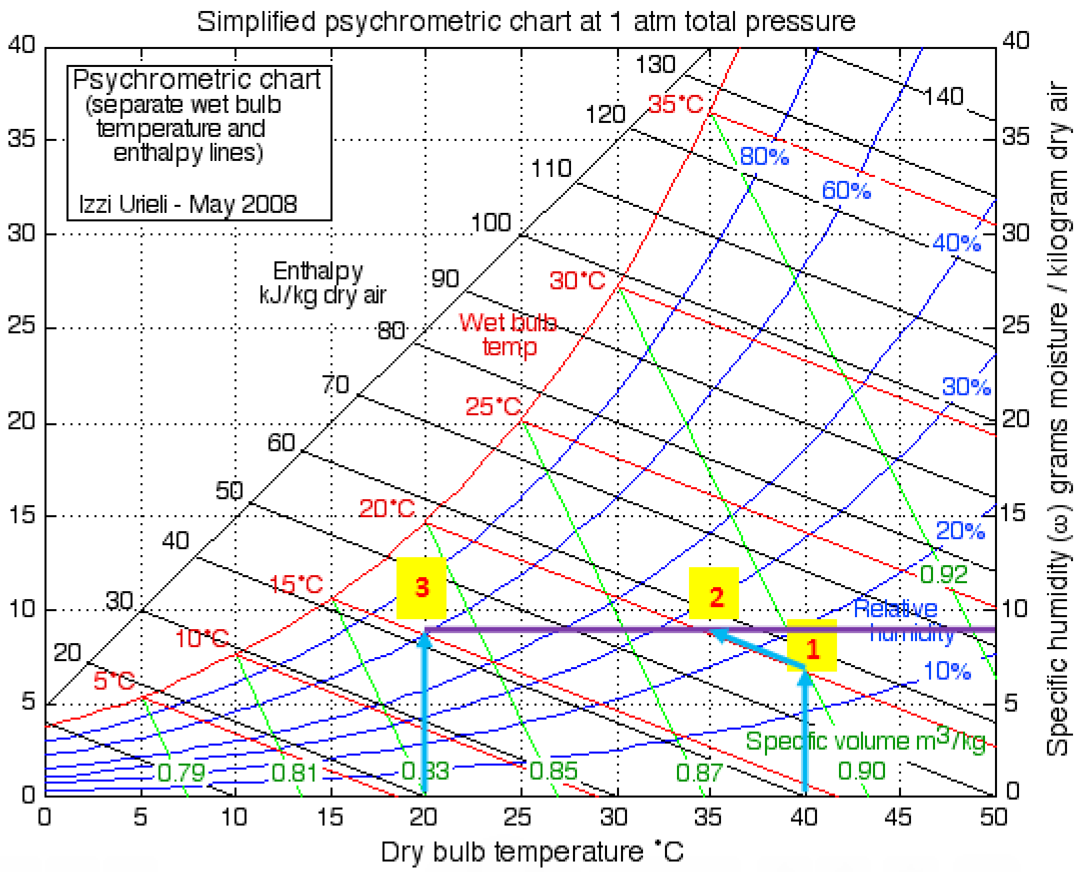
Prob.7.3.1 Solve the above problem (i.e. problem 7.2.7) with Psychrometric chart:

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.

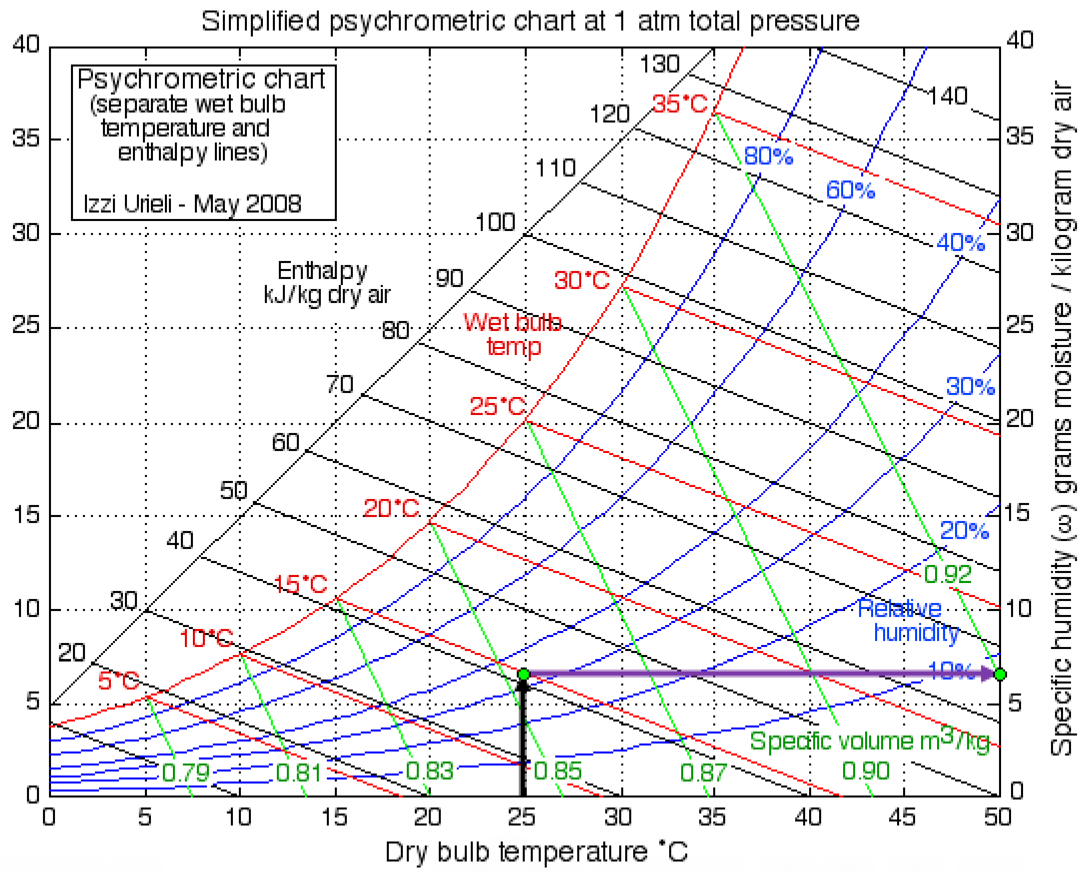
==

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 m^3/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

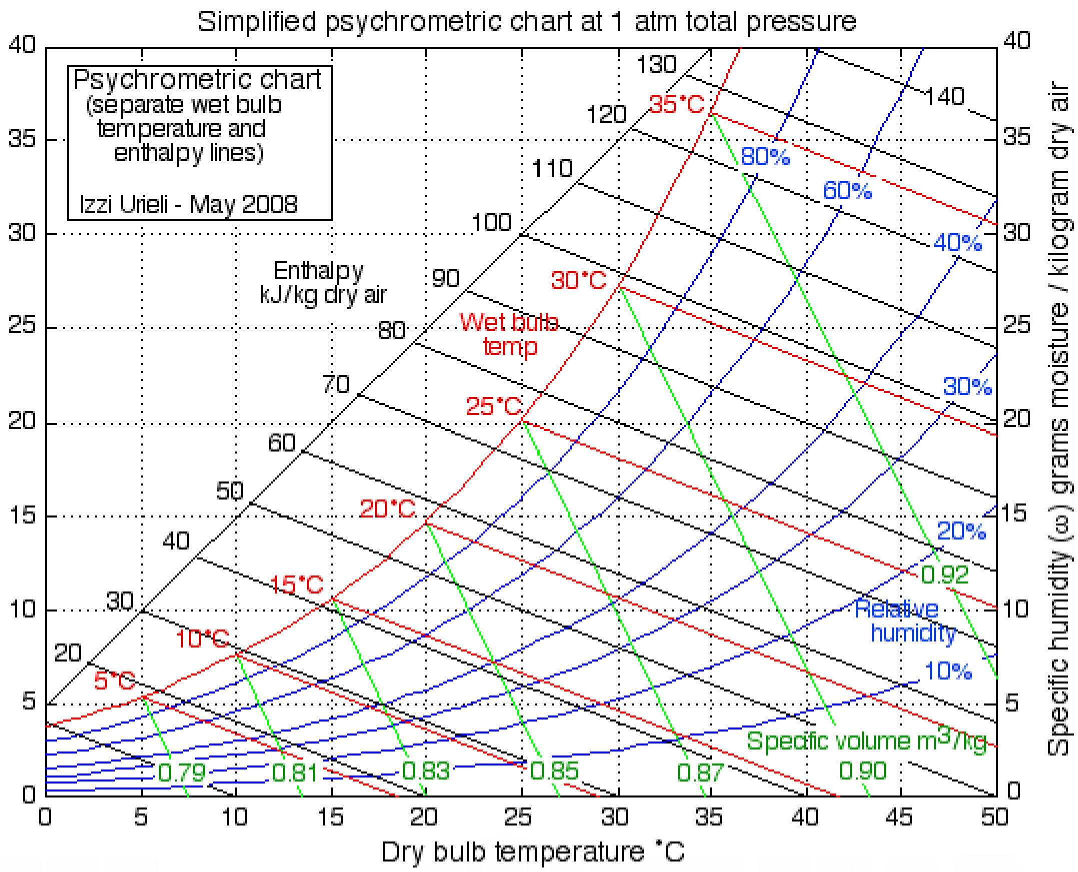
The required condition is achieved first by cooling and dehumidification and then by heating. Estimate: (i) capacity of cooling coil in Tons of refrigeration (ii) capacity of heating coil in kW (iii) amount of water vapor removed in kg/h. [VTU]

Solution:

This problem is solved very conveniently with Psychrometric chart:

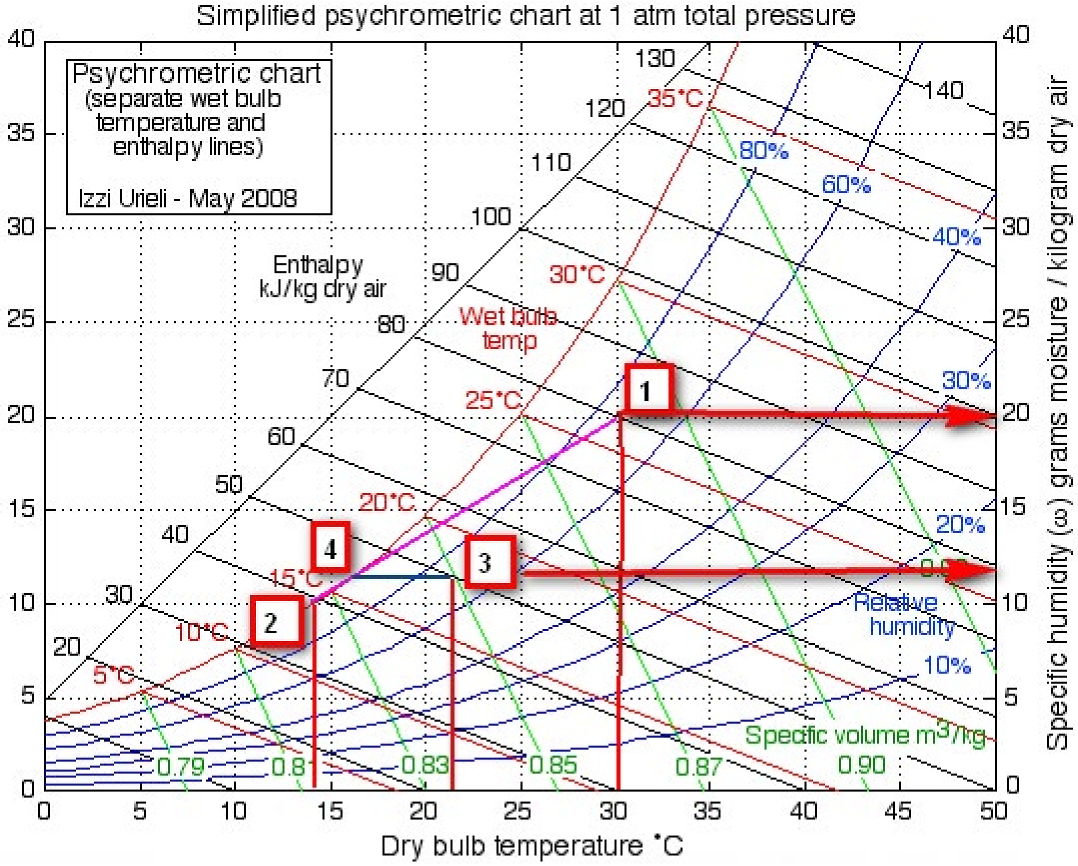
Following are the steps:

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.

===

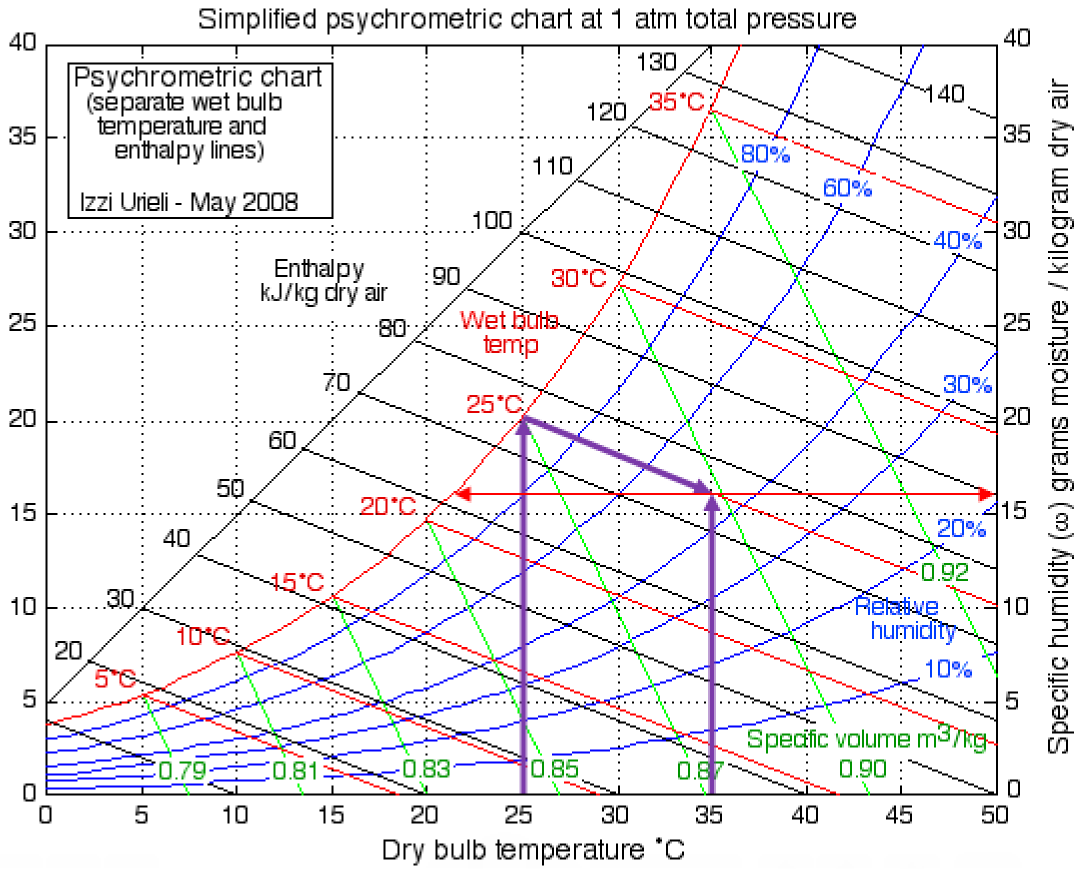
Prob.7.3.4 A mixture of air and water vapor enters an adiabatic saturator at 35 C and leaves at 25 C at 1 atm pressure. Determine: (i) sp. humidity (ii) RH, and (iii) dew point of the entering air. [VTU]

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.
2. 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.

==

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^3/min is mixed adiabatically with the outside air at 32 C DBT and 60% RH at a rate of 20 m^3/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:

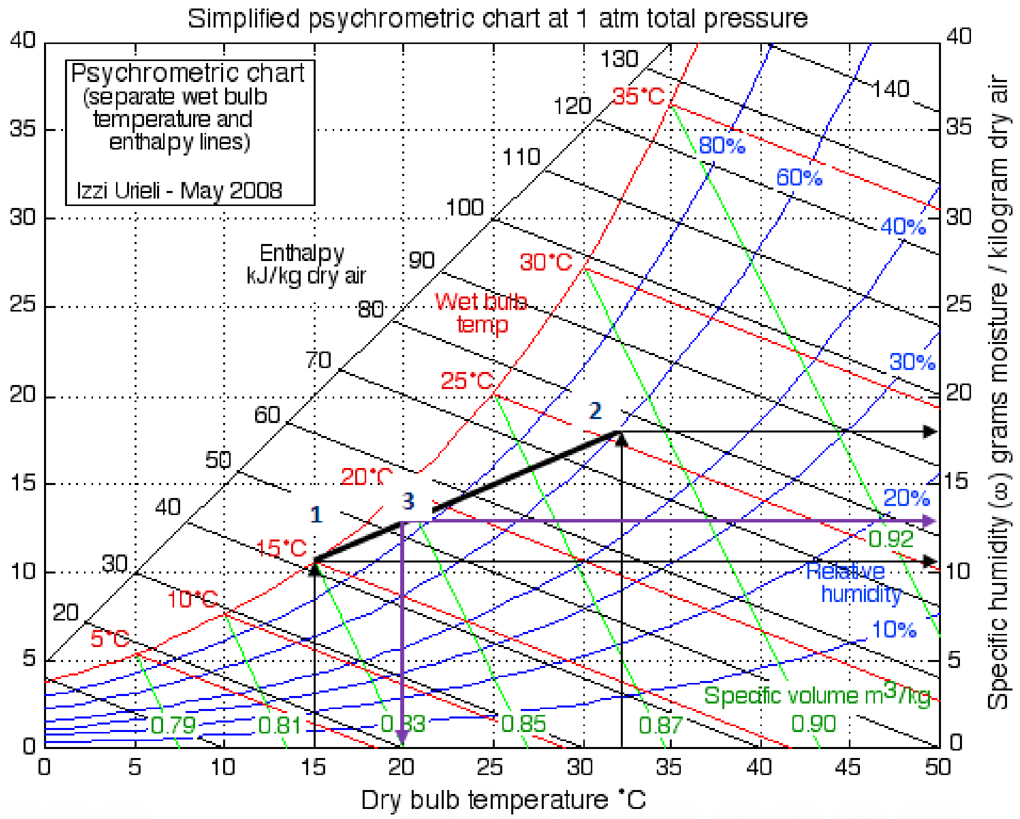
From the chart:

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 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 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.

===

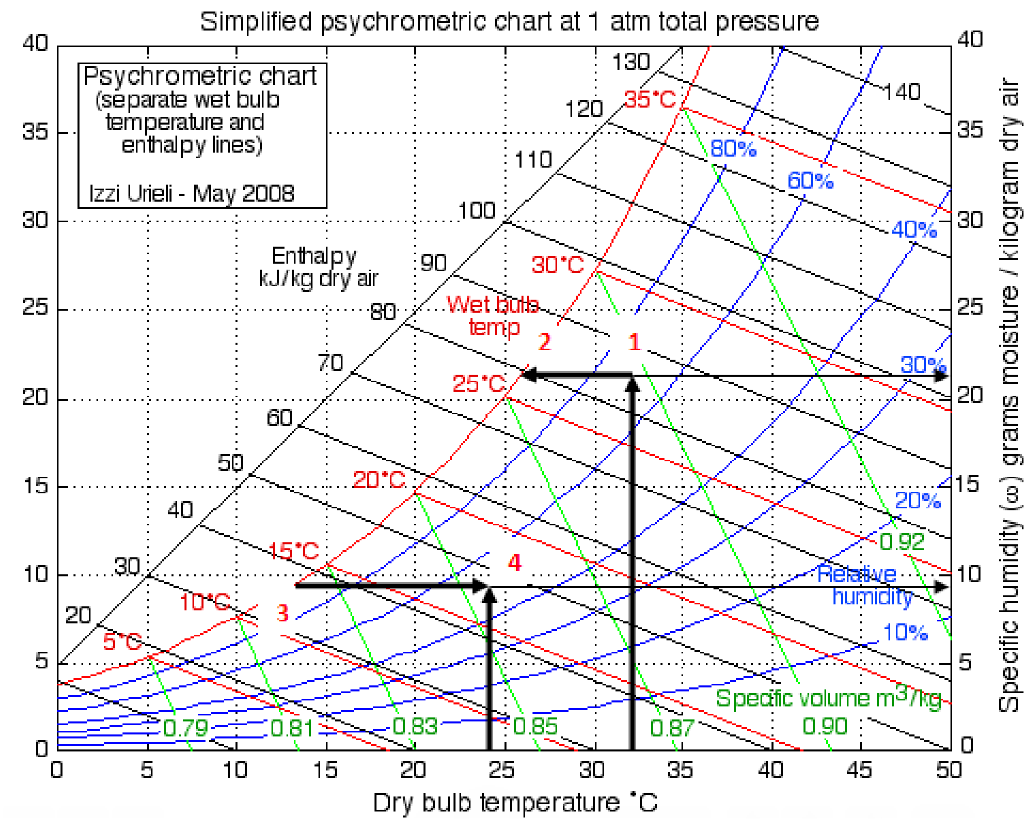
Prob.7.3.6 Air enters at 32 C and RH of 70% in a summer air conditioning system where the air is cooled and then dehumidified. The air leaving the cooling coil is saturated at the coil temp. It is then heated to comfort condition of 24 C and 50% RH. Sketch the flow diagram of the system and represent 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, and (iv) 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 … 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 kJ/kg dry air …. Ans.

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

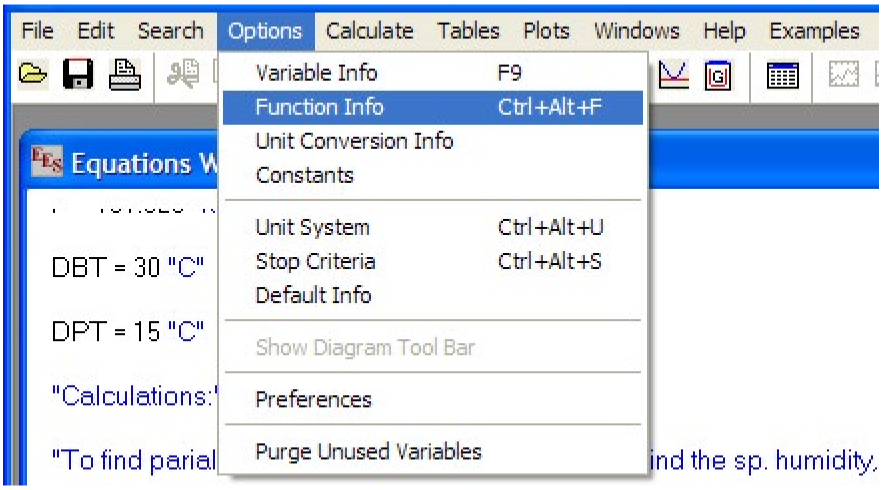
==

7.4 Problems solved with EES:

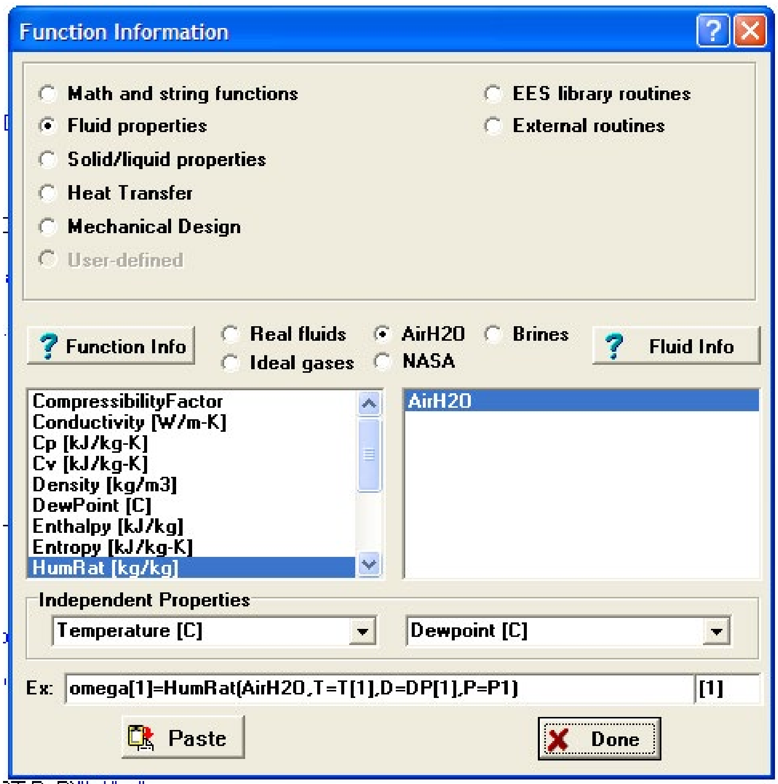
Note 1: EES has built-in Functions for Psychrometric properties. *This makes it very convenient to make Psychrometric calculations with EES.*

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

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



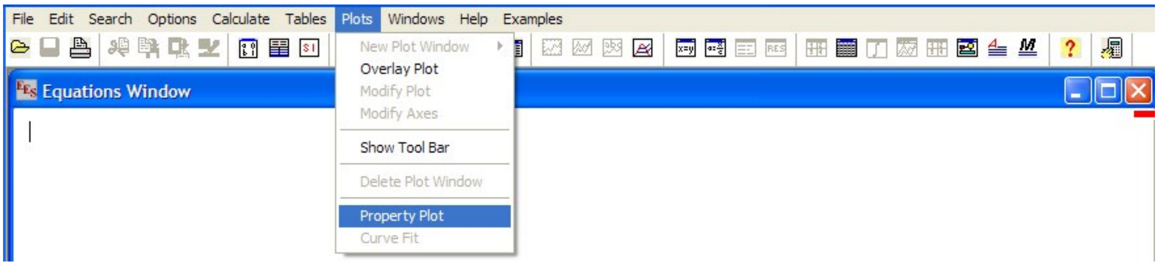
2. Clicking on Function Info gives following window. Here you choose Fluid Properties and AirH2O radio buttons as shown:



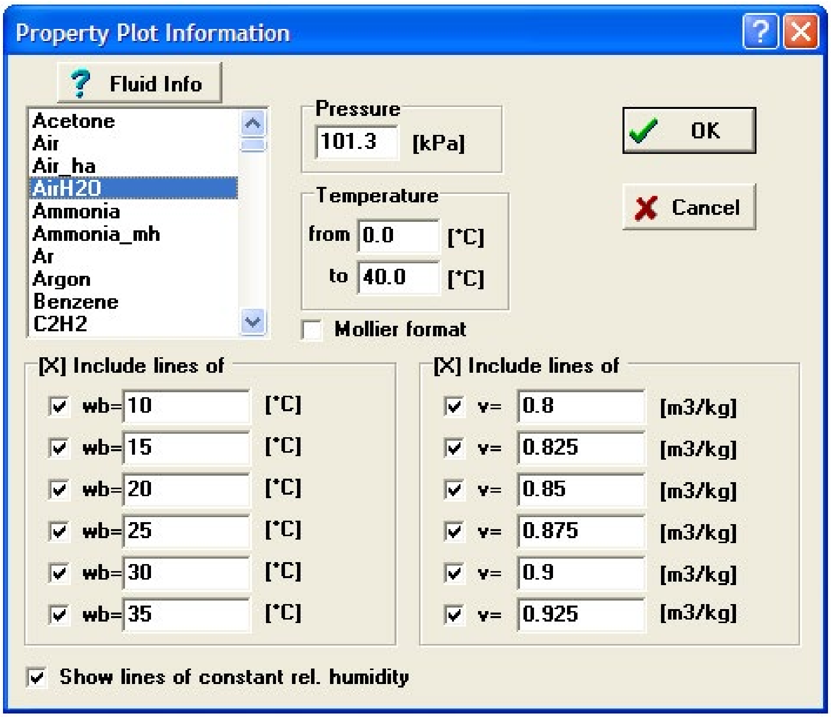
Now, all Psychrometric Functions are available for use in calculations.

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

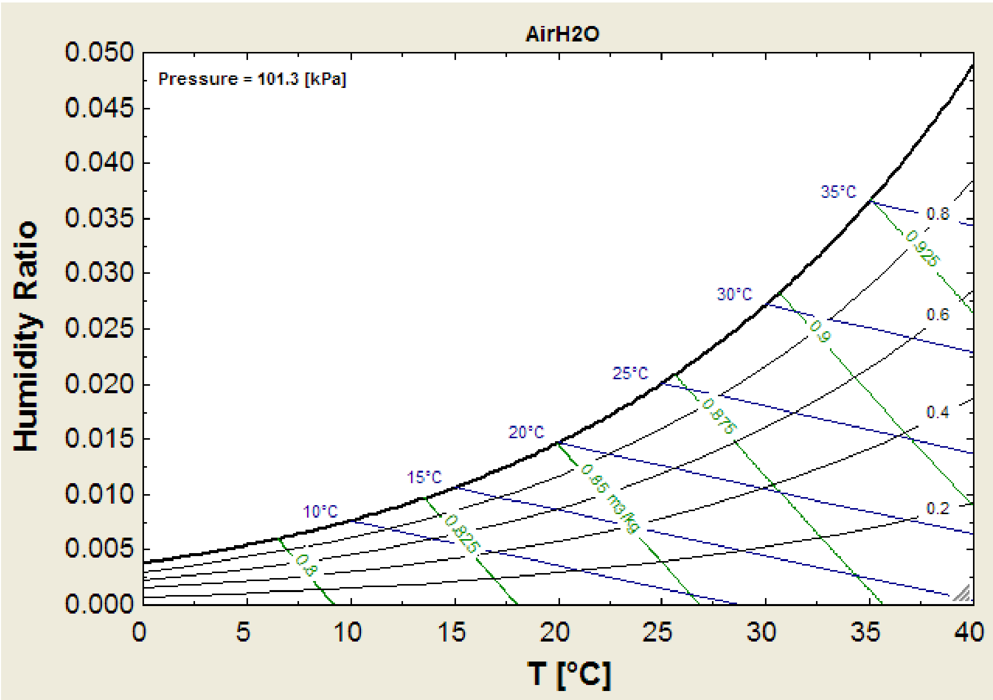
Go to Plots Menu and choose 'Property Plots':



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



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]	DPT = 15 [C]	h = 57.42 [kJ/kg]
ω = 0.01065 [kg/kg]	P = 101.3 [kPa]	p_a = 99.62 [kPa]
p_w = 1.705 [kPa]	rh = 0.4017 [-]	ρ_w = 0.01219 [kg/m^3]
R_w = 0.4619 [kJ/kg-K]		

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 kg/m^3 … Ans.

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

==

$UnitSystem SI kg kPa C

"**Prob.7.4.2** A room measures 5m x 5m x 3 m. 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_a = 85.15 [kg]	m_w = 0.6826 [kg]
ω = 0.008025 [kg/kg]	P = 100 [kPa]	p_a = 98.73 [kPa]
p_w = 1.274 [kPa]	RH = 0.3 [-]	R_a = 0.287 [kJ/kg-K]
R_w = 0.4619 [kJ/kg-K]	Vol = 75 [m^3]	

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, and (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]

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"

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

$moisture_{removed}$ = 0.01184 [kg/kg] $q_{coolingcoil}$ = 49.83 [kJ/kg]

$q_{heatingcoil}$ = 11.32 [kJ/kg]

Thus:

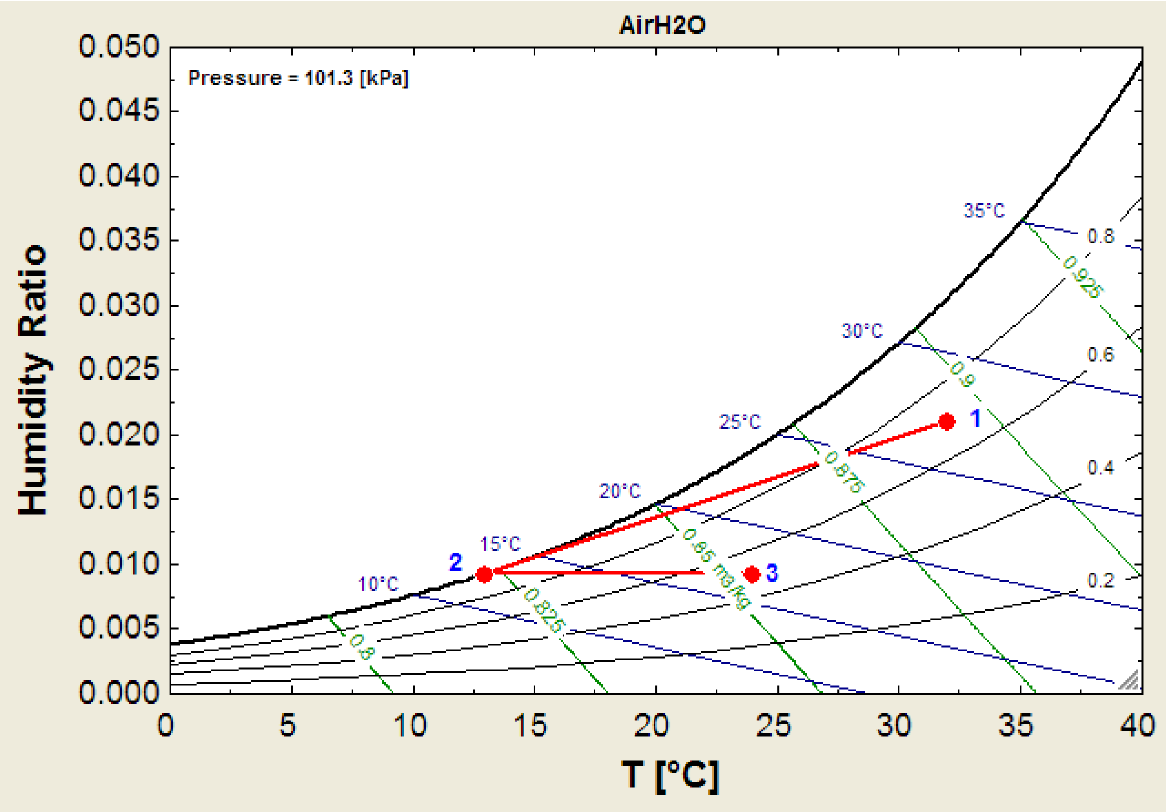
Moisture removed in cooling coils = 0.01184 kg/kg dry air …. Ans.

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.

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]

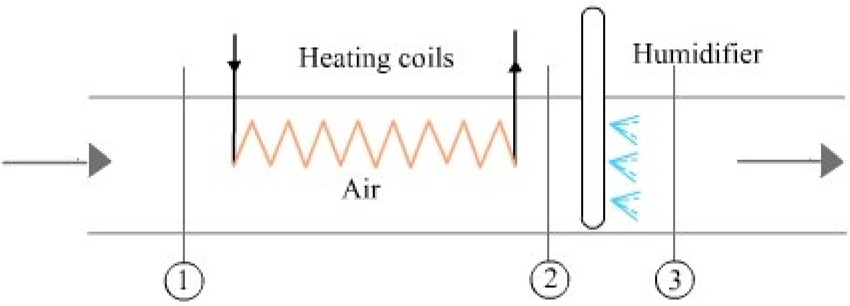


Fig.Prob.7.4.4. Heating and humidifying

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"

Results:

Unit Settings: SI C kPa kJ mass deg

BF = 0.4

P1 = 101.3 [kPa]

Vol = 18 [m^3]

m_a = 21.92 [kg]

$Q_{heating}$ = 4.778 [kW]

$m_{w,humidifier}$ = 3.613 [kg/h]

T_{heater} = 35.42 [C]

Thus:

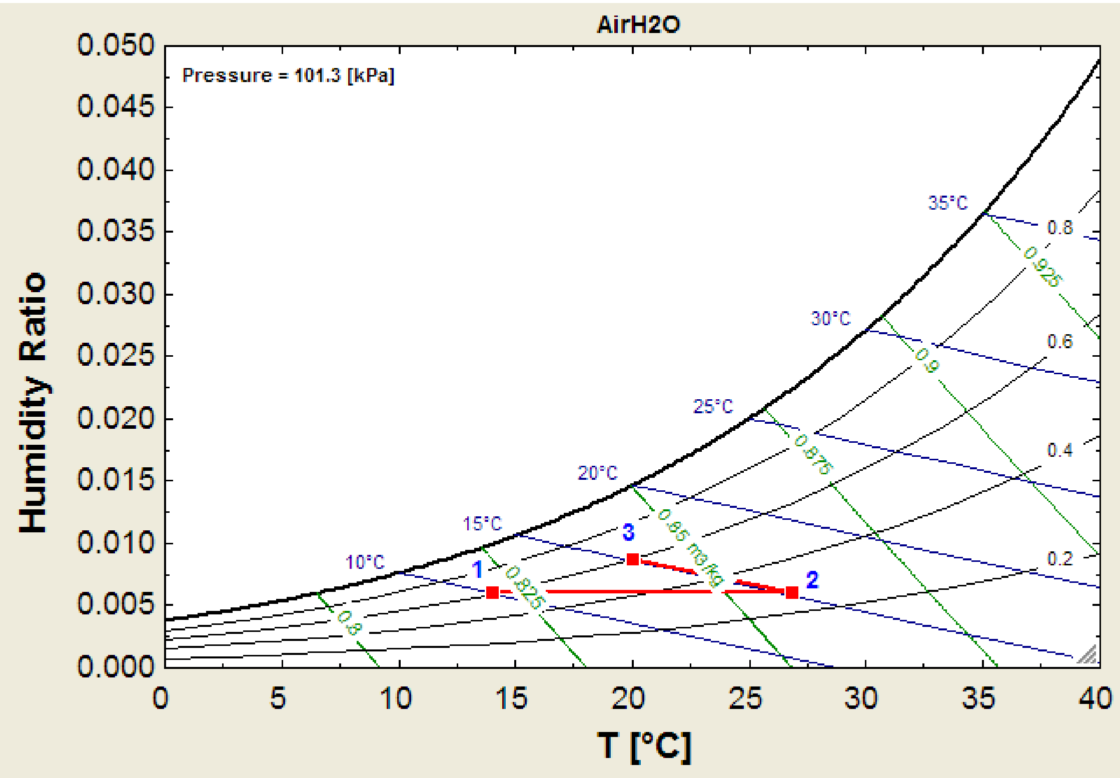
Heating capacity of heater coils = Q_heating = 4.778 kW …. Ans.

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:



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"**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^3 of air at room conditions. Assume that the total pressure is 1.013 bar. [VTU]"

EES Solution:

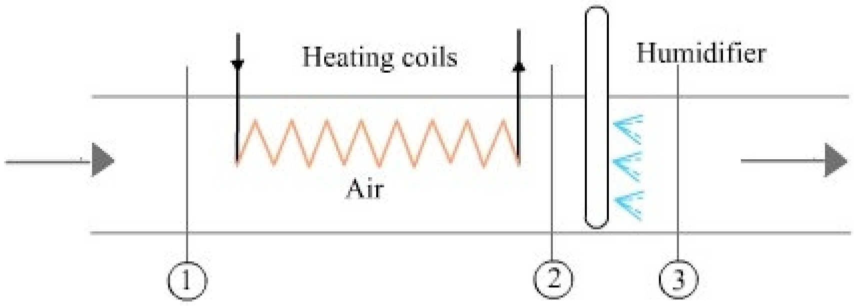


Fig.Prob.7.4.5 Heating and humidification

"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 = (omega[3] – omega[2]) / v[3] "kg per m^3 of air at room conditions"

Results:

Unit Settings: SI C kPa kJ mass deg

m_w = 0.003455 [kg/m^3·of·room·air]	P1 = 101.3 [kPa]

And:

Arrays Table

Sort	ω_i [kg/kg]	rh_i	T_i [C]	h_i [kJ/kg]	v_i [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

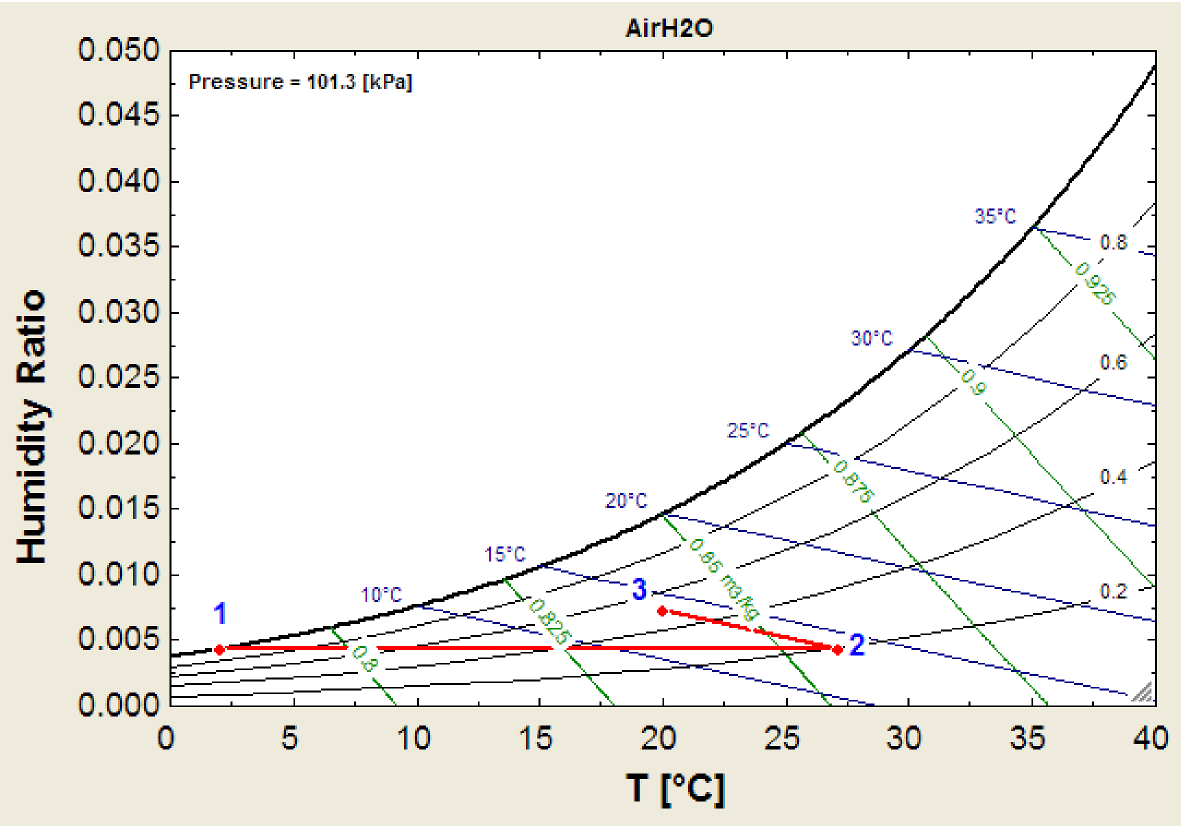
Thus:

Temp to which air is heated = T[2] = 27.14 C …. Ans.

Mass of air condensed per m^3 of room air = m_w = 0.003455 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.

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



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"**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]"

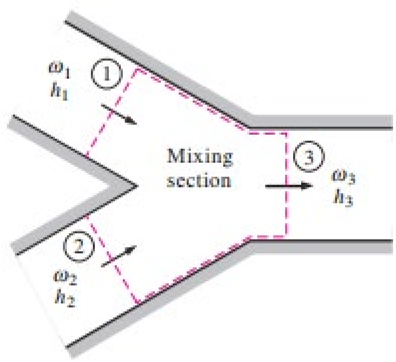


Fig.Prob.7.4.6 Adiabatic mixing of two air streams

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)"…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* omega[1] + m_a2 * omega[2] = m_a3 * omega[3]"…finds omega[3]"

"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:

Unit Settings: SI C kPa kJ mass deg

m_{a1} = 183.4 [kg/min] m_{a2} = 491.6 [kg/min] m_{a3} = 675 [kg/min]   P1 = 101.3 [kPa]

And:

Arrays Table

Main

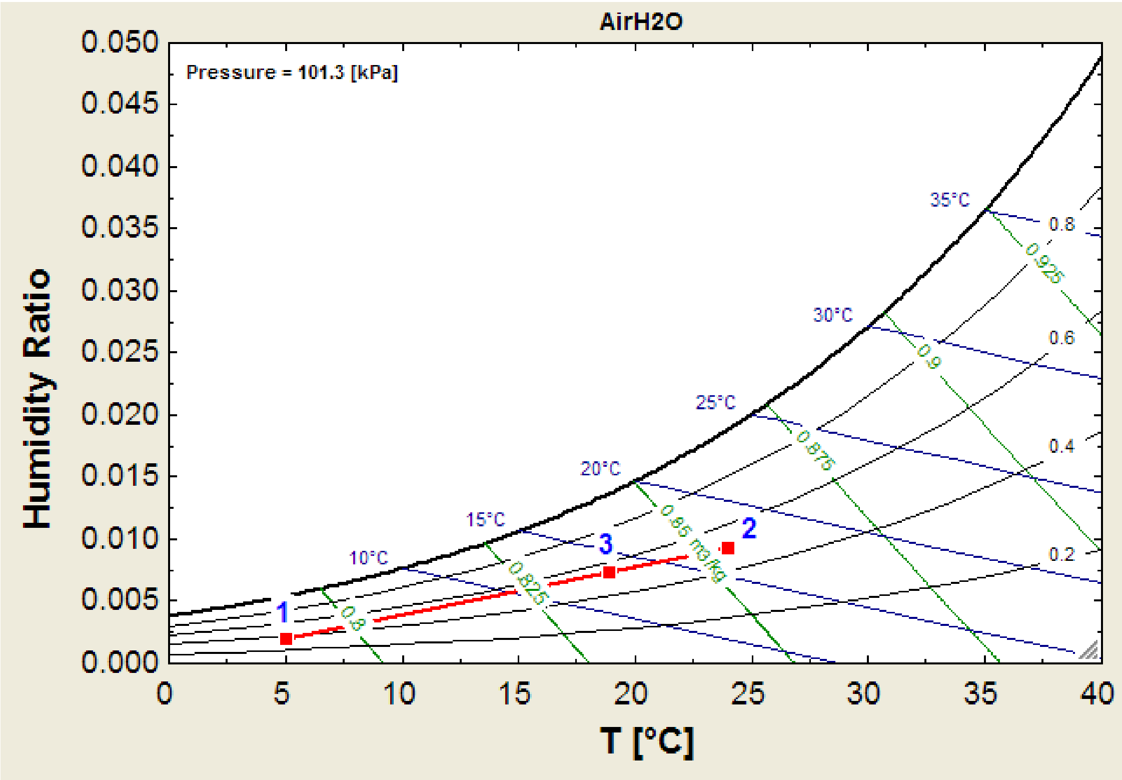
Sort	1 ω_i [kg/kg]	2 rh_i	3 T_i [C]	4 h_i [kJ/kg]	5 v_i [m3/kg]
[1]	0.002		5	10.05	0.7905
[2]	0.009299	0.5	24	47.83	0.8543
[3]	0.007316		18.89	37.56	

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:

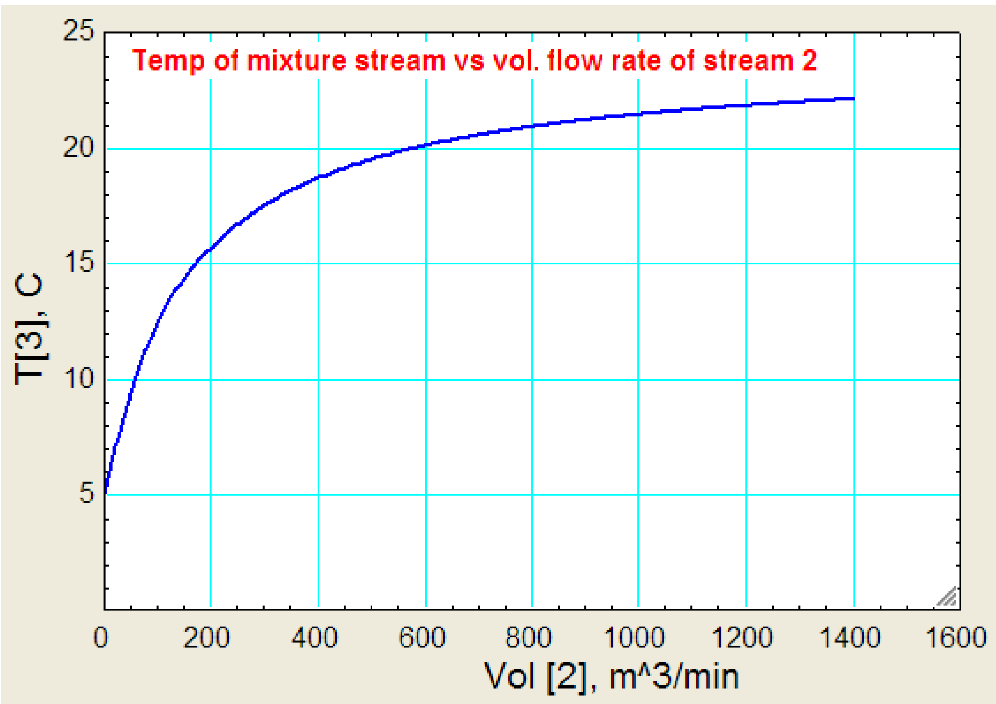


(b) Plot the exit temp T[3] vs volume flow rate of stream 2, ranging from 0 to 1400 m^3/min:

First, compute the Parametric Table:

1..15	Vol_2 [m3/min]	T_3 [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:



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"**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]"

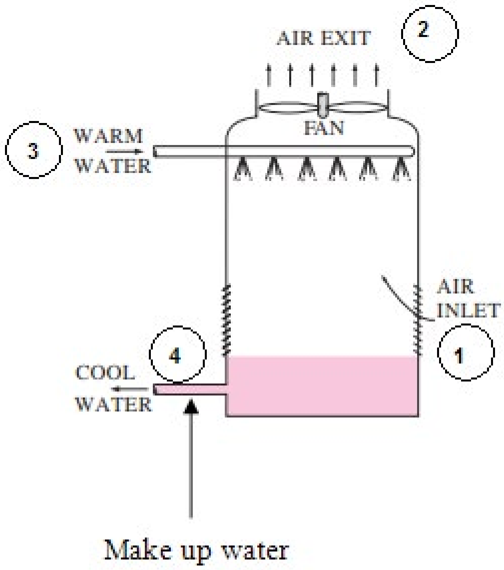


Fig.Prob.7.4.7 Wet cooling tower

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"

"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"m^3/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_3 = 40 [kg/s]	mw_4 = 39.43 [kg/s]
mw_{makeup} = 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]	v1 = 0.848 [m^3/kg]	$Vol1_{air}$ = 23.91 [m^3/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 m^3/s … Ans.

===

7.5 Problems solved with TEST:

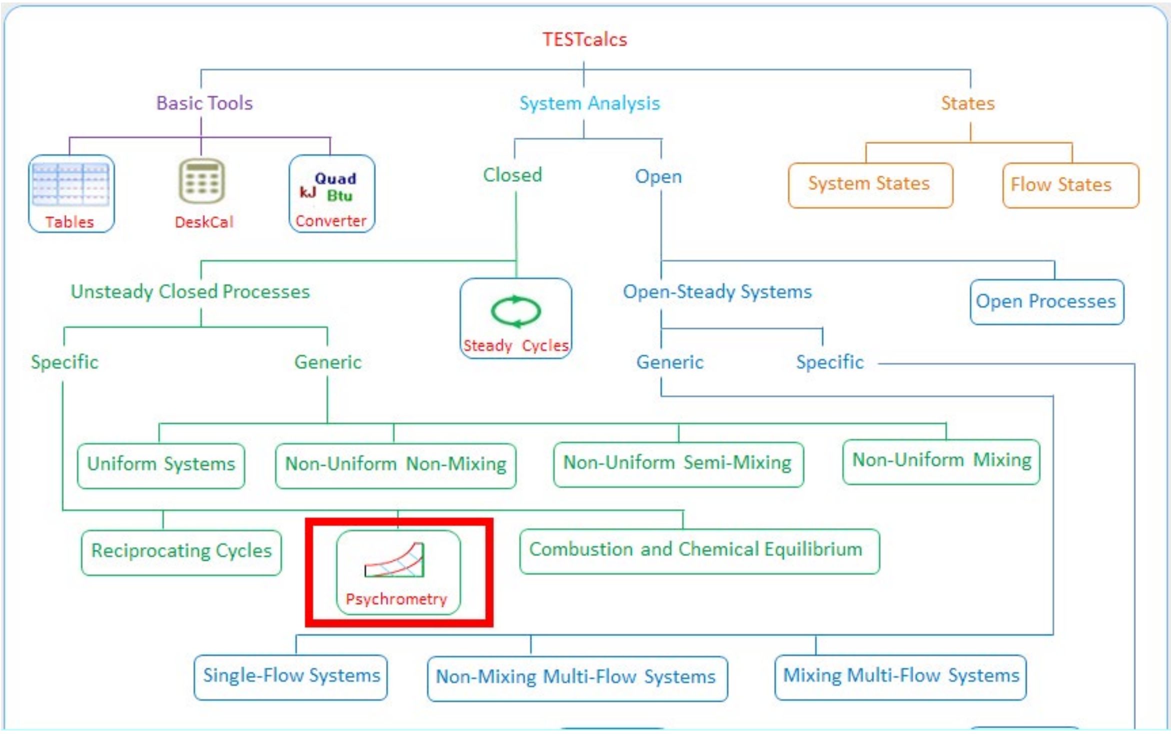
Note: It is extremely easy and convenient to solve Psychrometric problems in TEST.

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]

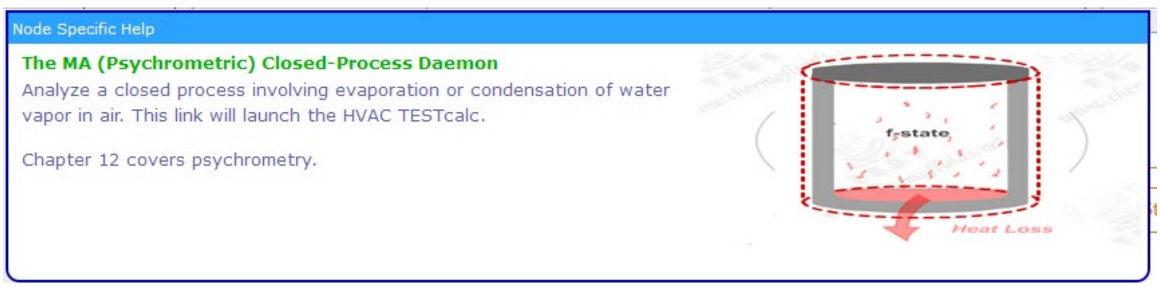
TEST Solution:

Following are the steps:

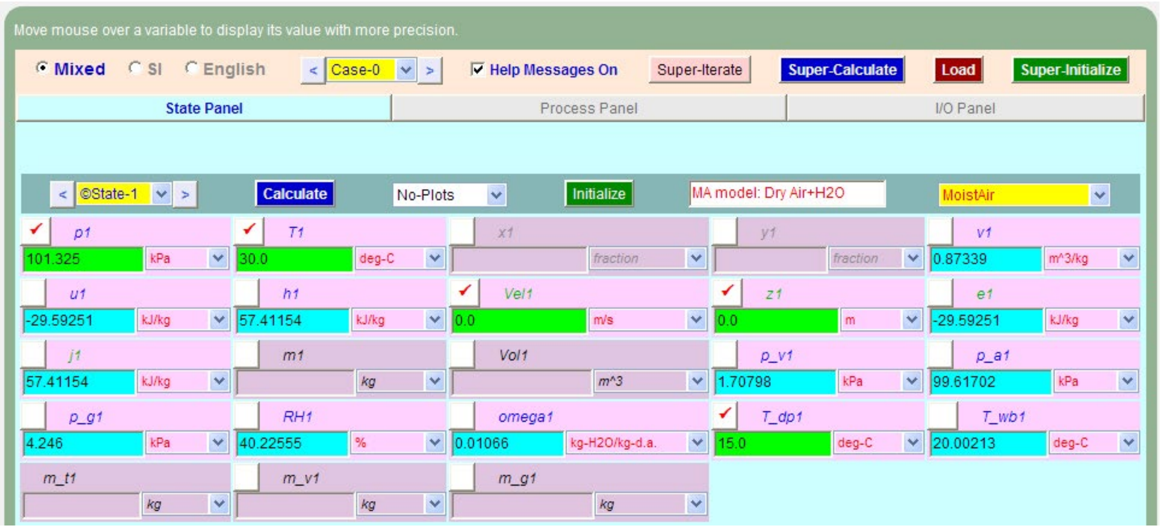
1. After logging in to TEST (www.thermofluids.net), go to the 'TESTCalcs tree', and choose the **System Analysis-Closed-Psychrometry** as shown below:



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:



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 kJ/kg …. 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 kg/m^3 … 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 ----------------------------------

#
```

#----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	303.2	293.2	288.2	0.8734	0.4	57.4	0.0107

==

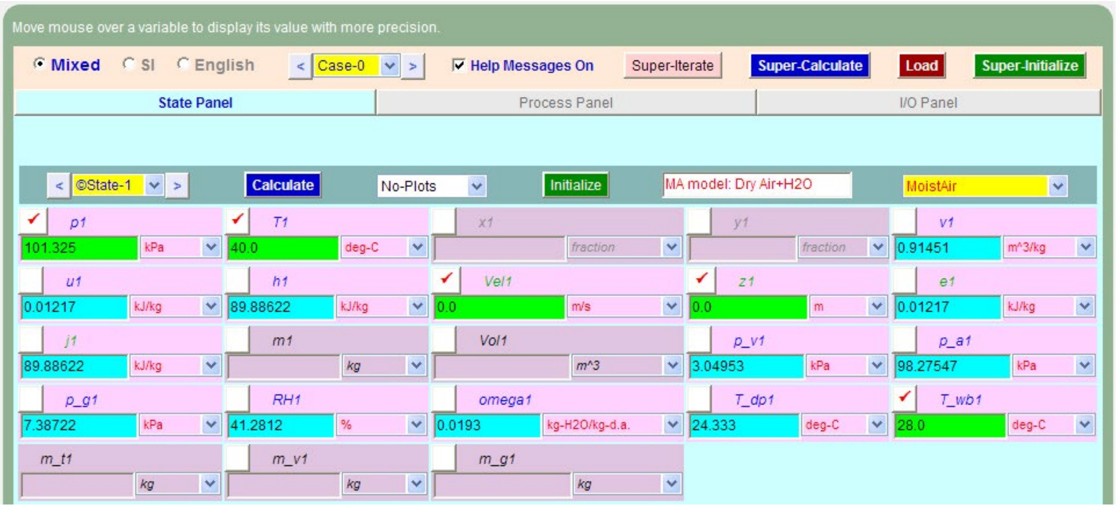
Prob. 7.5.2 A sling psychrometer reads 40 C DBT and 28 C WBT. Find the following: (i) sp. humidity, (ii) RH, (iii) Dew point temp,and (iv) Vapor density. [VTU]

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:



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:

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 kg/m^3 … 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;
```

#––––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	301.2	297.5	0.9145	0.41	89.9	0.0193

==

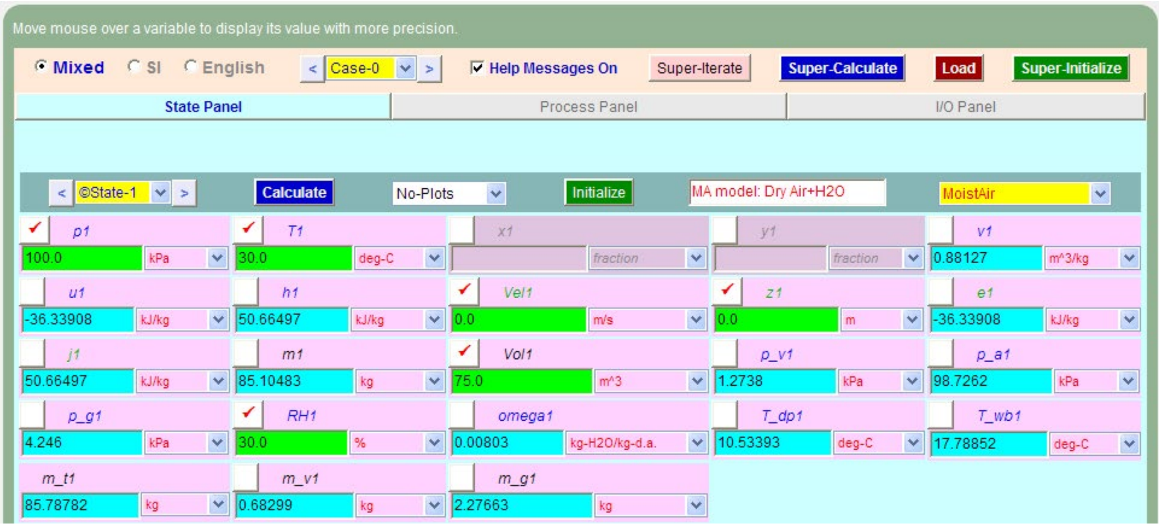
Prob.7.5.3 A room measures 5m × 5m × 3m. It contains atmospheric air at 100 kPa, DBT = 30 C, RH = 30%. Find the mass of dry air and the mass of associated water vapor in the room. [VTU]

TEST Solution:

Following are the steps:

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

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:



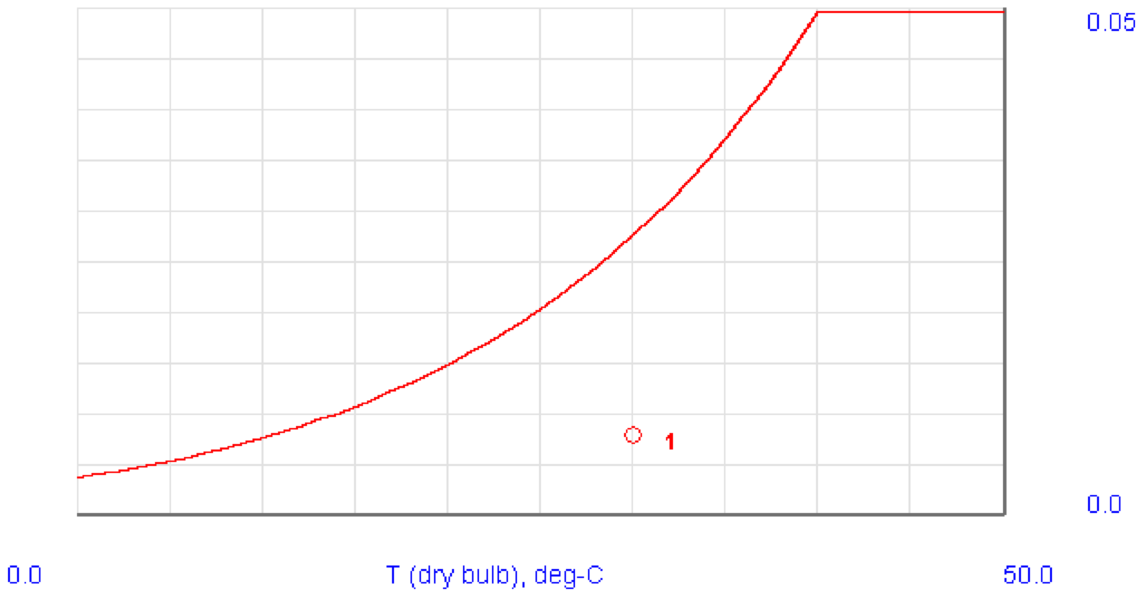
Thus:

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

Mass of water vapor = m_v1 = 0.68299 kg … 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:



6. Click on SuperCalculate and see the TEST code etc in the I/O panel:

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

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

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

States {

State-1: MoistAir;

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 %; }

}

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

```
#******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(K)	WBT(K)	DPT(K)	v(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

==

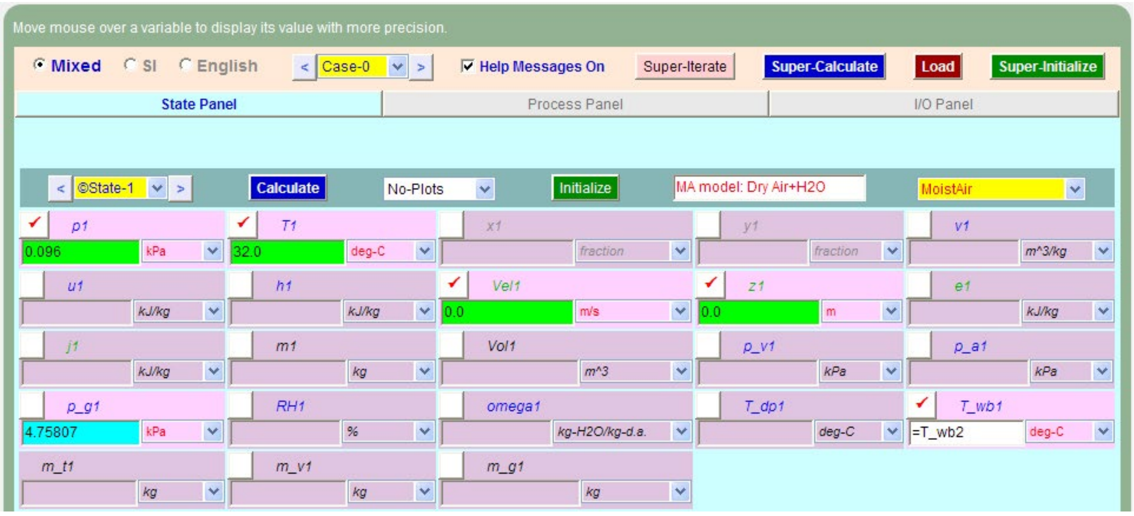
Prob.7.5.4 As a result of adiabatic saturation of moist air in a steady flow device at a constant pressure of 96 N/m^2, the temp of moist air at initial condition from 32 C is reduced to 22 C at sat. condition. Calculate the RH of moist air at the initial condition.[VTU]

TEST Solution:

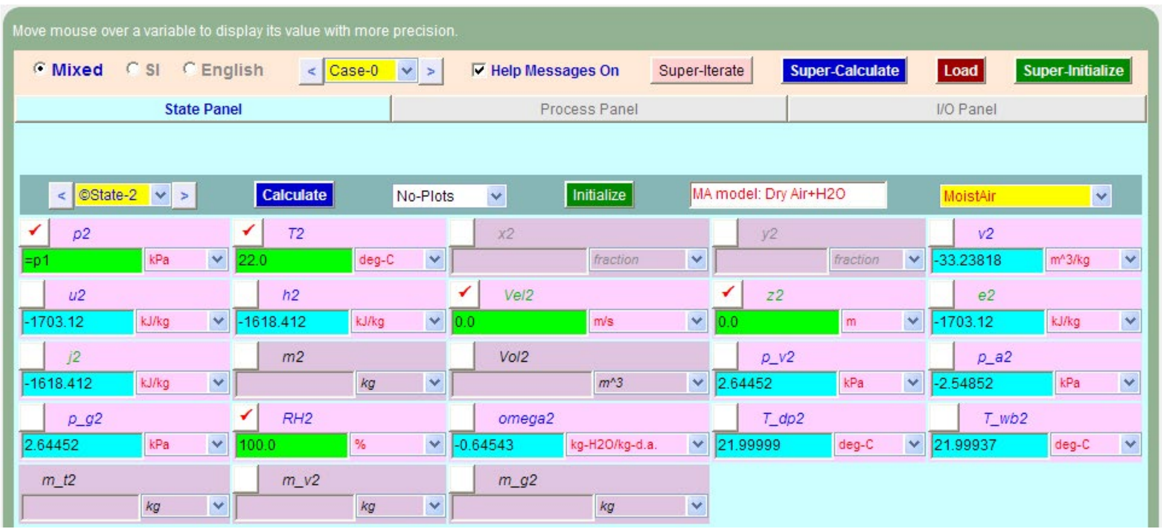
Following are the steps:

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

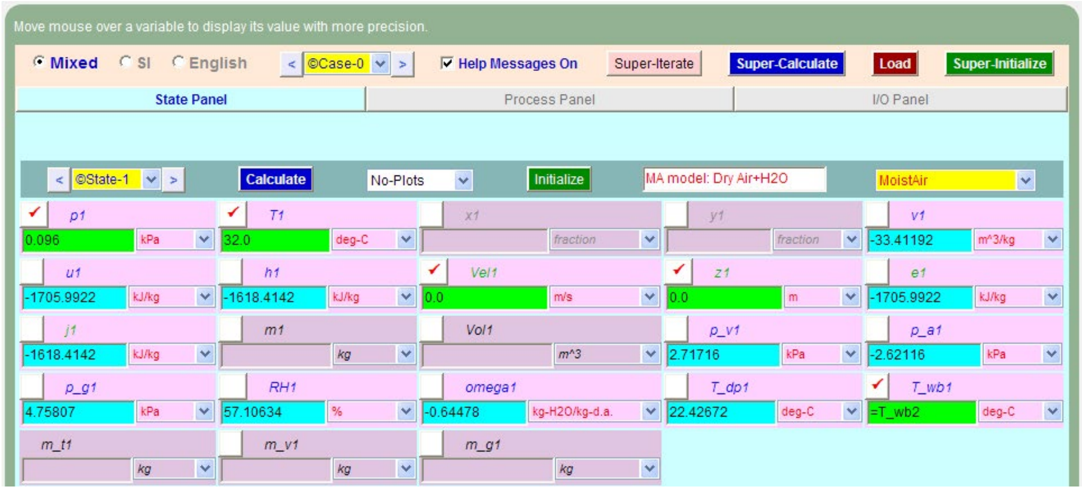
3. Fill up the given parameters i.e. p = 0.096 kPa, DBT = 32 C and Wet bulb temp,T_wb1 = T_wb2 (yet to be determined) in the following screen and hit Enter. We get:



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



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:



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.

==

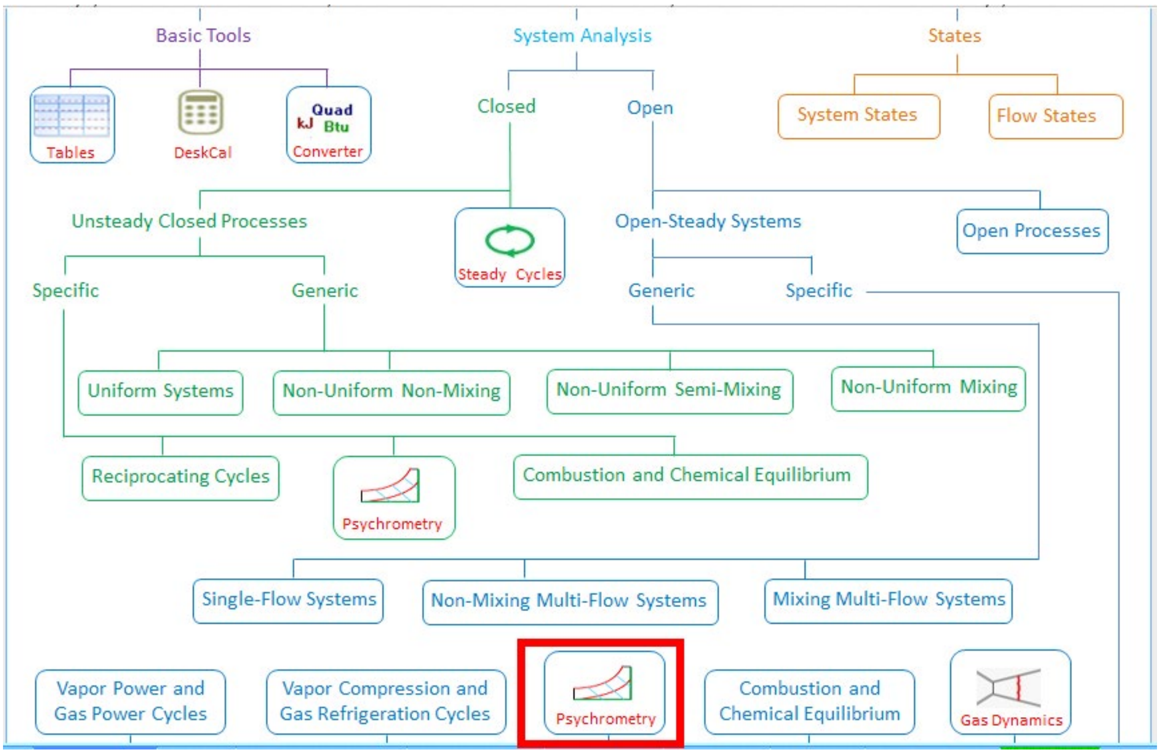
Prob.7.5.5 Moist air enters a humidifier-heater unit at 26 C and 80% RH. It is to leave at 26 C and 50% RH. For a flow rate of 0.47 m^3/s, find the refrigeration in tons and the heating required in kW. [VTU]

TEST Solution:

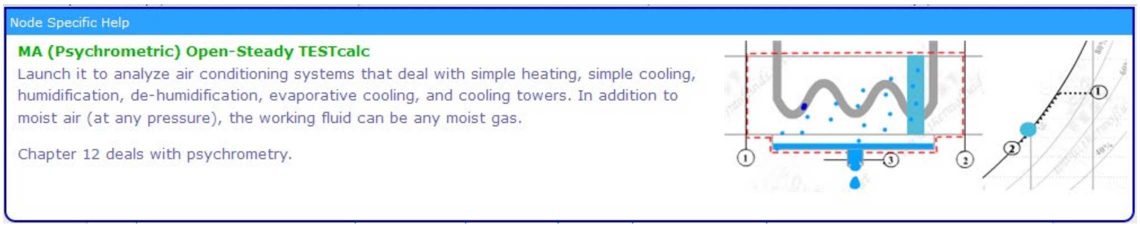
First, the air is cooled at const. sp. humidity to reduce the RH to 50% (process 1-3), and then heated at const. sp. humidity to 26 C.(process 3-2)

Following are the steps:

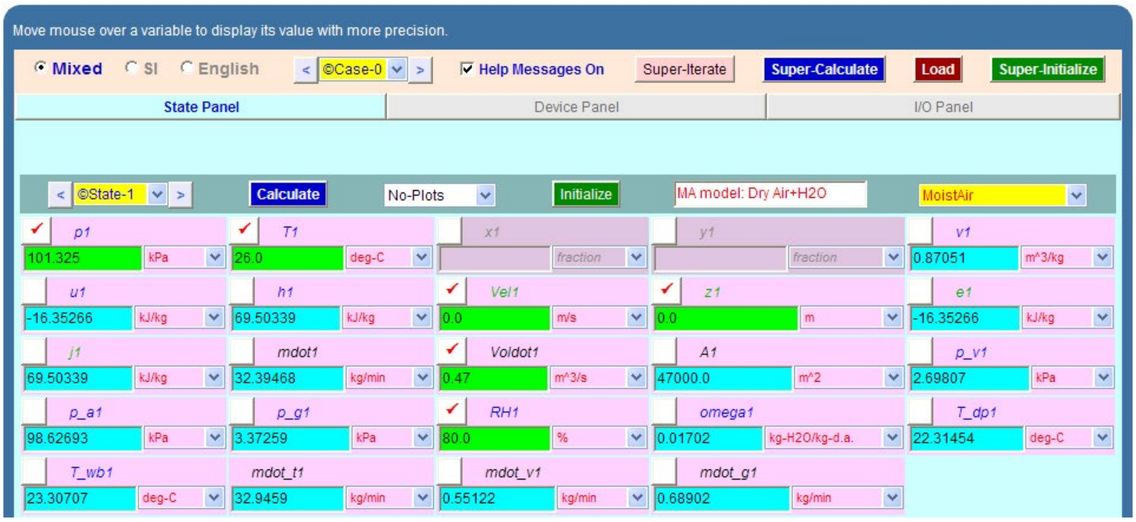
1. From the TESTCalcs tree, choose Open System-Psychrometry:



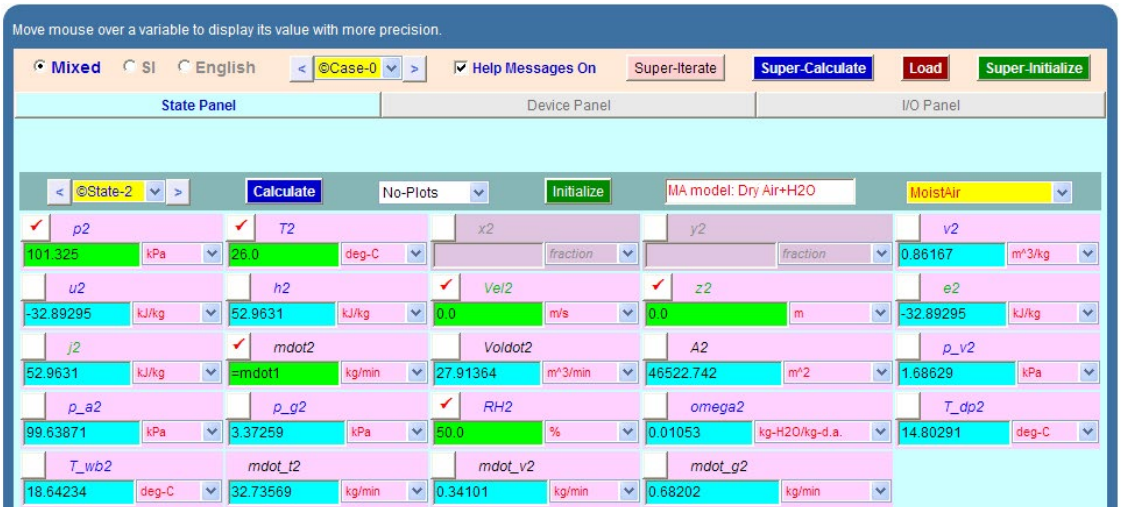
2. Hovering the mouse pointer over Psychrometry gives following explanatory pop-up:



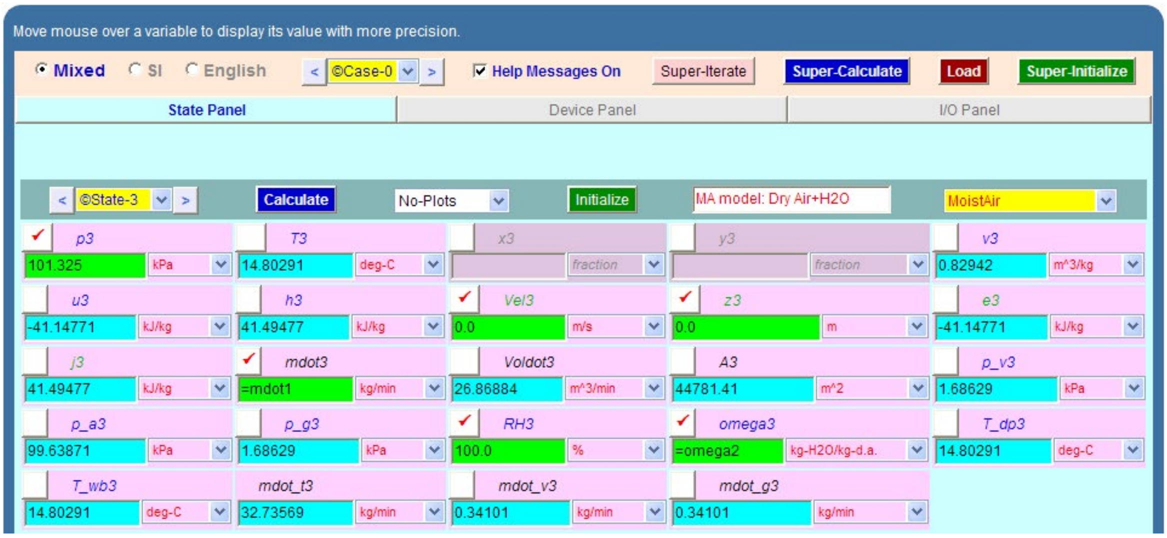
3. Click on Psychrometry, and we get the following window with moist air as default material. Fill up the data for state 1, i.e. T1 = 26 C, Voldot1 = 0.47 m^3/s, RH1 = 80%, and hit Enter. We get:



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:



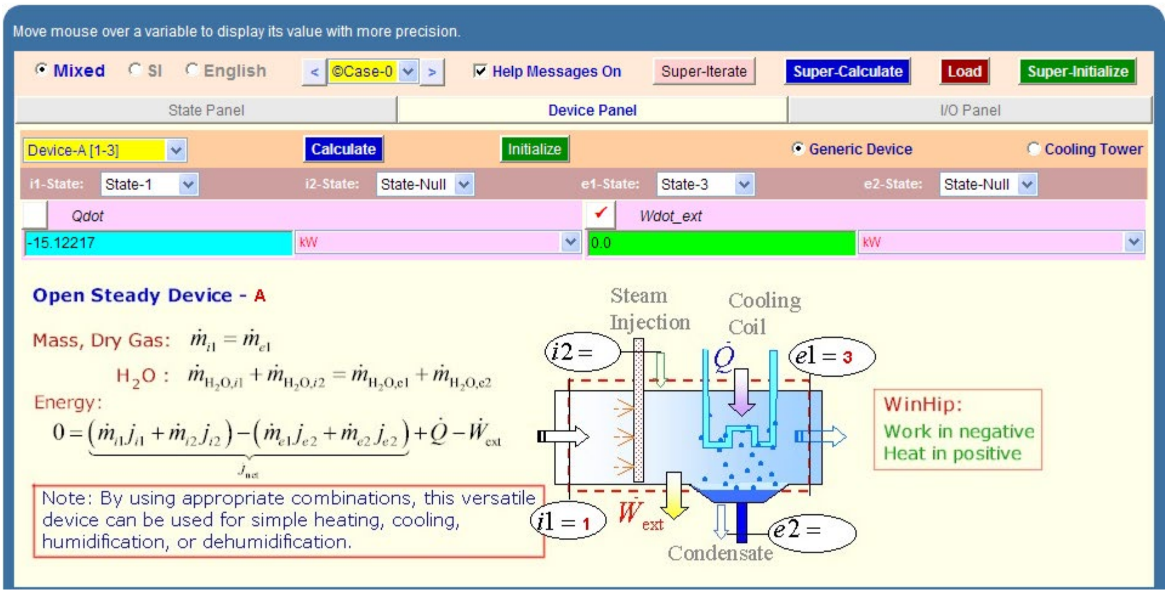
5. Go to State 3, i.e. state after cooling. Fill up omega3 = omega2 (since the sp. humidity, omega remains const. during heating), mdot3 = mdot1, RH3 = 100%, since condensation has occurred. Hit Enter, and we get:



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

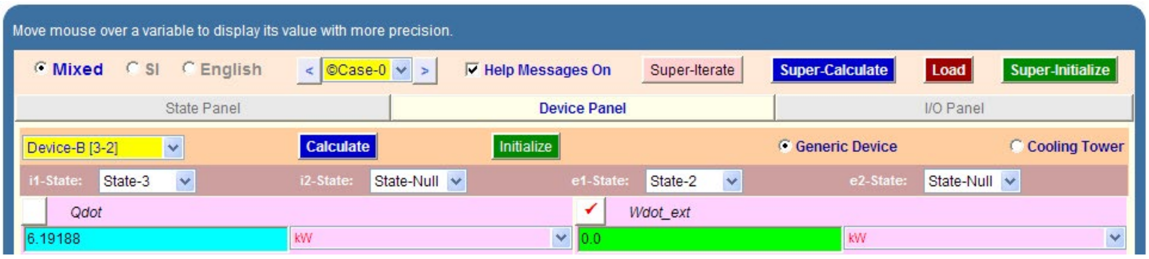
Amount of water vapor removed = (mdot_v1 – mdot_v3) = 0.21021 kg/min. … Ans.

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:



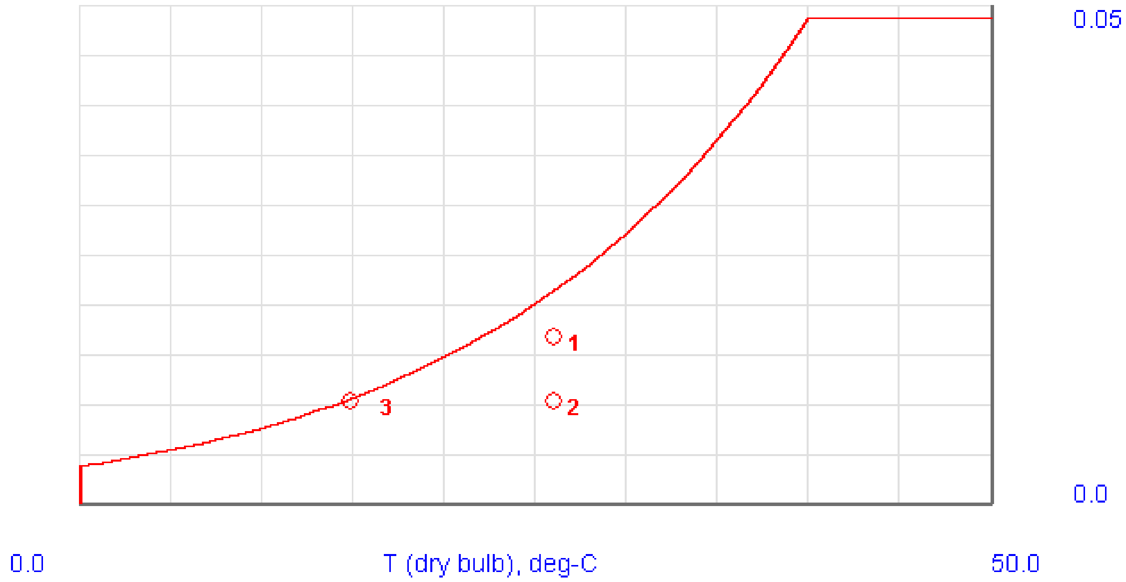
Note that refrigeration (negative since heat is going out of system) is chosen in tons and is equal to -15.122 kW = 4.3 tons, (since 1 ton of refrogeration = 211 kJ/min) … Ans.

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:



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.; }

```
                }

                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)	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: **Qdot= 6.1918793 kW**;

==

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 m^3/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.

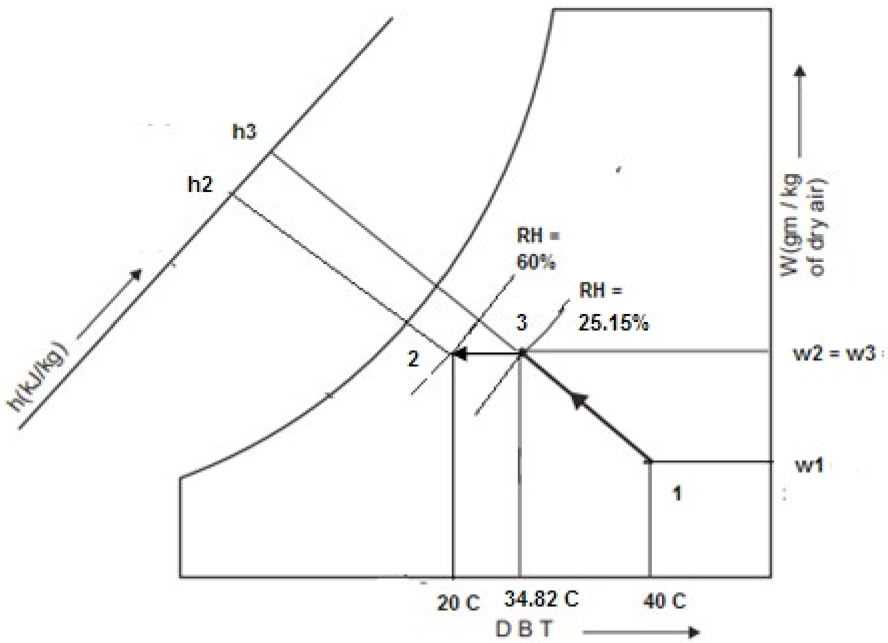
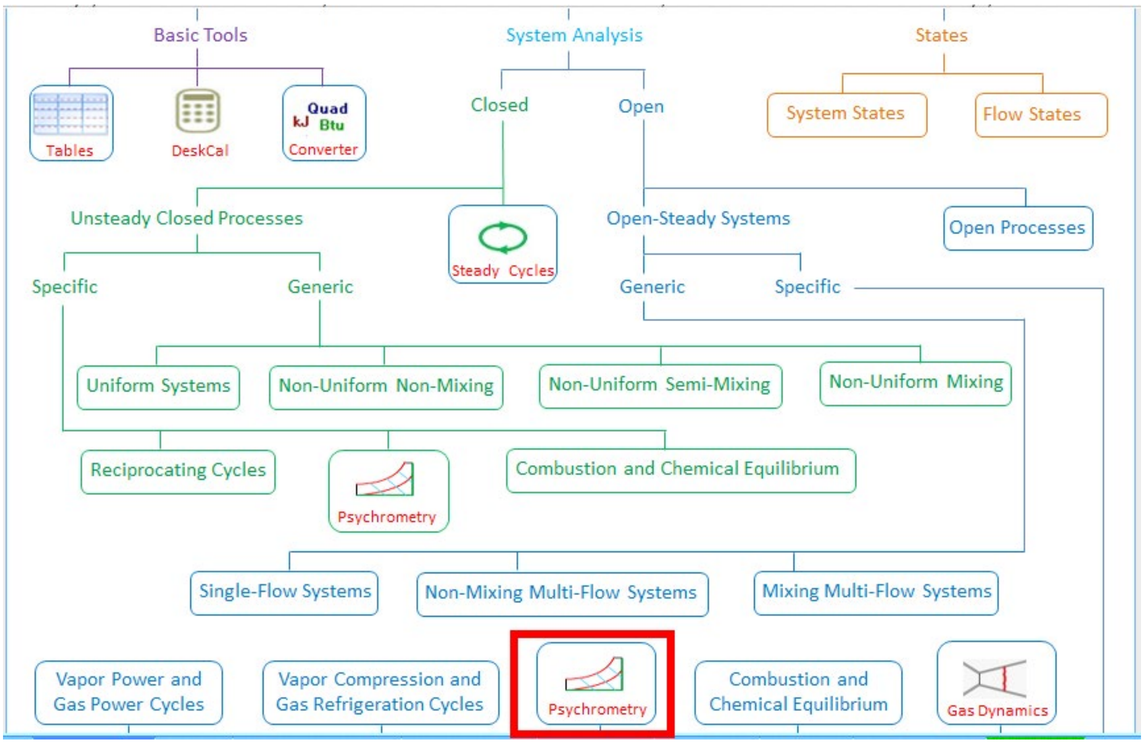


Fig.Prob.7.5.6 Adiabatic humidification and heating

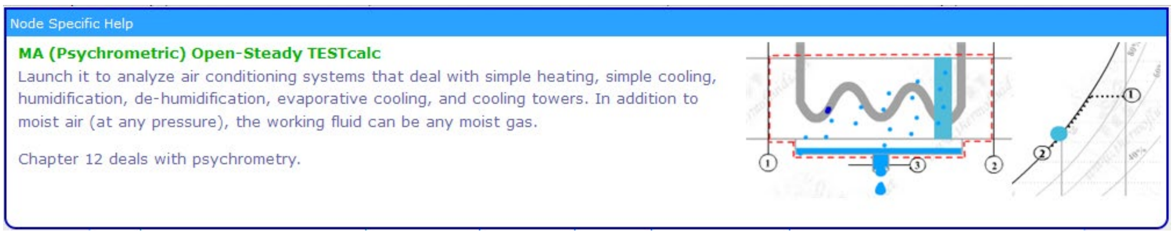
TEST Solution:

Following are the steps:

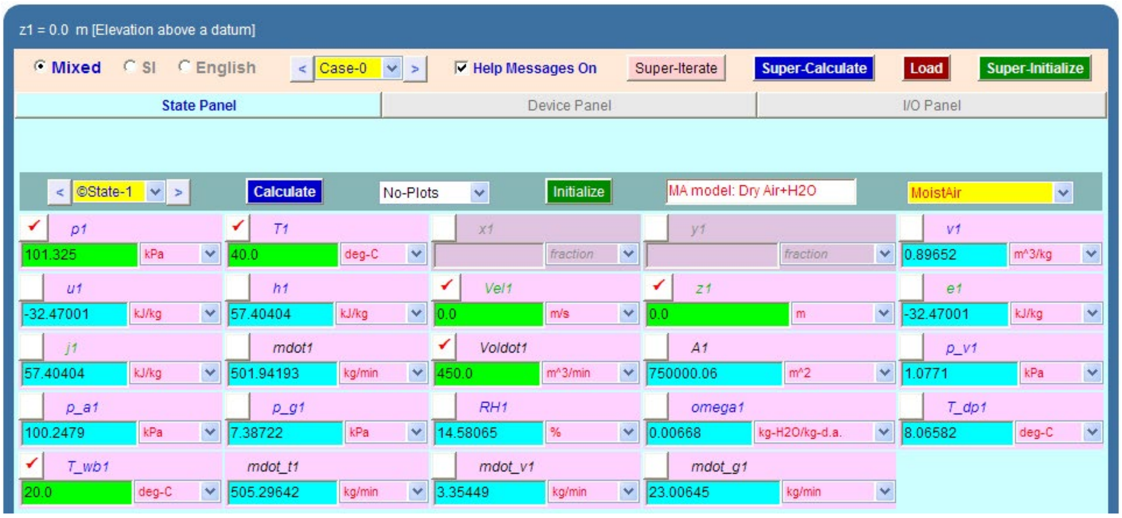
1. From the TESTCalcs tree, choose Open System-Psychrometry:



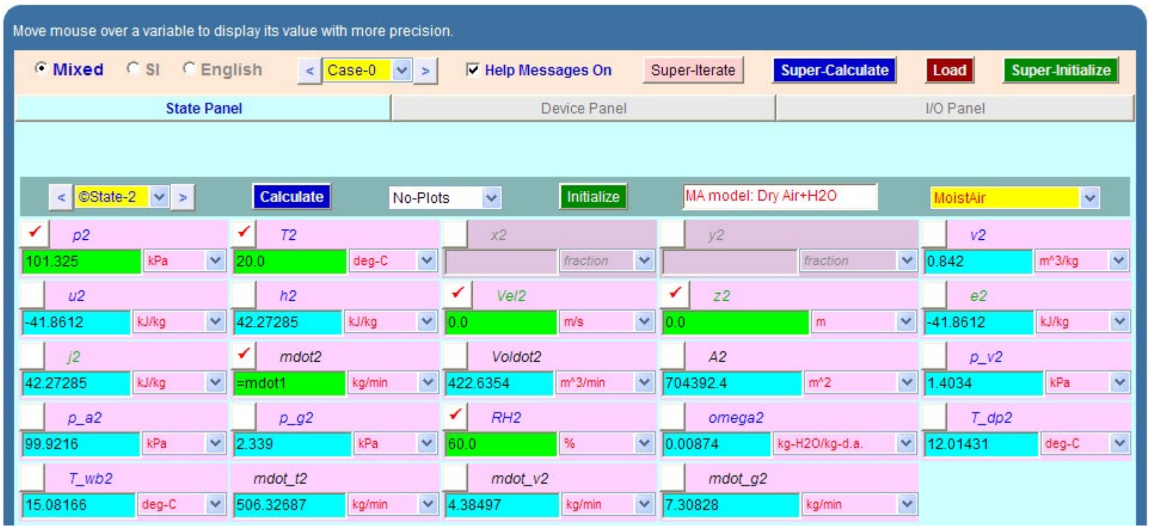
2. Hovering the mouse pointer over Psychrometry gives following explanatory pop-up:



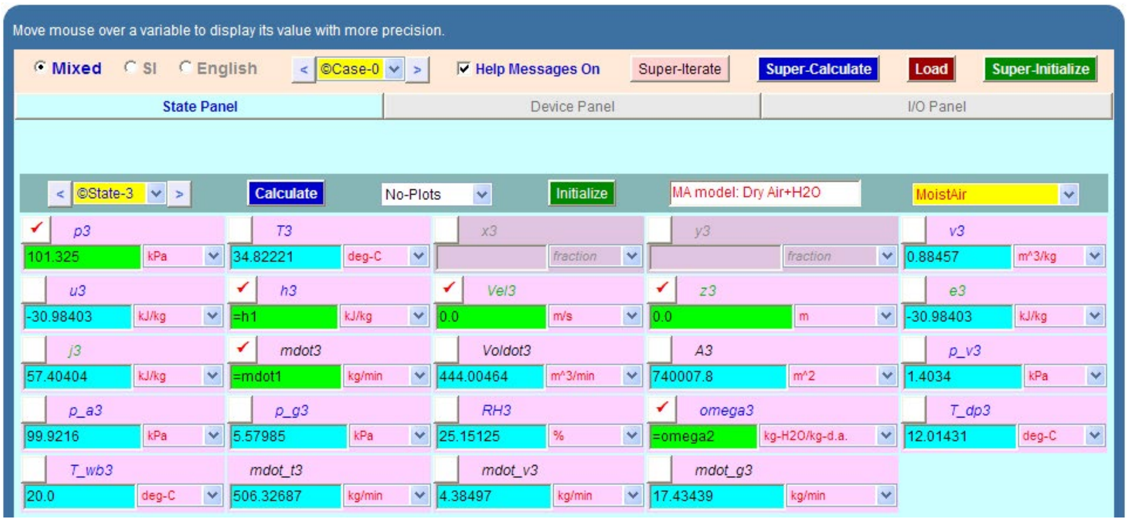
3. Click on Psychrometry, and we get the following window with moist air as default material. Fill up the data for state 1, i.e. T1 = 40 C, T_wb1 = 20 C, Voldot1 = 450 m^3/min, and hit Enter. We get:



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:

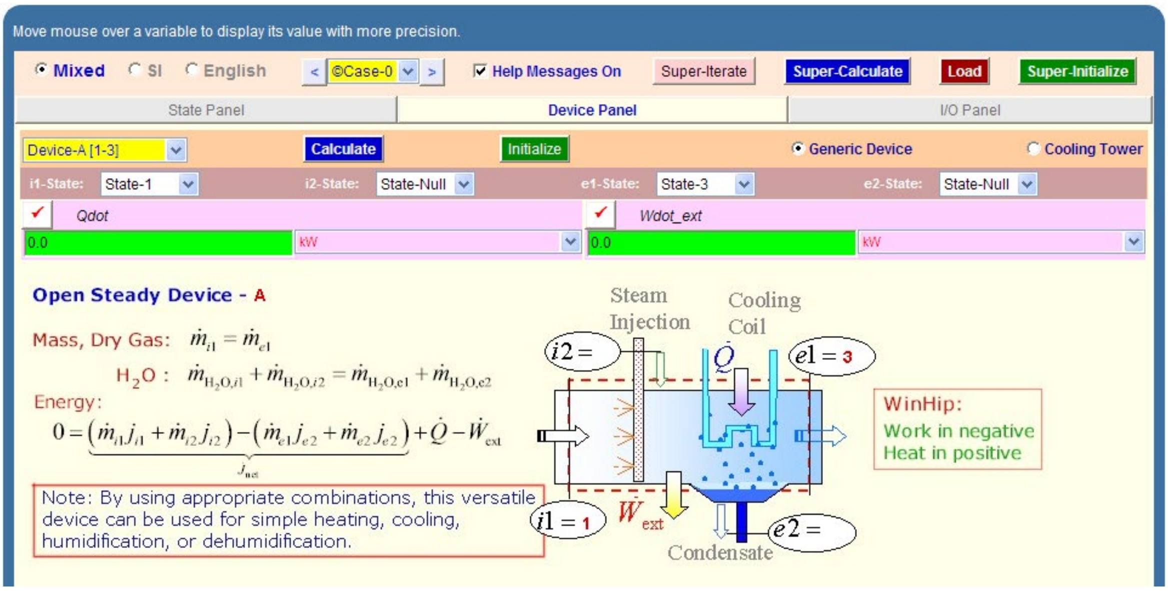


5. Go to State 3, i.e. state after adiabatic humidification. Fill up omega3 = omega2 (since the sp. humidity, omega remains const. during cooling), mdot3 = mdot1, h3 = h1 (for adiabatic process 1-3). Hit Enter, and we get:

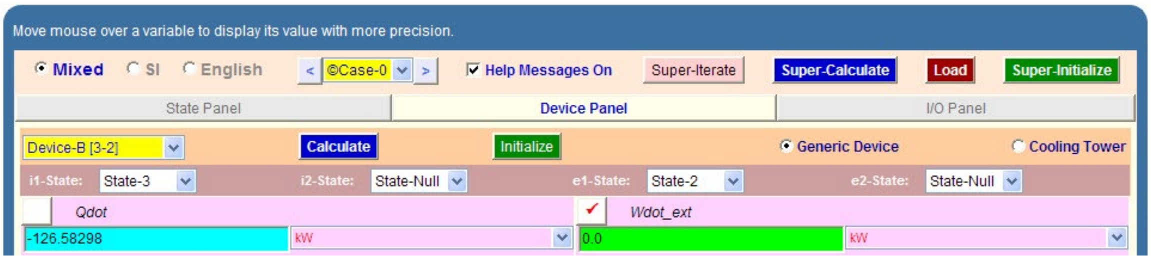


Note that RH3 = 25.15 %, T3 = 34.82 C, i.e. temp of air before it is cooled to 20 C in the refrigeration unit…. Ans.

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:

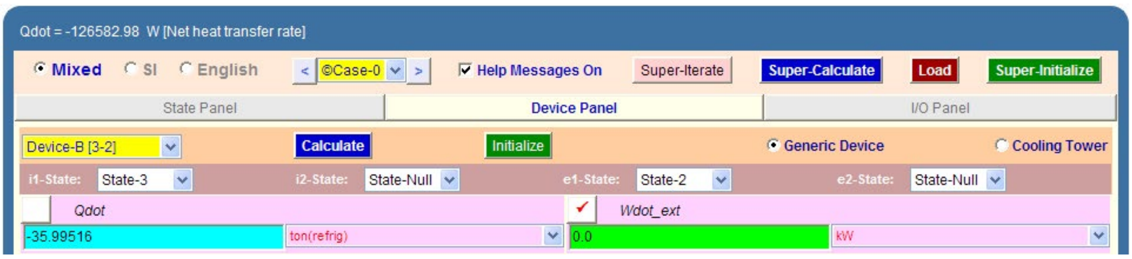


7. Go to Device B (i.e. cooling unit). Fill up State 3 and State 2 for i-1 state and e1-state, Wdot_ext = 0. Hit Enter. We get:



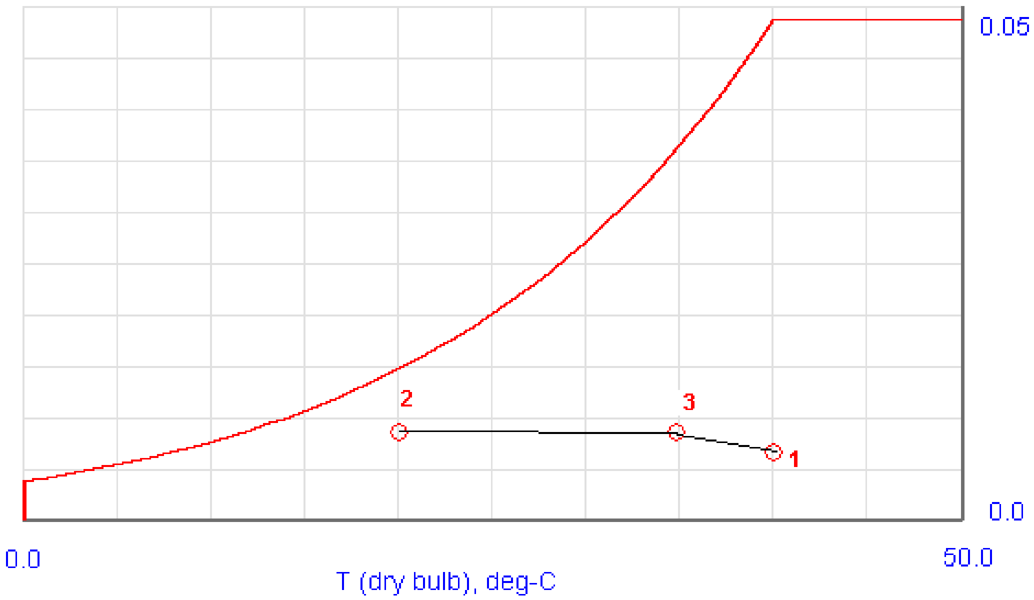
i.e. Heat removed in cooling unit = Qdot = 126.58 kW (negative, since heat is removed).

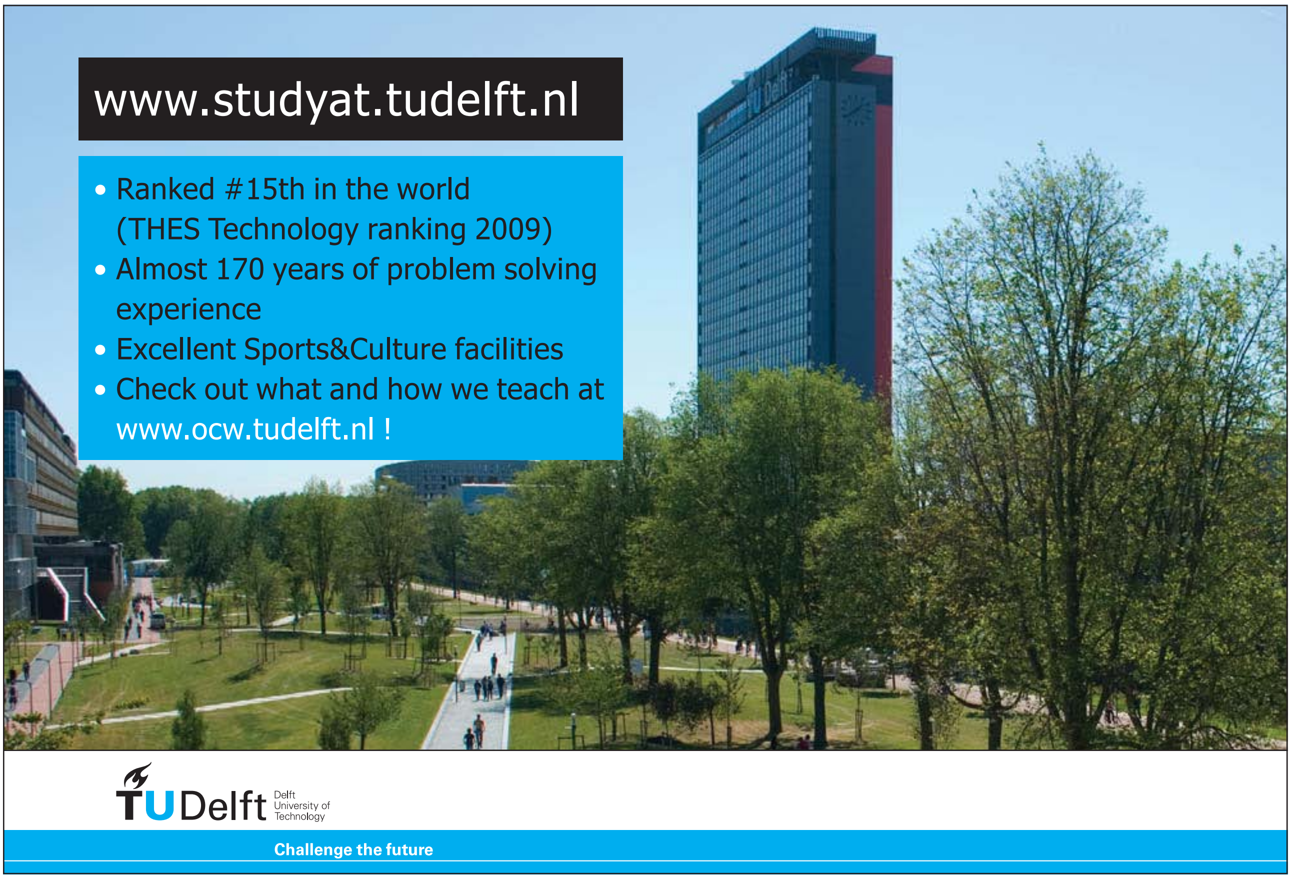
OR: we can get in Tons also in TEST:



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

Analysis

#

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

Given: **Qdot= 0.0 kW**; Wdot_ext= 0.0 kW;

Calculated:

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

Given: Wdot_ext= 0.0 kW;

Calculated: **Qdot= -126.582985 kW**;

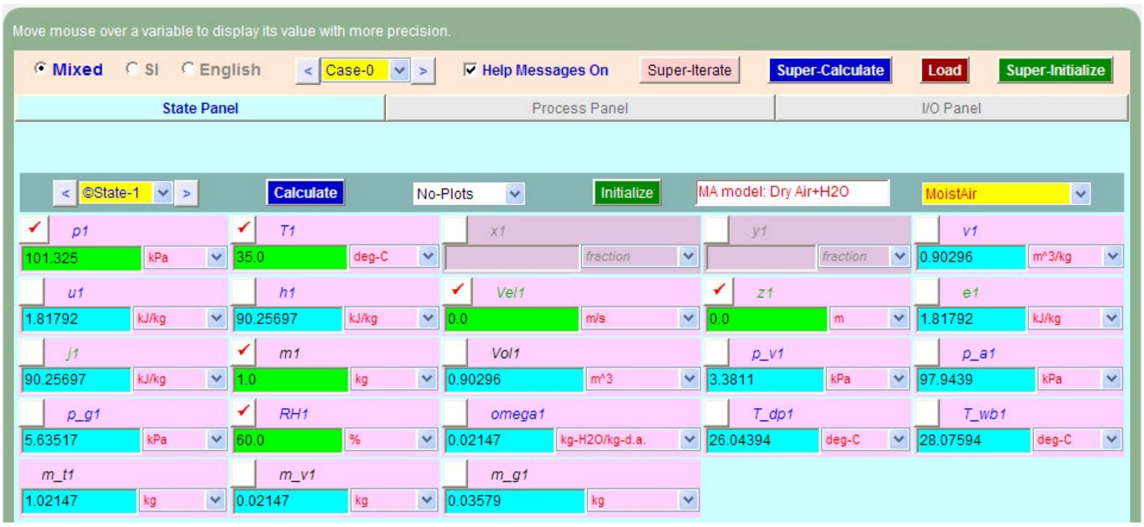
==

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.

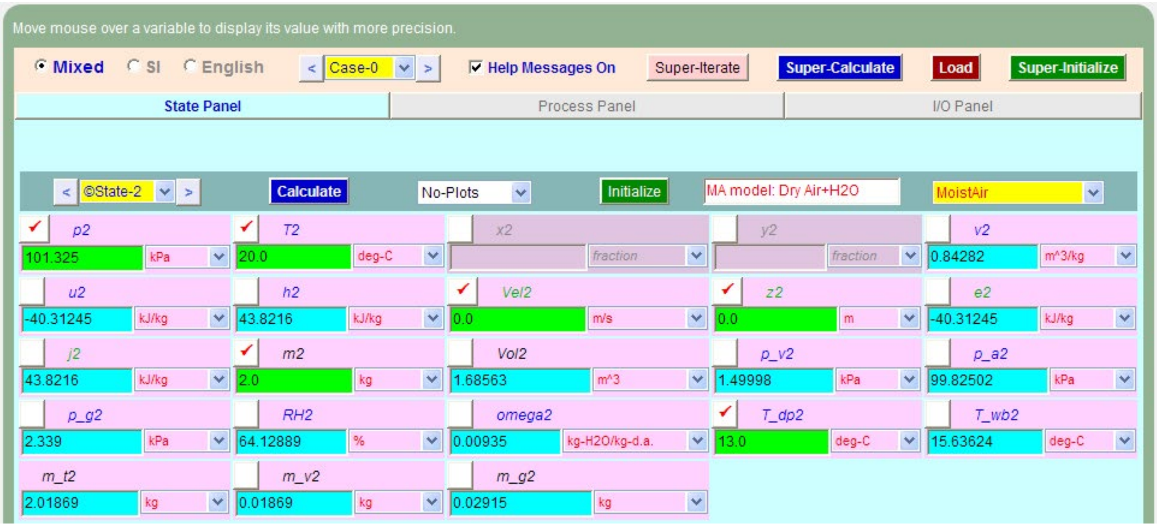
TEST Solution:

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

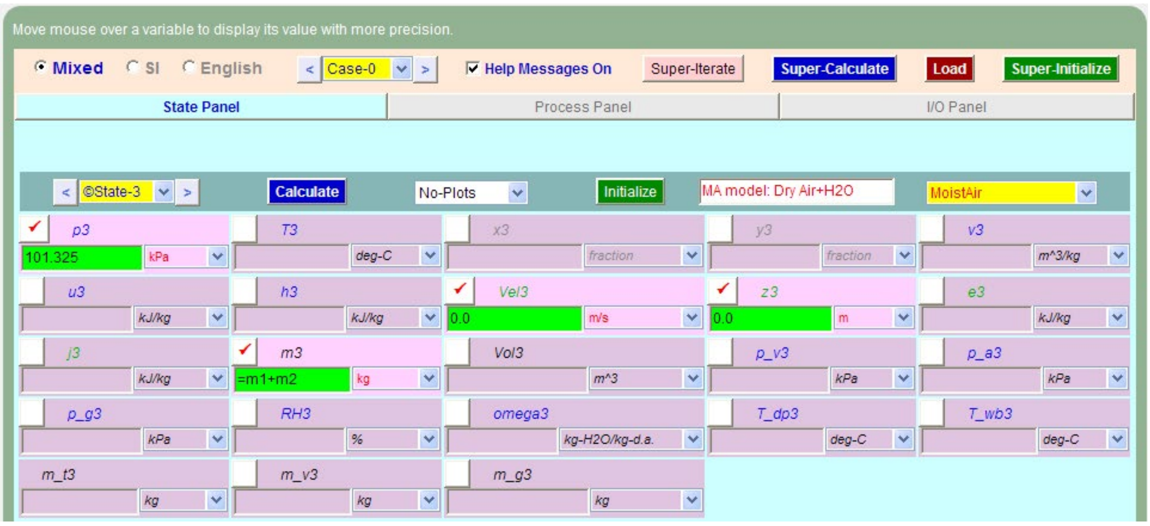
1. Enter data for State1: m1 = 1 kg, T1 = 35 C DBT, RH1 = 60%. P1 = 101.325 by default. Hit Enter. We get:



2. For State 2: m2 = 2 kg, T2 = 20 C, T_dp2 = 13 C. Hit Enter. We get:

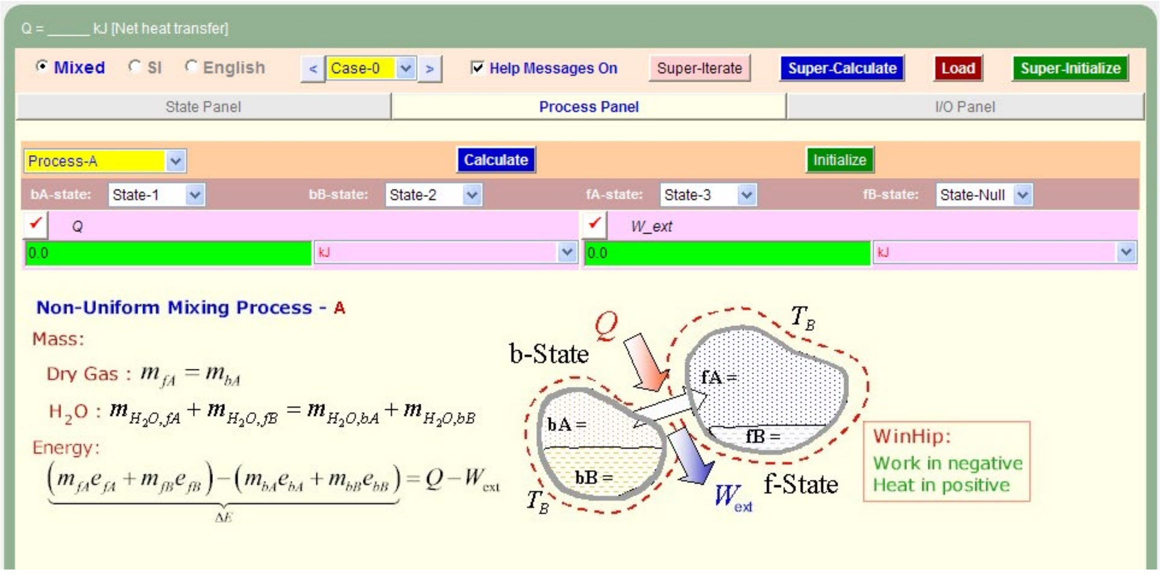


3. For State 3, enter known data: m3 = m1+m2, and hit Enter. We get:

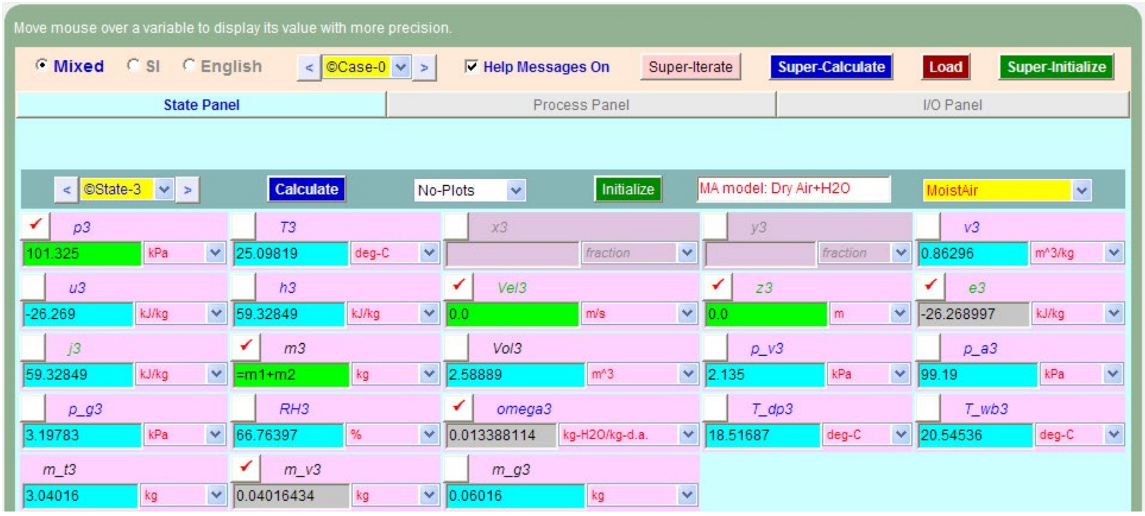


Note that above data was not enough. However, results will be up-dated after we go to Process panel.

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.

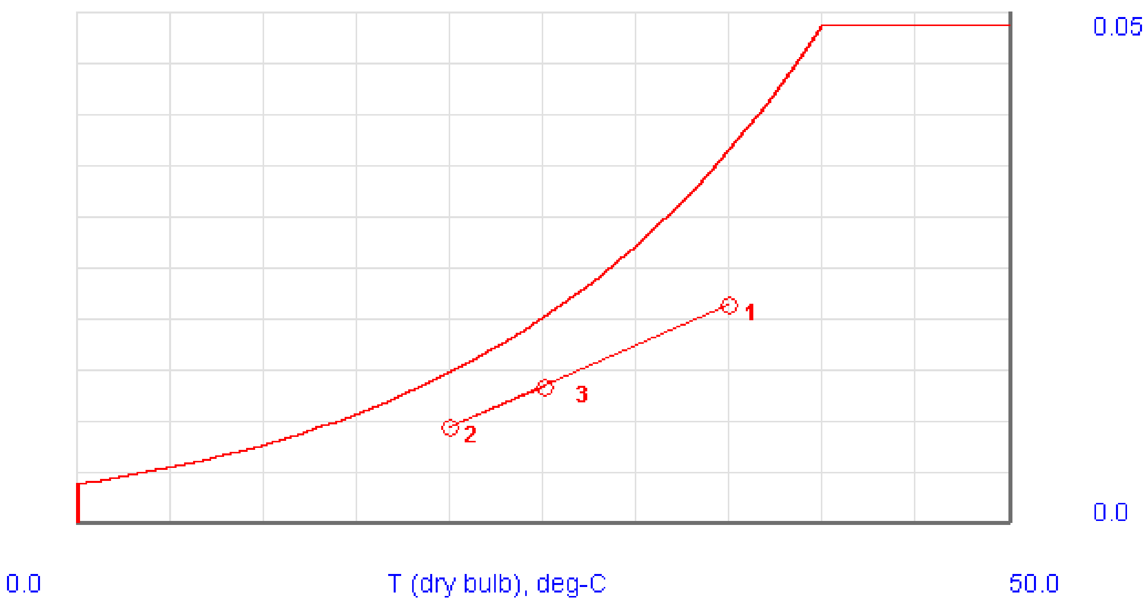


5. Now, all calculations are updated. Go to State 3, and see the results:



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

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

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

        States    {

                State-1: MoistAir;

                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 %; }

                State-2: MoistAir;

                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; }

                State-3: MoistAir;

                Given: { p3= 101.325 kPa; Vel3= 0.0 m/s; z3= 0.0 m; m3= "m1+m2" kg; }

                }

        Analysis        {

                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 -----------------------------------
```

```
#******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;
```

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;

#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]

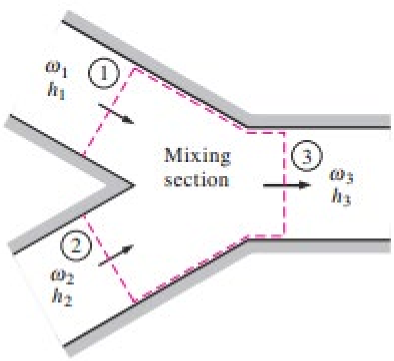
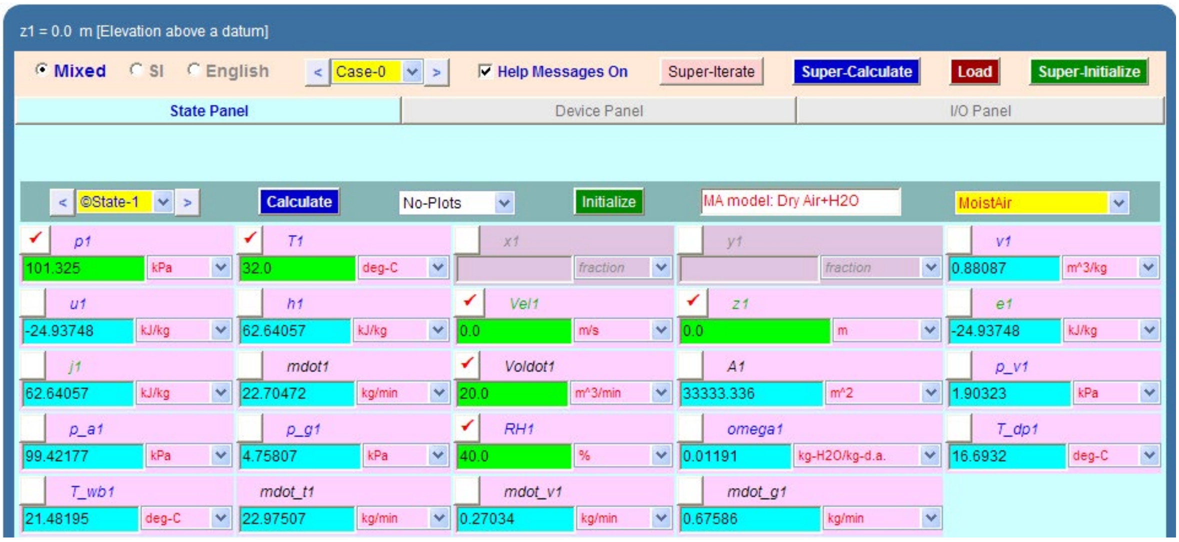


Fig.Prob.7.5.8 Adiabatic mixing of two air streams

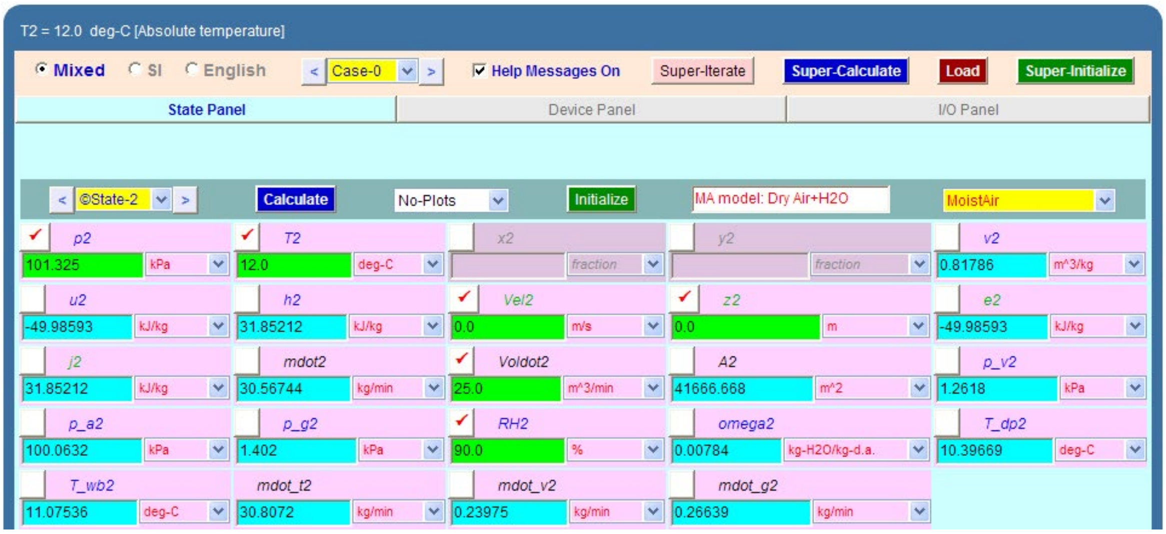
TEST Solution:

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

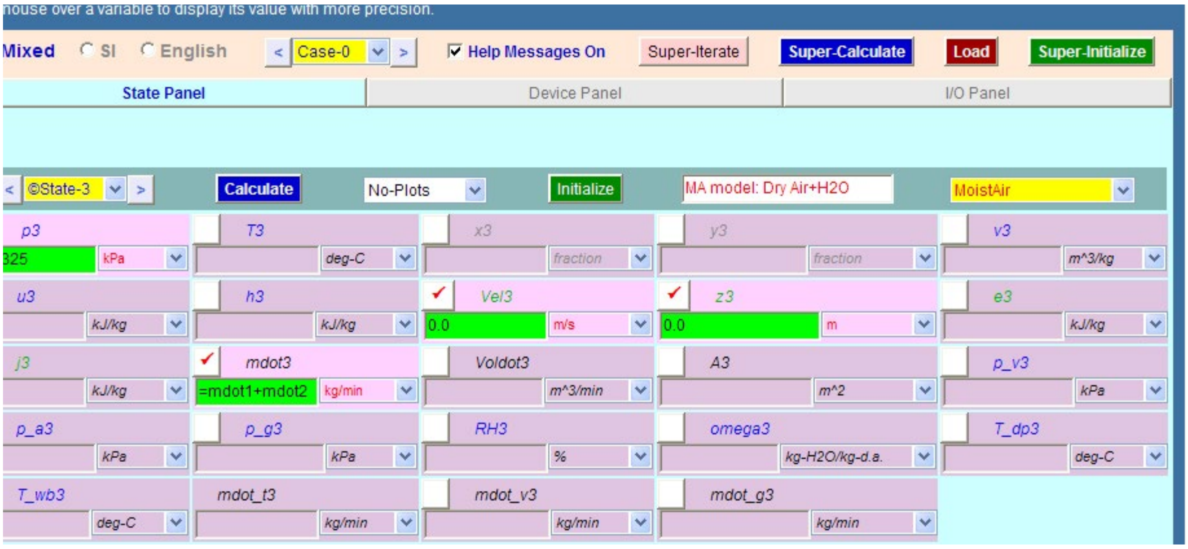
1. For stream 1, fill in parameters for State 1: i.e. T1 = 32 C, RH1 = 40%, Voldot1 = 20 m^3/min. Hit Enter. We get:



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

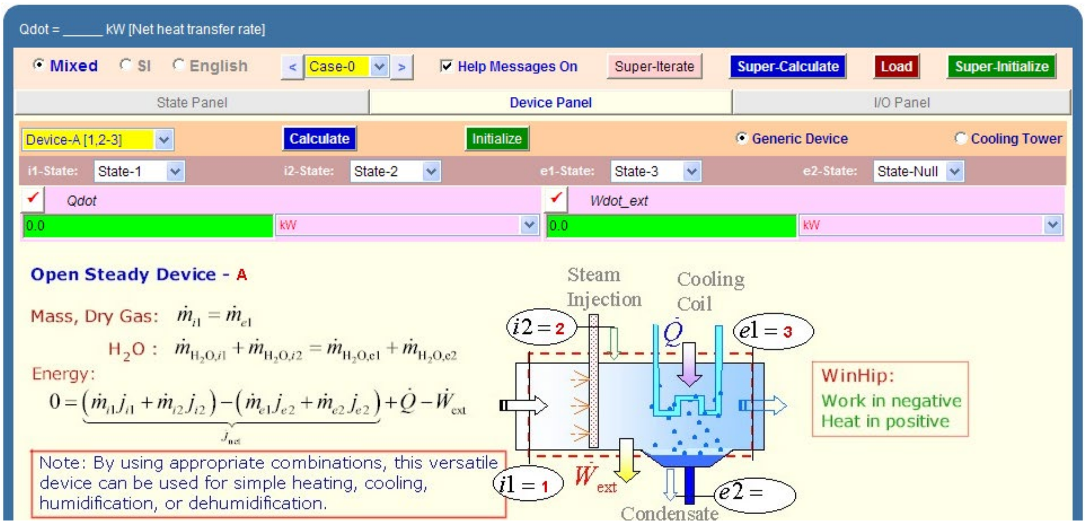


3. For mixture, i.e. State 3, enter known values. i.e. p3 is selected as 101.325 by default, mass of dry air, mdot3 = (mdot1 + mdot2), and hit Enter. We get the following:

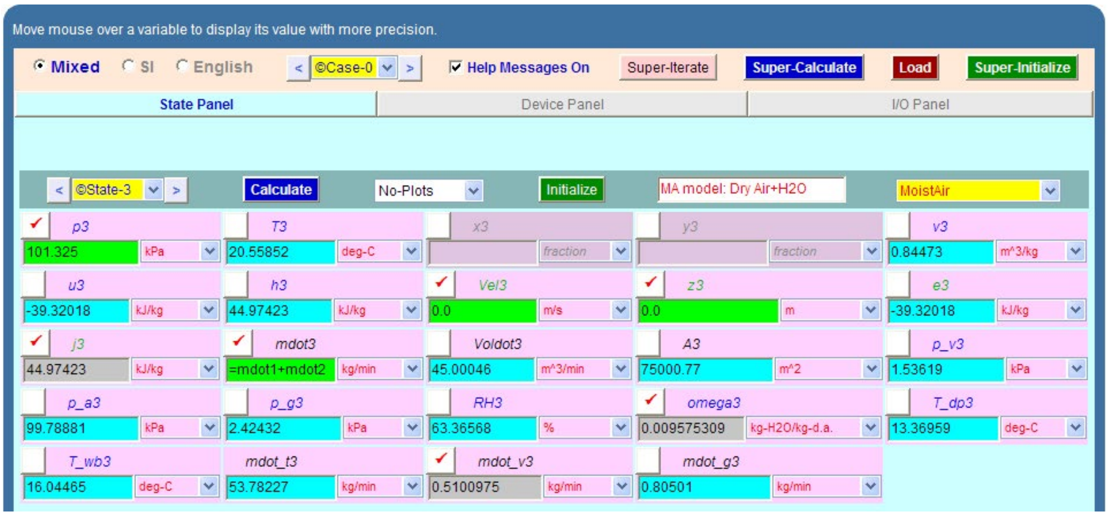


Note that data is not enough to calculate all parameters. They will be calculated and posted back when we fill in data in the Device Panel.

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:



Thus:

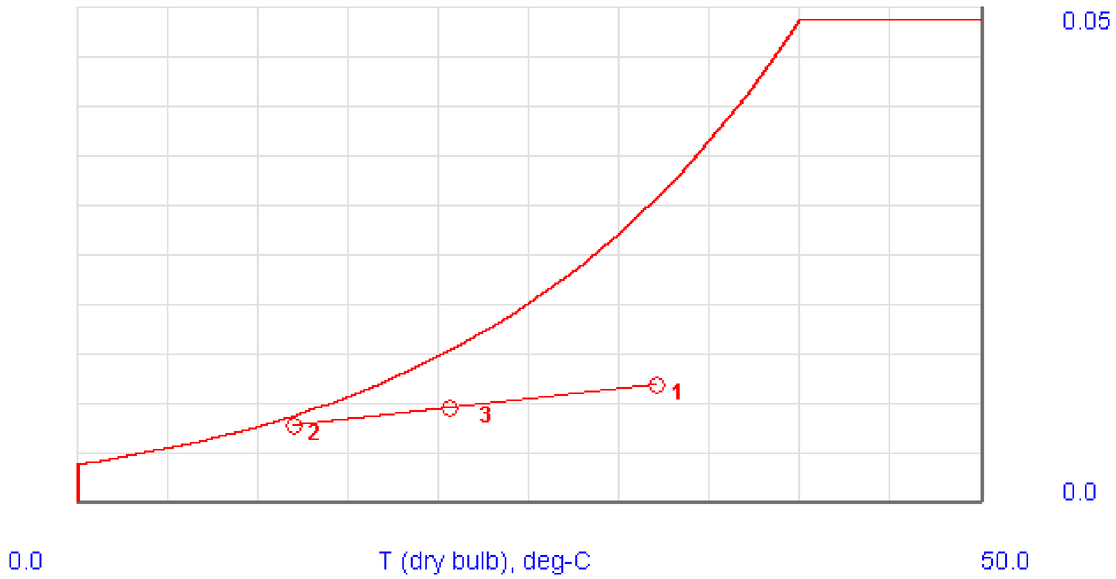
Sp. humidity of mixture = omega3 = 0.009575 jgH2O/kg dry air … Ans.

RH of mixture = RH3 = 63.36% … Ans.

Dry bulb temp = T3 = 20.56 C … Ans.

Vol. flow rate of mixture = Voldot3 = 45 m^3/min … Ans.

6. Plots widget gives State points on a psychrometric chart:



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 %; }

```
                    State-3: MoistAir;

                    Given: { p3= 101.325 kPa; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= “mdot1+mdot2” kg/min;
}

                    }

          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; }

                    }

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

#******DETAILED OUTPUT:
```

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;
#----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	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;

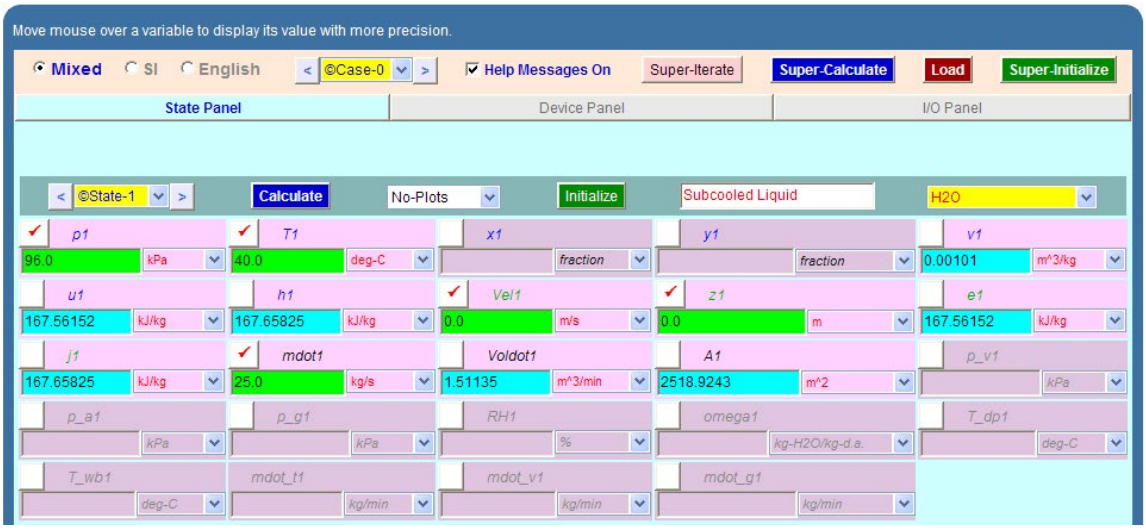
==

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]

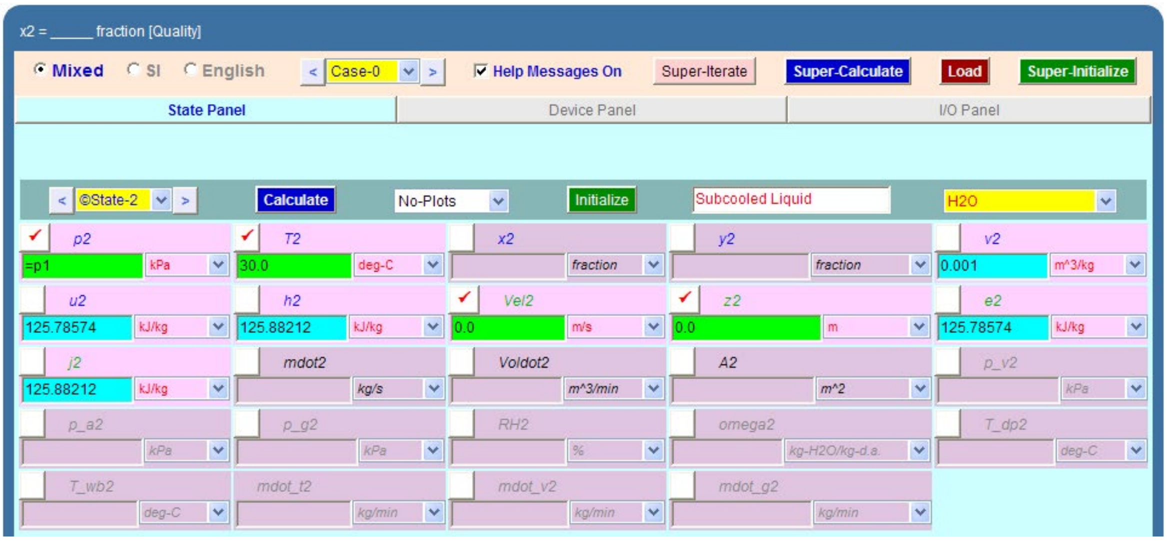
TEST Solution:

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

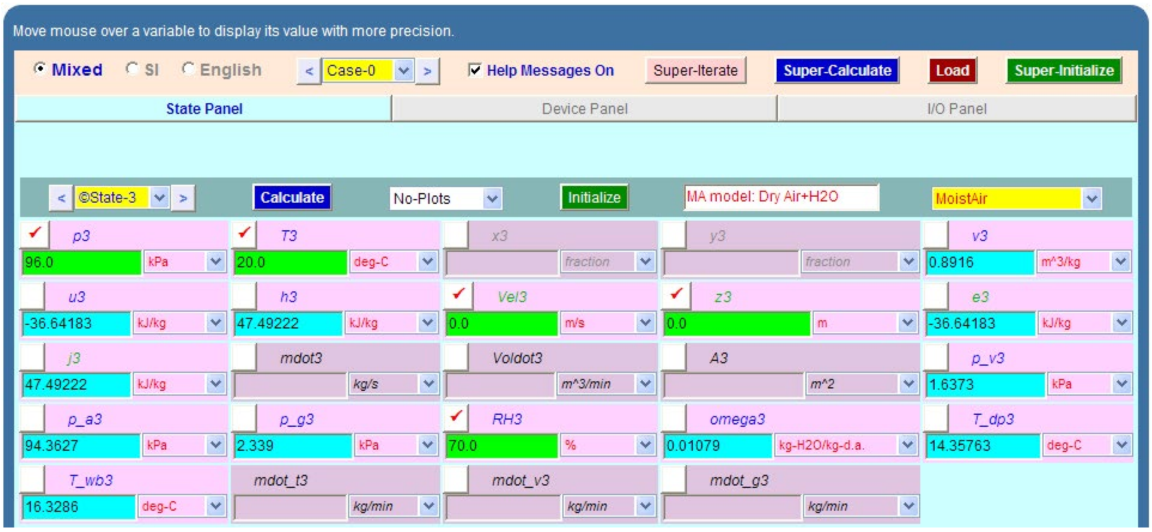
1. Choose H2O as the working substance, fill in the data for State 1, i.e. water entering the tower: Enter p1 = 96 kPa, T1 = 40 C, mdot1 = 25 kg/s. Hit Enter. We get:



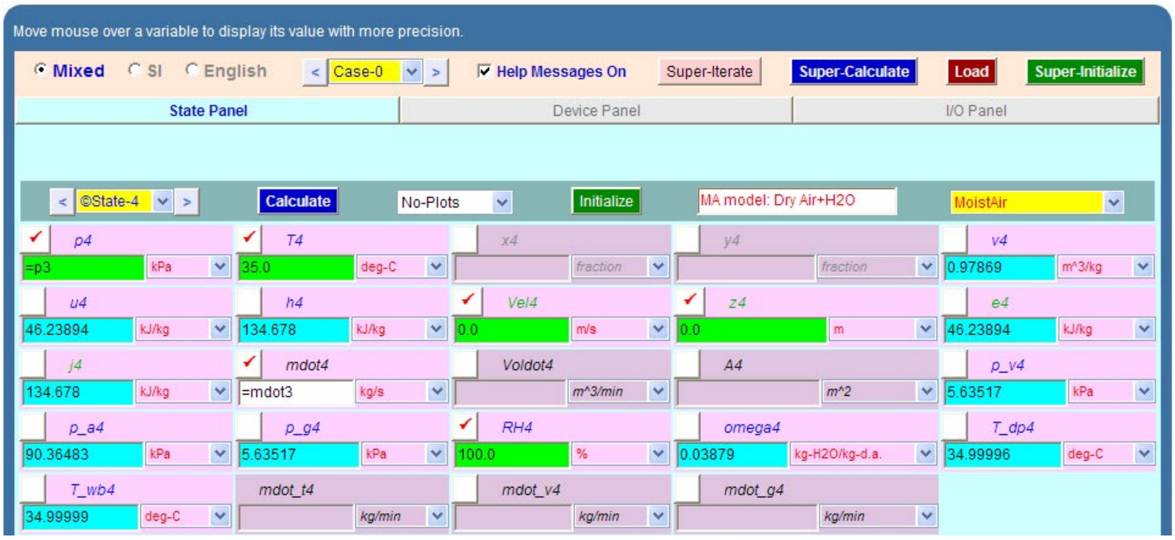
2. For State 2, i.e. water leaving the tower: Enter p2 = p1, T2 = 30 C, hit Enter. We get:



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:

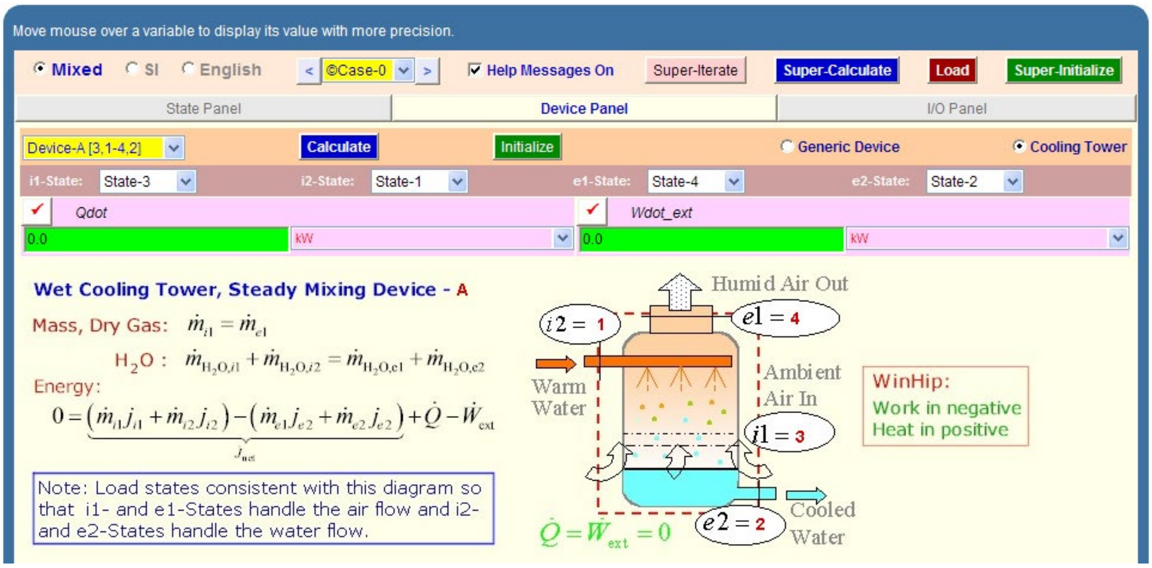


4. For State 4, i.e. air leaving the tower: enter p4 = p3, T4 = 35 C, RH4 = 100% (since saturated), and mdot4 = mdot3 (since amount of dry air does not change), hit Enter. We get:

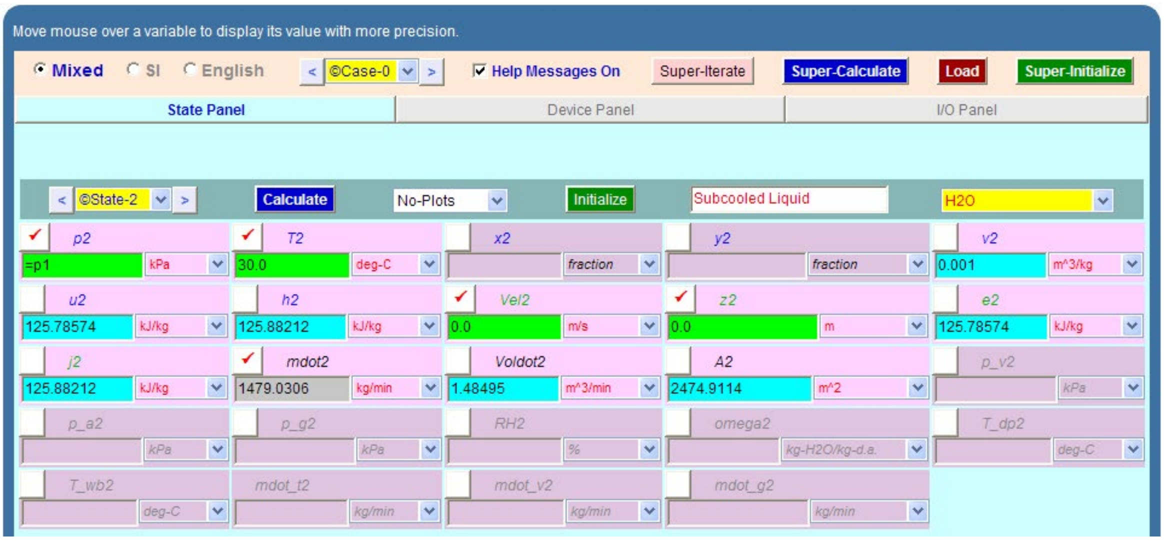


Amount of mdot4 will be automatically posted later, after we complete the Device panel and SuperCalculate.

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:

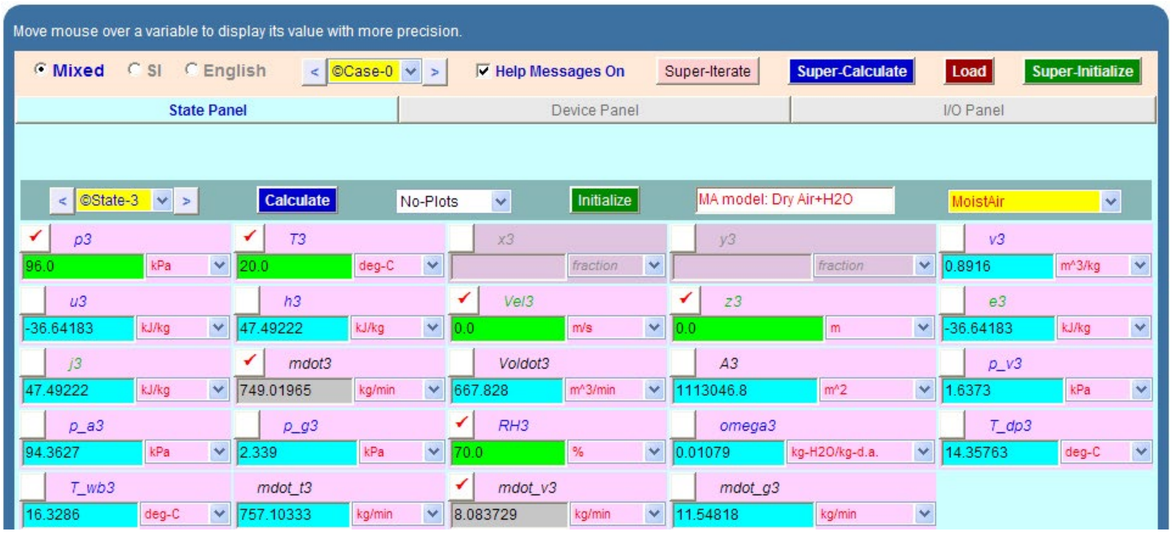


6. Click on SuperCalculate. Now, all calculations are up-dated and relevant parameters are posted to respective State panels. Go to State 2, and see the following:



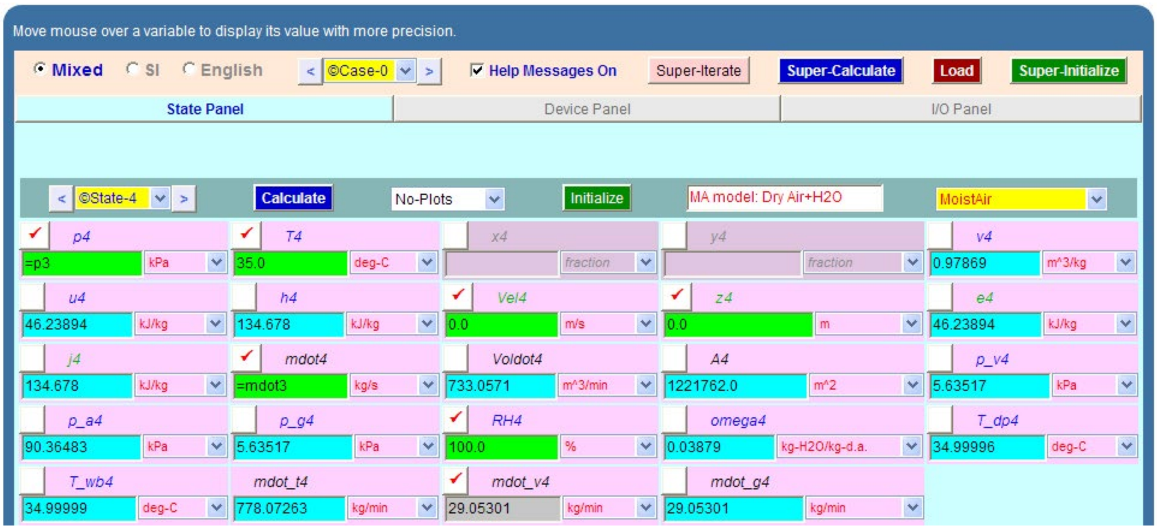
Note that the quantity of water leaving the tower = mdot2 = 1479 kg/min.

7. State 3 shows:



Note that Volume of air entering the tower = Voldot 3 = 667.8 m^3/min = 11.13 m^3/s …. Ans.

8. And, State 4 shows:



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

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;
```

```
#                   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;
#
#----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			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	C	H	O	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]

Relative atomic masses:

Substance	Symbol	Rel. atomic mass	Rel. molecular mass
Carbon	C	12	-
Hydrogen	H2	1	2
Oxygen	O2	16	32
Nitrogen	N2	14	28
Sulphur	S	32	-
Carbon monoxide	CO	-	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

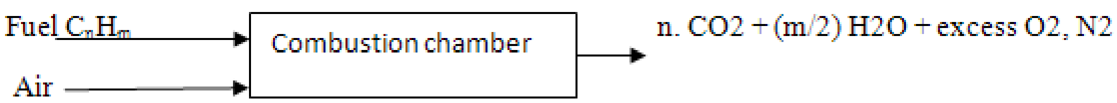
Fuel-Air ratio = 1/AF

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_nH_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" –→ means 150% theoretical air.

"90% Theoretical air" -→ means 10% deficient air.

Equivalence ratio (φ):

It is defined as:

$$\phi = \text{Equivalence\_ratio} = \frac{\text{Actual\_FA\_ratio}}{\text{Stoichiometric\_FA\_ratio}}$$

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:

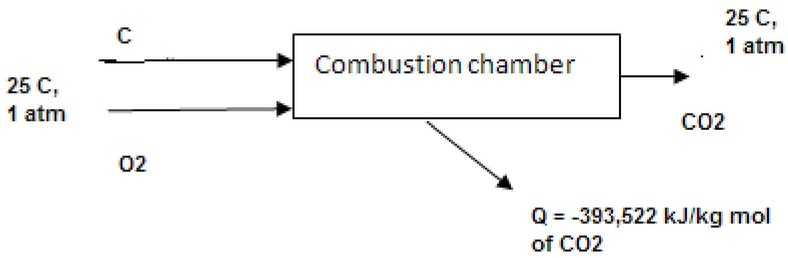
Mole fraction of CO2 = y_{co2} = 0.1/1 = 0.1.

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.

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. $$\sum_r n_i \cdot h_i + Q = \sum_p n_e \cdot h_e$$

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 kJ/kg mol. Negative sign indicates an *exothermic reaction*, i.e. heat is released.

This is known as *enthalpy of formation* (h_{f0}) 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, Reactions: *Enthalpy of Formation Table*

☑ SI Units ☐ English Units

Molar Specific Enthalpy of Formation, Gibbs Function of Formation, and Absolute Entropy at 25°C, 1 atm

Substance	Formula (Phase)	$\bar{M}$	$\bar{h}_f^\circ$	$\bar{g}_f^\circ$	$\bar{s}^\circ$
		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(l)	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(l)	C8H18(l)	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(l)	32.04	-238,660	-166,360	126.80
Ethyl Alcohol	C2H5OH(g)	46.07	-235,310	-168,570	282.59
Ethyl Alcohol	C2H5OH(l)	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 Δh between the standard state and the state in question to the enthalpy of formation. i.e.

$$h_{T,p} = h_{f0} + \left(h(T,p) - h\left(T_{ref}, p_{ref}\right)\right) = h_{f0} + \Delta h$$

Urieli has calculated the values of Δh 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.

Ideal Gas Enthalpy of Carbon Dioxide (CO2)

Enthalpy of Formation: -393,522 (kJ/kmol)

Molecular Weight: 44.01 (kg/kmol)

Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [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

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

Ideal Gas Enthalpy of Carbon Monoxide (CO)

Enthalpy of Formation: -110,527 (kJ/kmol)
Molecular Weight: 28.01 (kg/kmol)

Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [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	5039	820	15814	1340	33250	2100	60375
480	5336	830	16134	1360	33944	2150	62195
490	5633	840	16455	1380	34640	2200	64019
500	5931	850	16777	1400	35358	2250	65847
510	6229	860	17099	1420	36038	2300	67676
520	6528	870	17422	1440	36739	2350	69509
530	6828	880	17746	1460	37441	2400	71346
540	7128	890	18071	1480	38144	2450	73183
550	7428	900	18397	1500	38848	2500	75023
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 [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [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
470	5873	820	18768	1340	40708	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
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	960	24343	1620	53805	2800	115294
620	11226	970	24749	1640	54771	2850	118048
630	11591	980	25157	1660	55739	2900	120813
640	11958	990	25568	1680	56710	3000	126360

Ideal Gas Enthalpy of Nitrogen (N_2)

Enthalpy of Formation: 0 (kJ/kmol)
Molecular Weight: 28.013 (kg/kmol)

Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]
298	0						
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
470	5024	820	15673	1340	32870	2100	59748
480	5319	830	15989	1360	33558	2150	61557
490	5616	840	16305	1380	34246	2200	63371
500	5912	850	16623	1400	34936	2250	65187
510	6207	860	16941	1420	35626	2300	67007
520	6503	870	17259	1440	36319	2350	68827
530	6800	880	17579	1460	37013	2400	70651
540	7097	890	17899	1480	37708	2450	72480
550	7395	900	18221	1500	38404	2500	74312
560	7694	910	18541	1520	39102	2550	76145
570	7993	920	18863	1540	39801	2600	77981
580	8293	930	19185	1560	40499	2650	79819
590	8593	940	19509	1580	41200	2700	81659
600	missing	950	19832	1600	41902	2750	83502
610	missing	960	20157	1620	42606	2800	85345
620	missing	970	20482	1640	43311	2850	87190
630	9799	980	20807	1660	44017	2900	89036
640	10103	990	21134	1680	44724	3000	92738

Ideal Gas Enthalpy of Oxygen (O_2)

Enthalpy of Formation: 0 (kJ/kmol)
Molecular Weight: 32 (kg/kmol)

Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [kJ/kmol]	Temp. [K]	Enthalpy [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
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(K), h and u(kJ/kg), s° (kJ/kg · K)

				when $\Delta s = 0$[1]						when $\Delta s = 0$	
T	h	u	s°	p_r	v_r	T	h	u	s°	p_r	v_r
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)*

T(K), h and u(kJ/kg), $s°$ (kJ/kg · K)

				when $\Delta s = 0$[1]						when $\Delta s = 0$	
T	h	u	$s°$	p_r	v_r	T	h	u	$s°$	p_r	v_r
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

Source: Tables A-22 are based on J. H. Keenan and J. Kaye, *Gas Tables*, Wiley, New York, 1945.

TABLE A-23 Ideal Gas Properties of Selected Gases

T(K), $\bar{h}$ and $\bar{u}$(kJ/kmol), $\bar{s}°$(kJ/kmol · K)

	Carbon Dioxide, CO_2 ($\bar{h}_f^\circ = -393{,}520$ kJ/kmol)			Carbon Monoxide, CO ($\bar{h}_f^\circ = -110{,}530$ kJ/kmol)			Water Vapor, H_2O ($\bar{h}_f^\circ = -241{,}820$ kJ/kmol)			Oxygen, O_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			Nitrogen, N_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			
T	$\bar{h}$	$\bar{u}$	$\bar{s}°$	$\bar{h}$	$\bar{u}$	$\bar{s}°$	$\bar{h}$	$\bar{u}$	$\bar{s}°$	$\bar{h}$	$\bar{u}$	$\bar{s}°$	$\bar{h}$	$\bar{u}$	$\bar{s}°$	T
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

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

TABLE A-23 *(Continued)*

T(K), $\bar{h}$ and $\bar{u}$(kJ/kmol), $\bar{s}^\circ$(kJ/kmol · K)

	Carbon Dioxide, CO_2 ($\bar{h}_f^\circ = -393{,}520$ kJ/kmol)			Carbon Monoxide, CO ($\bar{h}_f^\circ = -110{,}530$ kJ/kmol)			Water Vapor, H_2O ($\bar{h}_f^\circ = -241{,}820$ kJ/kmol)			Oxygen, O_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			Nitrogen, N_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			
T	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	T
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

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

TABLE A-23 *(Continued)*

T(K), $\bar{h}$ and $\bar{u}$(kJ/kmol), $\bar{s}^\circ$(kJ/kmol · K)

	Carbon Dioxide, CO_2 ($\bar{h}_f^\circ = -393,520$ kJ/kmol)			Carbon Monoxide, CO ($\bar{h}_f^\circ = -110,530$ kJ/kmol)			Water Vapor, H_2O ($\bar{h}_f^\circ = -241,820$ kJ/kmol)			Oxygen, O_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			Nitrogen, N_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			
T	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	T
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	1000
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	1020
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	1040
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	1060
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	1080
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	1100
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	1120
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	1140
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	1160
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	1180
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	1200
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	1220
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	1240
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	1260
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	1280
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	1300
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	1320
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	1340
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	1360
1380	64,116	52,643	287.283	43,309	31,836	245.388	52,434	40,960	246.582	44,923	33,449	254.932	42,915	31,441	238.878	1380
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	1400
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	1420
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	1440
1460	68,748	56,609	290.542	46,110	33,971	247.360	56,128	43,989	249.185	47,831	35,692	256.978	45,682	33,543	240.827	1460
1480	69,911	57,606	291.333	46,813	34,508	247.839	57,062	44,756	249.820	48,561	36,256	257.474	46,377	34,071	241.301	1480

1500	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	1500
1520	72,246	59,609	292.888	48,222	35,584	248.778	58,942	46,304	251.074	50,024	37,387	258.450	47,771	35,133	242.228	1520
1540	73,417	60,613	292.654	48,928	36,124	249.240	59,888	47,084	251.693	50,756	37,952	258.928	48,470	35,665	242.685	1540
1560	74,590	61,620	294.411	49,635	36,665	249.695	60,838	47,868	252.305	51,490	38,520	259.402	49,168	36,197	243.137	1560
1580	76,767	62,630	295.161	50,344	37,207	250.147	61,792	48,655	252.912	52,224	39,088	259.870	49,869	36,732	243.585	1580
1600	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	1600
1620	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	1620
1640	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	1640
1660	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	1660
1680	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	1680
1700	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	1700
1720	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	1720
1740	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	1740

TABLE A-23 *(Continued)*

T(K), $\bar{h}$ and $\bar{u}$(kJ/kmol), $\bar{s}^\circ$(kJ/kmol · K)

	Carbon Dioxide, CO_2 ($\bar{h}_f^\circ = -393{,}520$ kJ/kmol)			Carbon Monoxide, CO ($\bar{h}_f^\circ = -110{,}530$ kJ/kmol)			Water Vapor, H_2O ($\bar{h}_f^\circ = -241{,}820$ kJ/kmol)			Oxygen, O_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			Nitrogen, N_2 ($\bar{h}_f^\circ = 0$ kJ/kmol)			
T	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	$\bar{h}$	$\bar{u}$	$\bar{s}^\circ$	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

Source: Tables A-23 are based on the JANAF Thermochemical Tables, NSRDS-NBS-37, 1971.

Another way is not to use the Tables, but calculate Δh as (cp . ΔT), 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]:

$$cp_{CO2}(T) := \left(45.369 + 3.688 \cdot 10^{-3} \cdot T - 9.619 \cdot 10^{5} \cdot T^{-2}\right) \quad \text{kJ/kmol}$$

$$cp_{CO}(T) := \left(28.068 + 4.631 \cdot 10^{-3} \cdot T - 0.258 \cdot 10^{5} \cdot T^{-2}\right) \quad \text{kJ/kmol}$$

$$cp_{H2O}(T) := 28.85 + 12.055 \cdot 10^{-3} \cdot T + 1.066 \cdot 10^{5} \cdot T^{-2} \quad \text{kJ/kmol}$$

$$cp_{O2}(T) := \left(30.255 + 4.207\cdot 10^{-3}\cdot T - 1.887\cdot 10^{5}\cdot T^{-2}\right)$$ 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

$$cp_{NH3}(T) := \left(29.747 + 25.108\cdot 10^{-3}\cdot T - 1.546\cdot 10^{5}\cdot T^{-2}\right)$$ kJ/kmol

$$cp_{CH4}(T) := \left(17.449 + 60.449\cdot 10^{-3}\cdot T + 1.117\cdot 10^{-6}\cdot T^{2} - 7.204\cdot 10^{-9}\cdot T^{3}\right)$$ kJ/kmol

$$cp_{SO2}(T) := \left(47.381 + 6.66\cdot 10^{-3}\cdot T - 8.439\cdot 10^{5}\cdot T^{-2}\right)$$ kJ/kmol

Then: $$\Delta h = \int_{T1}^{T2} cp(T)\, dT$$

Also, following Table from [Ref: 3] gives some equations for cp:

TABLE A-21 Variation of $\bar{c}_p$ with Temperature for Selected Ideal Gases

$$\frac{\bar{c}_p}{\bar{R}} = \alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4$$

T is in K, equations valid from 300 to 1000 K

Gas	α	$\beta \times 10^3$	$\gamma \times 10^6$	$\delta \times 10^9$	$\varepsilon \times 10^{12}$
CO	3.710	−1.619	3.692	−2.032	0.240
CO_2	2.401	8.735	−6.607	2.002	0
H_2	3.057	2.677	−5.810	5.521	−1.812
H_2O	4.070	−1.108	4.152	−2.964	0.807
O_2	3.626	−1.878	7.055	−6.764	2.156
N_2	3.675	−1.208	2.324	−0.632	−0.226
Air	3.653	−1.337	3.294	−1.913	0.2763
SO_2	3.267	5.324	0.684	−5.281	2.559
CH_4	3.826	−3.979	24.558	−22.733	6.963
C_2H_2	1.410	19.057	−24.501	16.391	−4.135
C_2H_4	1.426	11.383	7.989	−16.254	6.749
Monatomic gases[a]	2.5	0	0	0	0

[a]For monatomic gases, such as He, Ne, and Ar, $\bar{c}_p$ is constant over a wide temperature range and is very nearly equal to $5/2\,\bar{R}$.

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]:

$$HCV = \frac{1}{100} \cdot \left[35000 \cdot C + 143000 \cdot \left(H - \frac{O}{8} \right) + 9160 \cdot S \right] \quad \text{kJ/kg}$$

where C, H, O and S are percentages of carbon, hydrogen, oxygen and sulphur.

$$LCV = HCV - \frac{9}{100} \cdot H \cdot 2460 \quad \text{kJ/kg}$$

Values of enthalpy of combustion for some common hydrocarbon fuels at 25 C, 1 atm are given below. [Ref: 9, TEST software]:

Table G-2, Reactions: *Heating Values of Common Fuels*

☑ SI Units ☐ English Units

Properties of Some Common Fuels and Hydrocarbons

Fuel (Phase)	Formula	Molar Mass kg/kmol $\bar{M}$	Density[1] kg/L ρ	Enthalpy of Vaporization[2] kJ/kg Δh_v	Specific Heat[1] kJ/kg·K c_p	Higher Heating Value[3] kJ/kg HHV	Lower Heating Value[4] kJ/kg LHV
Carbon(s)	C	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(l)	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(l)	C2H6O	46.07	0.790	919	2.44	29,670	26,810
Propane(l)	C3H8	44.10	0.500	420	2.77	50,330	46,340
Butane(l)	C4H10	58.12	0.579	362	2.42	49,150	45,370
1-Pentene(l)	C5H10	70.13	0.641	363	2.20	47,760	44,630
Isopentane(l)	C5H12	72.15	0.626	-	2.32	48,570	44,910
Benzene(l)	C6H6	78.11	0.877	433	1.72	41,800	40,100
Hexene(l)	C6H12	84.16	0.673	392	1.84	47,500	44,400
Hexane(l)	C6H14	86.18	0.660	366	2.27	48,310	44,740
Toluene(l)	C7H8	92.14	0.867	412	1.71	42,400	40,500
Heptane(l)	C7H16	100.20	0.684	365	2.24	48,100	44,600
Octane(l)	C8H18	114.23	0.703	363	2.23	47,890	44,430
Decane(l)	C10H22	142.29	0.730	361	2.21	47,640	44,240
Gasoline(l)	CnH1.87n	100 - 110	0.72 - 0.78	350	2.4	47,300	44,000
Light Diesel(l)	CnH1.8n	170	0.78 - 0.84	270	2.2	46,100	43,200
Heavy Diesel(l)	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_2O in liquid phase in products.
4: H_2O 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.
$$\sum_r n_i \cdot h_i = \sum_p n_e \cdot h_e$$

i.e.
$$\sum_r n_i \cdot \left(h_{f0} + \Delta h\right)_i = \sum_p n_e \cdot \left(h_{f0} + \Delta h\right)_e$$

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 Potter and Somerton in their Schaum's Outline of Thermodynamics for Engineers, in which they assumed all the products to be N_2. We find it more convenient to use air assuming a representative value of the Specific Heat Capacity of Air: $C_{p,1000K}$ = 1.142 [kJ/kg.K]."

==

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

---

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^3 of CH4 + 2 m^3 of O2 = 1 m^3 of CO2 + 2 m^3 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.

==

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:

$C := 0.84 \quad H2 := 0.1 \quad N2 := 0.015 \quad O2 := 0.035 \quad Ash := 0.01$

Theoretical O2 required.... see problem 8.2.1:

For C: $C \cdot \frac{8}{3} = 2.24$ 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: $13.065 \cdot 0.77 + 0.015 = 10.075$ 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:

$$CO2 + N2 + O2 = 3.08 + 12.087 + 0.601 = 15.768 \quad kg$$

Then, mass analysis of dry products is:

N2: $\frac{12.087}{15.768} \cdot 100 = 76.655 \quad \%$

CO2: $\frac{3.08}{15.768} \cdot 100 = 19.533 \quad \%$

O2: $\frac{0.601}{15.768} \cdot 100 = 3.812 \quad \%$

Mass analysis is converted to volume analysis as follows:

N2: proportional volume: $\frac{76.655}{28} = 2.738$

CO2: proportional volume: $\frac{19.533}{44} = 0.444$

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: $\frac{0.444}{3.301} \cdot 100 = 13.45$ %

O2: $\frac{0.119}{3.301} \cdot 100 = 3.605$ %

==

Alternative method:

Consider 100 kg of fuel.

Convert the components to kmol and write down the combustion eqn.

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

$N_{N2} := \frac{1.5}{28}$ i.e. $N_{N2} = 0.054$ kmol

$N_{O2} := \frac{3.5}{32}$ i.e. $N_{O2} = 0.109$ kmol

Disregard ash, which does not react.

$7\ C + 5\ H_2 + 0.054\ N_2 + 0.109\ O_2 + a\ (O_2 + 3.76\ N_2) = x\ CO_2 + y\ H_2O + z\ N_2$

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:

$7\ C + 5\ H_2 + 0.054\ N_2 + 0.109\ O_2 + 9.391\ (O_2 + 3.76\ N_2) = 7\ CO_2 + 5\ H_2O + 35.364\ N_2$

Therefore, AF ratio:

$$AF = \frac{9.391 \cdot 4.76 \cdot 29}{100} = 12.963$$ **....stoichiometric AF ratio**

This matches well with the earlier AF value of 13.065

Then, mass analysis of dry products:

CO2: $$\frac{7 \cdot 44}{7 \cdot 44 + 35.364 \cdot 28} \cdot 100 = 23.725 \quad \%$$

N2: $$\frac{35.364 \cdot 28}{7 \cdot 44 + 35.364 \cdot 28} \cdot 100 = 76.275 \quad \%$$

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:

$$7\ CO_2 + 5\ H_2O + (35.364 + 9.391 * 0.2 * 3.76)\ N_2 + (9.391 * 0.2)\ O_2$$

Percentage of CO2, N2 and O2 by volume in products (remembering that the combustion eqn is a 'mole eqn' or 'volume eqn.'):

CO2: $$\frac{7}{7 + (35.364 + 9.391 \cdot 0.2 \cdot 3.76) + 9.391 \cdot 0.2} \cdot 100 = 13.644 \quad \%$$

N2: $$\frac{(35.364 + 9.391 \cdot 0.2 \cdot 3.76)}{7 + (35.364 + 9.391 \cdot 0.2 \cdot 3.76) + 9.391 \cdot 0.2} \cdot 100 = 82.695 \quad \%$$

O2: $$\frac{9.391 \cdot 0.2}{7 + (35.364 + 9.391 \cdot 0.2 \cdot 3.76) + 9.391 \cdot 0.2} \cdot 100 = 3.661 \quad \%$$

Note again, that these values match well with the values obtained earlier.

==

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)

psat := (kPa)	tsat := (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
10	45.81
15	53.97
20	60.06
25	64.97
30	69.1
40	75.87
50	81.33
75	91.78
100	99.63
125	105.99

Examples:

TSAT(P) := linterp(psat, tsat, P) TSAT(10) = 45.81 C

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:

C3H8 + 5.(1.5) (O2 + 3.76 N2) = 3. CO2 + 4. H2O + 18.8. N2 + (0.5 * 5) O2 + (0.5 * 5 * 3.76) N2

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

$p_w = y_{H2O} \cdot P$ ...partial pressure of water vapor

Now, mole fraction of water vapor = 10.61% = 0.1061

i.e. $p_w = 0.1061$ bar

i.e. $p_w := 10.61$ kPa

Now, corresponding to this p_w, find the sat. temp from the Mathcad Function written above:

$T_{dewpoint} := TSAT(p_w)$

i.e. $T_{dewpoint} = 46.806$ 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:

$$y_{H2O}(percent\_excess\_air) := \frac{4}{N_{tot}(percent\_excess\_air)}$$

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.

$p_w(percent\_excess\_air, P) := y_{H2O}(percent\_excess\_air) \cdot P$ bar...partial pressure of water vapor

Now, dew point temp is the sat. temp. of water vapor corresponding to this pw.

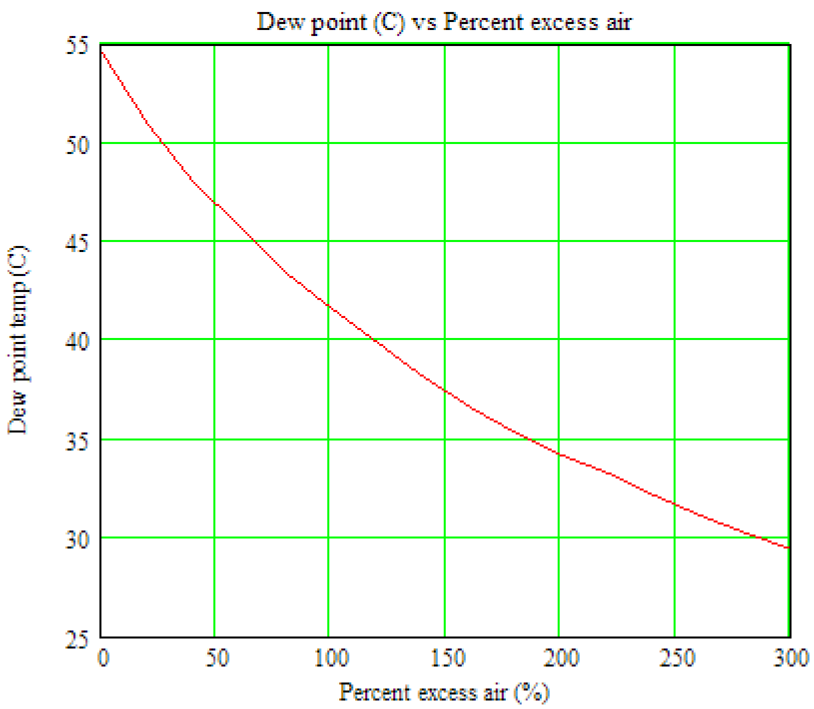
$T_{dewpoint}(percent\_excess\_air, P) := TSAT(p_w(percent\_excess\_air, P) \cdot 100)$ ...pressure in kPa

$T_{dewpoint}(percent\_excess\_air, P) = 46.806$ C ... Ans.

Now, plot $T_{dewpoint}$ vs percent excess air:

percent_excess_air := 0, 20 .. 300 ...define a range variable

percent_excess_air	$T_{dewpoint}$(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



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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. $AF_{stoich} = 15.136$ **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]

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_xH_y + 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: $2 \cdot 22.128 = 2 \cdot 12.1 + 2 \cdot 3.8 + 0.9 + b$ 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:

$C_{13}H_{23.112}$ + 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: $C_{13}H_{23.112}$ 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:

$C_{13}H_{23.112}$ + (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. $AF_{stoich} = 14.472$ **..Stoichiometric AF ratio by mass. .... Ans.**

Excess Air used:

Since actual AF > AF_{stoich}, excess air is used:

$$\frac{AF}{AF_{stoich}} = 1.178$$ **..i.e. 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. $$Q = \sum_{p} n_e \cdot \left(h_{f0} + \Delta h\right)_e - \sum_{r} n_i \cdot \left(h_{f0} + \Delta h\right)_i$$

Now, the eqn for the chemical reaction for stoichiometric combustion is:

$$C_8H_{18} + 12.5\ (O2 + 3.76\ N2) = 8\ CO2 + 9\ H2O + 12.5 * 3.76 * N2$$

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:

$$C_8H_{18} + 1.5 * 12.5 * (O2 + 3.76\ N2) = 6\ CO2 + 2\ CO + 9\ H2O + 7.25\ O2 + 70.5\ N2$$

All reactants and products are in gaseous condition.

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_{prod} and H_{react} separately, to apply the I Law:

$$H_{products} = \sum_{p} n_e \cdot (h_{f0} + \Delta h)_e$$

Now, Δh 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:

$$H_{products} := 6\cdot(-393520 + 4008) + 2\cdot(-110530 + 2975) + 9\cdot(-241820 + 3452) + 7.25\cdot(0 + 3029) + 70.5\cdot(0 + 2971)$$

i.e. $H_{products} = -4.466 \times 10^{6}$ kJ/kmol fuel

And, $H_{reactants} = \sum_{r} n_i \cdot (h_{f0} + \Delta h)_i$

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: $Q := H_{products} - H_{reactants}$

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 Δh 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) --> $(h_{400} - h_{298})$ = (13372 - 9364) = 4008 kJ/kmol

CO (g) --> $(h_{400} - h_{298})$ = (11644 - 8669) = 2975 kJ/kmol

H2O (g) --> $(h_{400} - h_{298})$ = (13356 - 9904) = 3452 kJ/kmol

O2 (g) --> $(h_{400} - h_{298})$ = (11711 - 8682) = 3029 kJ/kmol

N2 (g) --> $(h_{400} - h_{298})$ = (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 Δh as (cp . ΔT), 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:

$$cp_{CO2}(T) := \left(45.369 + 3.688 \cdot 10^{-3} \cdot T - 9.619 \cdot 10^{5} \cdot T^{-2}\right) \quad \text{kJ/kmol}$$

$$cp_{CO}(T) := \left(28.068 + 4.631 \cdot 10^{-3} \cdot T - 0.258 \cdot 10^{5} \cdot T^{-2}\right) \quad \text{kJ/kmol}$$

$$cp_{H2O}(T) := 28.85 + 12.055 \cdot 10^{-3} \cdot T + 1.066 \cdot 10^{5} \cdot T^{-2} \quad \text{kJ/kmol}$$

$cp_{O2}(T) := \left(30.255 + 4.207 \cdot 10^{-3} \cdot T - 1.887 \cdot 10^{5} \cdot T^{-2}\right)$ 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

$cp_{NH3}(T) := \left(29.747 + 25.108 \cdot 10^{-3} \cdot T - 1.546 \cdot 10^{5} \cdot T^{-2}\right)$ kJ/kmol

$cp_{CH4}(T) := \left(17.449 + 60.449 \cdot 10^{-3} \cdot T + 1.117 \cdot 10^{-6} \cdot T^{2} - 7.204 \cdot 10^{-9} \cdot T^{3}\right)$ kJ/kmol

$cp_{SO2}(T) := \left(47.381 + 6.66 \cdot 10^{-3} \cdot T - 8.439 \cdot 10^{5} \cdot T^{-2}\right)$ 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_{400} - h_{298}) = $\int_{298}^{400} cp_{O2}(T)\, dT = 3.074 \times 10^{3}$ kJ/kmol

N2 (g) --> (h_{400} - h_{298}) = $\int_{298}^{400} cp_{N2}(T)\, dT = 2.986 \times 10^{3}$ kJ/kmol

Then, we have:

$$H_{products} := 6\cdot(-393520 + 3936) + 2\cdot(-110530 + 3006) + 9\cdot(-241820 + 3463) + 7.25\cdot(0 + 3074) + 70.5\cdot(0 + 2986)$$

i.e. $H_{products} = -4.465 \times 10^{6}$ kJ/kol fuel

And, $H_{reactants} = \sum_{r} n_i \cdot (h_{f0} + \Delta h)_i$

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: $Q := H_{products} - H_{reactants}$

i.e. $Q = -4.257 \times 10^{6}$ 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_8H_{18}, 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_8H_{18} + 3 * 12.5 (O2 + 3.76) N2 = 8 CO2 + 9 H2O + 25 O2 + 141 N2

For adiabatic flame temp, Q = 0:

Then:

$$H_{reactants} = H_{products} \qquad \text{.....eqn. (A)}$$

And, $$H_{reactants} = \sum_{r} n_i \cdot \left(h_{f0} + \Delta h\right)_i$$

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,

$$H_{products} = \sum_{p} n_e \cdot (h_{f0} + \Delta h)_e$$

i.e. $$H_{products} = 8\cdot(-393520 + \Delta h_{CO2}) + 9\cdot(-241820 + \Delta h_{H2O}) + 25\cdot(0 + \Delta h_{O2}) + 141\cdot(0 + \Delta h_{N2})$$

....siince h_{f0} = 0 for O2 and N2

i.e. $$H_{products} = -8\cdot 393520 - 9\cdot 241820 + 8\cdot\Delta h_{CO2} + 9\cdot\Delta h_{H2O} + 25\cdot\Delta h_{O2} + 141\cdot\Delta h_{N2}$$

i.e. $$H_{products} = -5.325\cdot 10^6 + (8\cdot\Delta h_{CO2} + 9\cdot\Delta h_{H2O} + 25\cdot\Delta h_{O2} + 141\cdot\Delta h_{N2})$$

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):

$$(8\cdot\Delta h_{CO2} + 9\cdot\Delta h_{H2O} + 25\cdot\Delta h_{O2} + 141\cdot\Delta h_{N2}) = 5.325\cdot 10^6 - 2.499\cdot 10^5$$

i.e. $$(8\cdot\Delta h_{CO2} + 9\cdot\Delta h_{H2O} + 25\cdot\Delta h_{O2} + 141\cdot\Delta h_{N2}) = 5.075 \times 10^6$$ **.....eqn. (B)**

Assuming that all the products are only N2, we get an approx. value for T_{flame}. 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_{flame}.

We get, approx: $T_{flame} = 1190$ K

Now, start trial and error process to satisfy eqn. (B):

T = 1100 K: LHS of eqn. (B) becomes:

$8\cdot38894 + 9\cdot30167 + 25\cdot26217 + 141\cdot24757 = 4.729\times10^{6}$ ...less than RHS of eqn. (B)

T = 1140 K: LHS of eqn. (B) becomes:

$8\cdot41120 + 9\cdot31876 + 25\cdot27632 + 141\cdot26091 = 4.985\times10^{6}$ ...slightly less than RHS of eqn. (B)

T = 1200 K: LHS of eqn. (B) becomes:

$8\cdot44484 + 9\cdot34476 + 25\cdot29765 + 141\cdot28108 = 5.374\times10^{6}$ ..slightly more than RHS of eqn. (B)

Therefore, interpolate between 1140 K and 1200 K to get the value of T_{flame} to satisfy eqn. (B):

For 1 deg: $$\frac{5.374\times10^{6} - 4.985\times10^{6}}{60} = 6.483\times10^{3}$$

Therefore: $$T_{flame} := 1200 - \frac{\left(5.374\times10^{6} - 5.075\times10^{6}\right)}{\left(6.483\times10^{3}\right)}$$

$T_{flame} = 1.154\times10^{3}$ **K ....Adiabatic flame temp ... Ans.**

Alternatively:

We can use eqns for cp to get Δh for the different components of products, and determine T_{flame} as follows:

We have the eqn. (B):

$$\left(8\cdot\Delta h_{CO2} + 9\cdot\Delta h_{H2O} + 25\cdot\Delta h_{O2} + 141\cdot\Delta h_{N2}\right) = 5.075\times10^{6}$$ **.....eqn. (B)**

Start with a guess value:

TTflame := 1000 K.....guess value

Given

$$\left[\left(8\cdot\int_{298}^{TTflame} cp_{CO2}(T)\,dT + 9\cdot\int_{298}^{TTflame} cp_{H2O}(T)\,dT + 25\cdot\int_{298}^{TTflame} cp_{O2}(T)\,dT\right) \ldots + 141\cdot\int_{298}^{TTflame} cp_{N2}(T)\,dT\right] = 5.075\cdot 10^{6}$$

$\mathrm{Find}(TTflame) = 1.1599\times 10^{3}$

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.

$\text{percent\_excess\_air} := 200$ ..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:

$$H_{reactants} = H_{products}$$ .....**eqn. (A)**

And, $$H_{reactants} = \sum_{r} n_i \cdot \left(h_{f0} + \Delta h\right)_i$$

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 .

Note that $H_{reactants}$ at 25 C does not depend on excess air.

And, we will write $H_{products}$ as a function of percent_excess_air:

$$H_{products} = \sum_{p} n_e \cdot \left(h_{f0} + \Delta h\right)_e$$

i.e.

$$H_{products}(percent\_excess\_air) = 8\cdot\left(-393520 + \Delta h_{CO2}\right) + 9\cdot\left(-241820 + \Delta h_{H2O}\right) \ldots$$
$$+ 12.5\cdot\frac{percent\_excess\_air}{100}\cdot\left(0 + \Delta h_{O2}\right) \ldots$$
$$+ 12.5\cdot 3.76\cdot\left(1 + \frac{percent\_excess\_air}{100}\right)\cdot\left(0 + \Delta h_{N2}\right)$$

....siince h_{f0} = 0 for O2 and N2

Writing Δh as integral of cp.ΔT, we get:

$$H_{products}(percent\_excess\_air) := \left[\begin{array}{l} 8\cdot\left(-393520 + \int_{298}^{TTflame} cp_{CO2}(T)\, dT\right) + 9\cdot\left(-241820 + \int_{298}^{TTflame} cp_{H2O}(T)\, dT\right) \ldots \\ + 12.5\cdot\frac{percent\_excess\_air}{100}\cdot\left(0 + \int_{298}^{TTflame} cp_{O2}(T)\, dT\right) \ldots \\ + 12.5\cdot 3.76\cdot\left(1 + \frac{percent\_excess\_air}{100}\right)\cdot\left(0 + \int_{298}^{TTflame} cp_{N2}(T)\, dT\right) \end{array}\right]$$

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

$$\left[\begin{array}{l} 8\cdot\left(-393520 + \int_{298}^{TTflame} cp_{CO2}(T)\, dT\right) + 9\cdot\left(-241820 + \int_{298}^{TTflame} cp_{H2O}(T)\, dT\right) \ldots \\ + 12.5\cdot\frac{percent\_excess\_air}{100}\cdot\left(0 + \int_{298}^{TTflame} cp_{O2}(T)\, dT\right) \ldots \\ + 12.5\cdot 3.76\cdot\left(1 + \frac{percent\_excess\_air}{100}\right)\cdot\left(0 + \int_{298}^{TTflame} cp_{N2}(T)\, dT\right) \end{array}\right] = -2.499\times 10^{5}$$

Tflame(percent_excess_air) := Find(TTflame) ...Get Tflame as a function of percent_excess_air

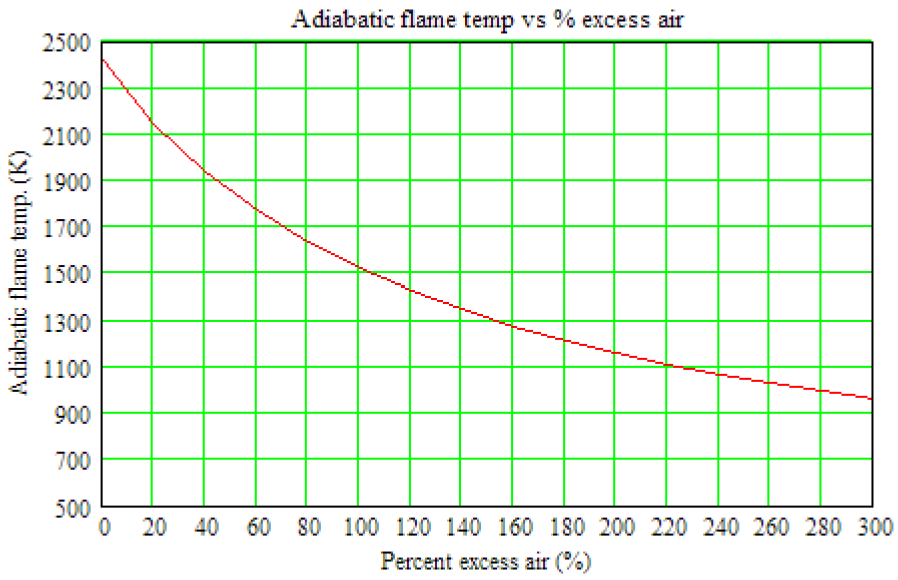
i.e. Tflame(percent_excess_air) = 1.16×10^3 K

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


Adiabatic flame temp vs % excess air
Adiabatic flame temp. (K)
2500
2300
2100
1900
1700
1500
1300
1100
900
700
500
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
Percent excess air (%)

===

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) = x [H2O] + y [CO2] + z [SO2] + w [N2]"

"Collect coeffs of carbon atoms:"

N_C = y

"Collect coeffs of oxygen atoms:"

N_O2 + 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 = 0.09375
w = 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_{actual} = 12	$AF_{stoichio}$ = 12.7
N_C = 7.167 [kmol]	N_{H2} = 4 [kmol]	N_{O2} = 0.0625 [kmol]
N_S = 0.09375 [kmol]	N_{tot} = 41.84 [kmol]	Ratio = 0.9451
Vol_{CO2} = 17.13 [%]	Vol_{N2} = 82.65 [%]	Vol_{SO2} = 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.

==

"**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 * 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]

$AF_{massbasis} = 17.26$

$b = 13.84$ [kmol]

$Percent_{theor,air} = 114$ [%]

$T_{dewpoint} = 49.95$ [C]

$y_{H2O} = 0.1216$

$AF_{kmolbasis} = 67.85$

$AF_{stoichio} = 15.14$

$N_{tot} = 113.8$ [kmol]

$p_w = 12.32$ [kPa]

$x = 1.538$ [kmol]

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.

==

"**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" "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_{H2O} = 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.

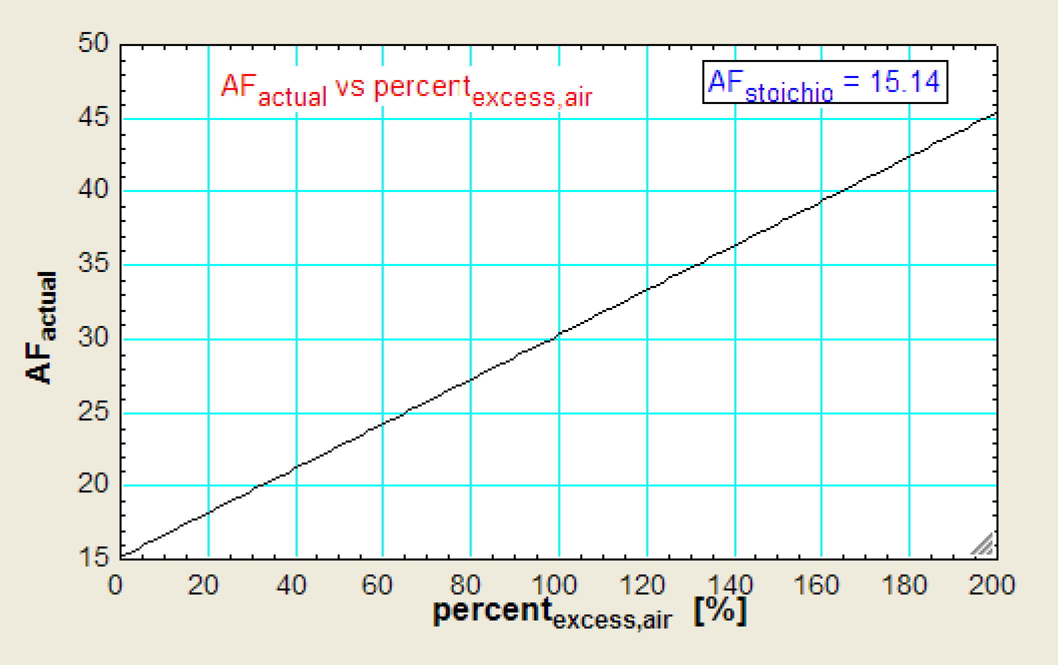
(b) Also, plot the actual AF ratio and dew point temp as excess air varies from 0 to 200%:

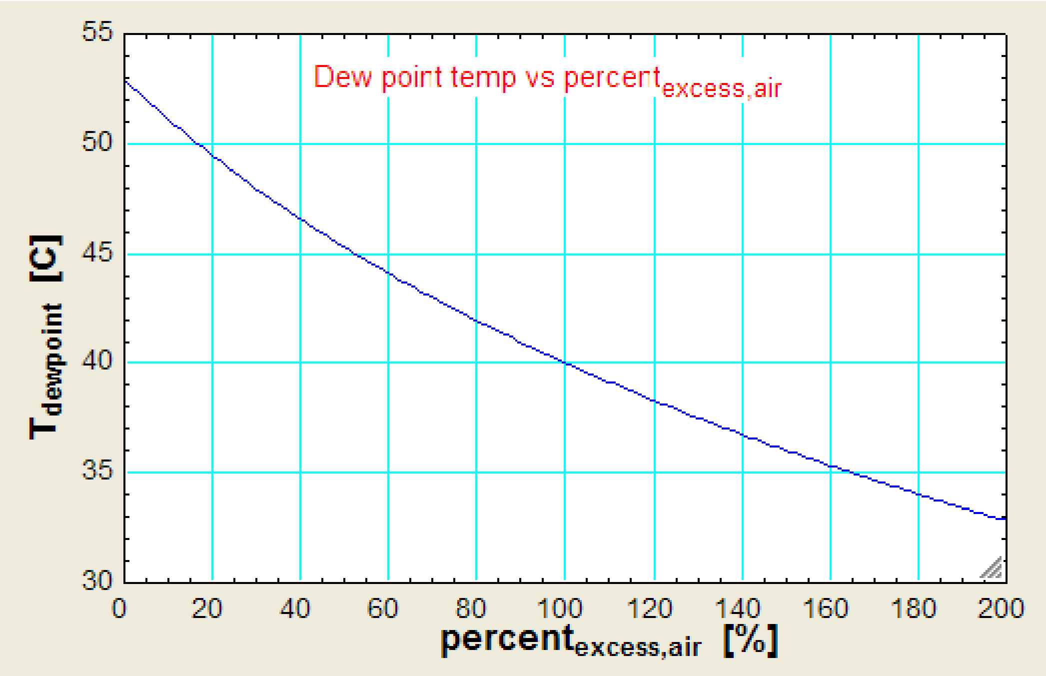
First, compute the Parametric Table:

Table 1

1..11	$percent_{excess,a}$ [%]	AF_{actual}	$T_{dewpoint}$ [C]
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

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:"

Excess_air = Ratio – 100 "%"

Results:

Unit Settings: SI C kPa kJ mass deg

$a = 21.89$ [kmol]

$AF_{massbasis} = 24.1$

$AF_{stoichio} = 15.03$

$Air_{for,C} = 987.8$ [kg]

$Air_{for,H2} = 514.8$ [kg]

$Air_{total} = 1503$ [kg]

$b = 9.277$ [kmol]

$Excess_{air} = 60.41$ [%]

$percent_{carbon} = 85.2$ [%]

$percent_{hydrogen} = 14.8$ [%]

$Ratio = 160.4$

$x = 8.9$ [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
```

```
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
```

```
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

"_________________________________"
```

```
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_f0 = 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"

"(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

$h_{f0,CH4,g}$ = -74850 [kJ/kmol]
$h_{f0,CO2,g}$ = -393520 [kJ/kmol]
$h_{f0,H2O,liq}$ = -285820 [kJ/kmol]
$h_{f0,H2O,vap}$ = -241820 [kJ/kmol]
$H_{P,case,a}$ = -965160 [kJ/kmol]
$H_{P,case,b}$ = -877160 [kJ/kmol]
$H_{P,case,c}$ = -791656 [kJ/kmol]
$H_{P,case,d}$ = -791695 [kJ/kmol]
$h_{RP,caseb,perkg}$ = -50144 [kJ/kg]
$h_{RP,casec,perkg}$ = -50037 [kJ/kg]
$h_{RP,cased,perkg}$ = -50069 [kJ/kg]
$h_{RP,case,a}$ = -890310 [kJ/kmol]
$h_{RP,case,b}$ = -802310 [kJ/lmol]
$h_{RP,case,c}$ = -800593 [kJ/kmol]
$h_{RP,case,d}$ = -801097
$h_{RP,perkg,case,a}$ = -55644 [kJ/kg]
$H_{R,case,a}$ = -74850 [kJ/kmol]
$H_{R,case,b}$ = -74850 [lJ/kmol]
$H_{R,case,c}$ = 8937 [kJ/kmol]
$H_{R,case,d}$ = 9402
T = 1000 [K]

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

$h_{f0,C8H18,liq}$ = -249950 [kJ/kmol] H_P = -250989 [kJ/kmol]

H_R = -250989 [kJ/kmol] T1 = 298 [K]

T_{flame} = 961.7 [K]

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:"

"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]
$h_{f0,C8H18,liq}$ = -249950 [kJ/kmol]	H_P = -250470 [kJ/kmol]
H_R = -250470 [kJ/kmol]	$percent_{excess,air}$ = 100 [%]
T1 = 298 [K]	T_{flame} = 1507 [K]

Thus:

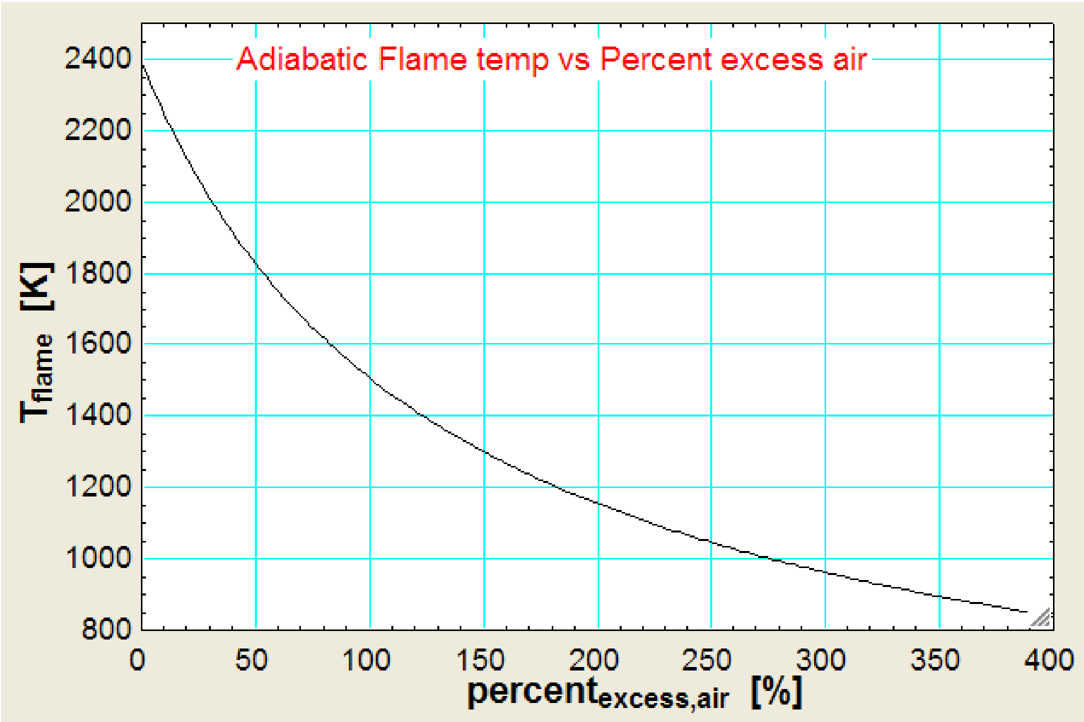
Adiabatic flame temp for 100% excess air = 1507 K … Ans.

(b) Also, plot the adiabatic flame temp as excess air varies from 0 to 300%:

First, compute the Parametric Table:

1..21	1 $percent_{excess,a}$ [%]	2 T_{flame} [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)

P1 / Pf = (N_reactants / N_products) * (T1 / Tf) "….finds Pf, kPa"

"Now, to find heat transfer, Q: Apply the I Law:"

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"

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

$N_{products}$ = 13.38	$N_{reactants}$ = 13.38	P1 = 200 [kPa]
Pf = 671.1 [kPa]	Q = 70647 [kJ/kmol]	R_u = 8.314 [kJ/kmol-K]
T1 = 298 [K]	Tf = 1000 [K]	U_P = -679451 [kJ/kmol]
U_R = -608804 [kJ/kmol]		

Thus:

Final pressure, Pf = 671.1 kPa …. Ans.

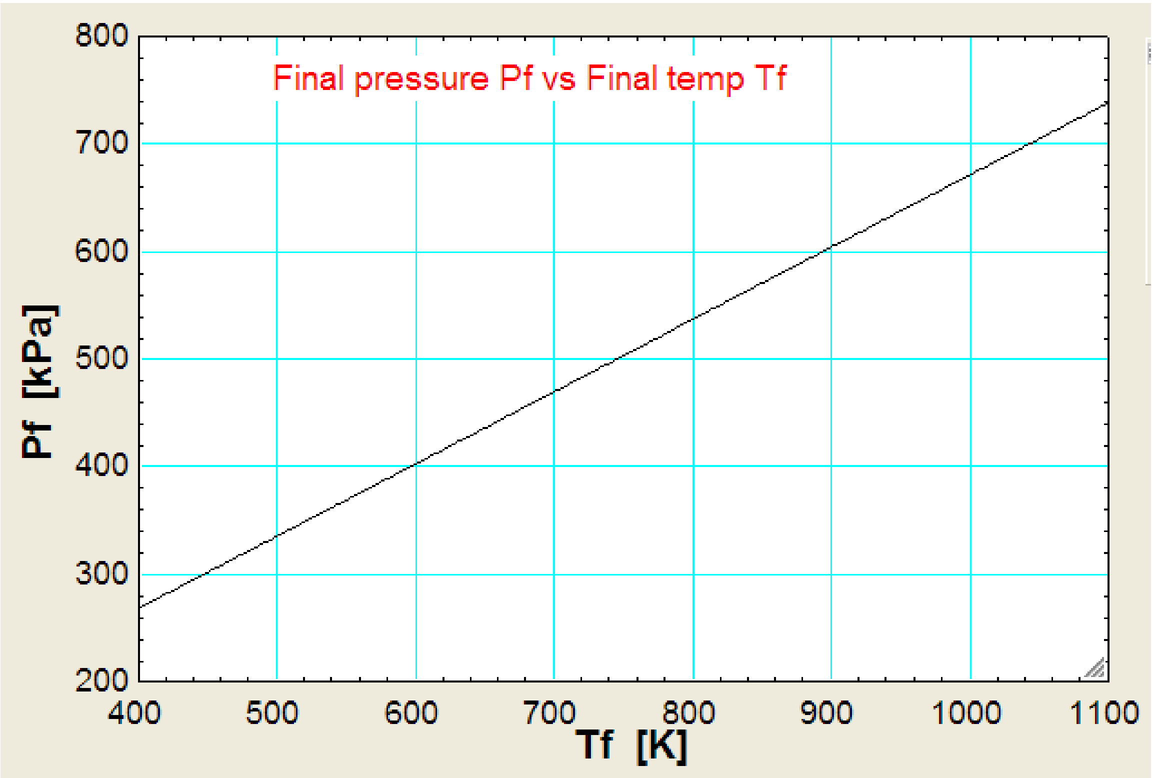
Heat transfer, Q = 70647 kJ/kmol fuel … Ans.

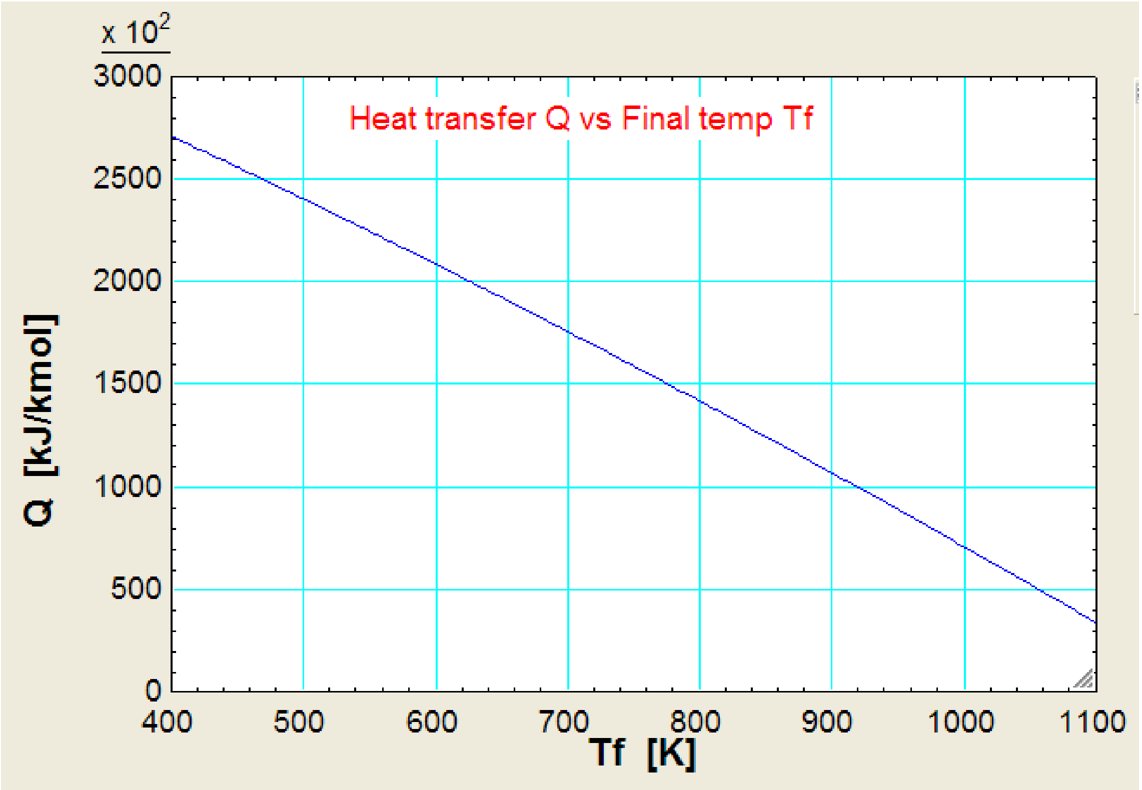
(b) Plot final pressure and heat transfer as the final temp varies from 400 K to 1100 K:

First, compute the Parametric Table:

1..8	Tf [K]	Pf [kPa]	Q [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:





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"**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:

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"

"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]	

Thus:

Heat transfer, Q = -44732 kJ/kmol of fuel …. Ans. (-ve sign indicates heat being rejected)

==

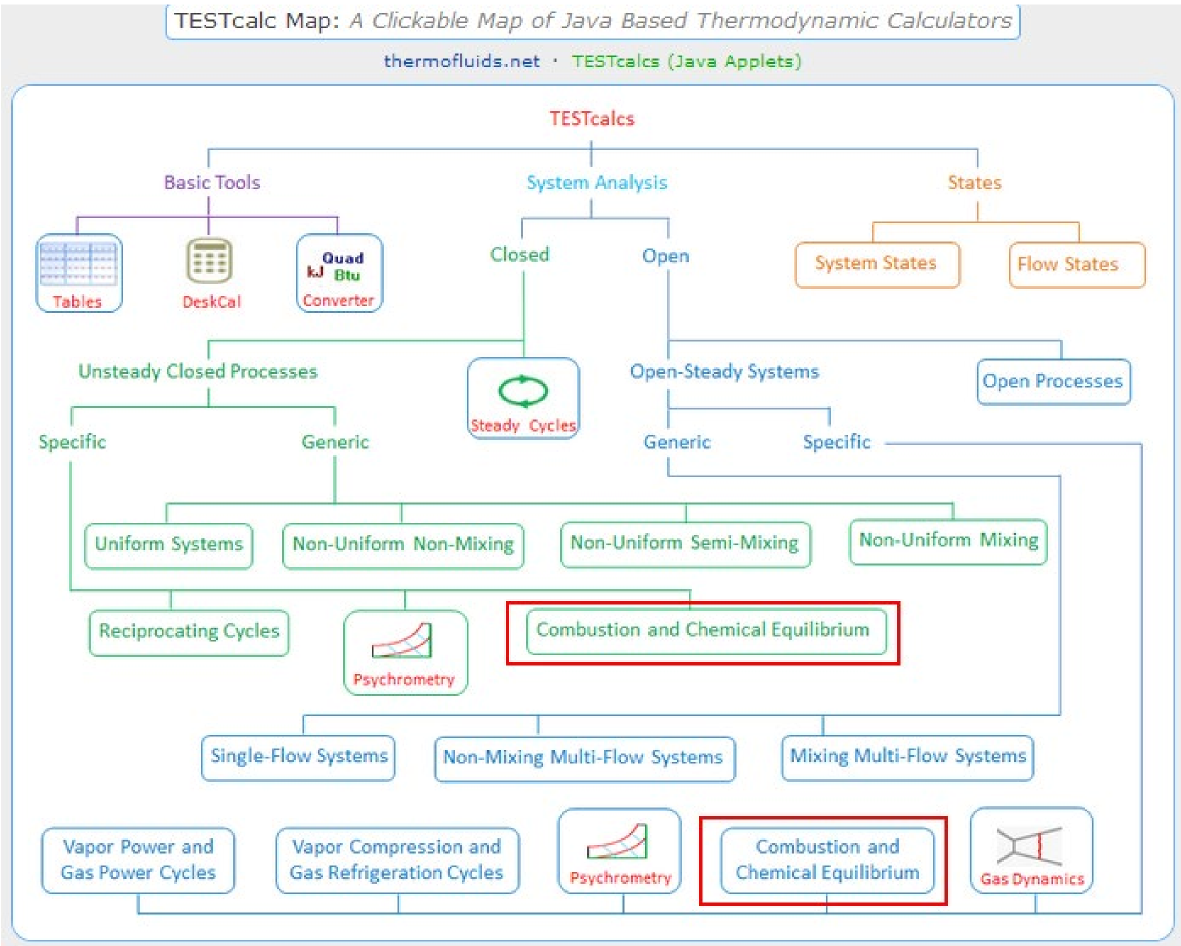
8.4 Problems solved with TEST:

It is very easy and convenient to make combustion calculations with TEST.

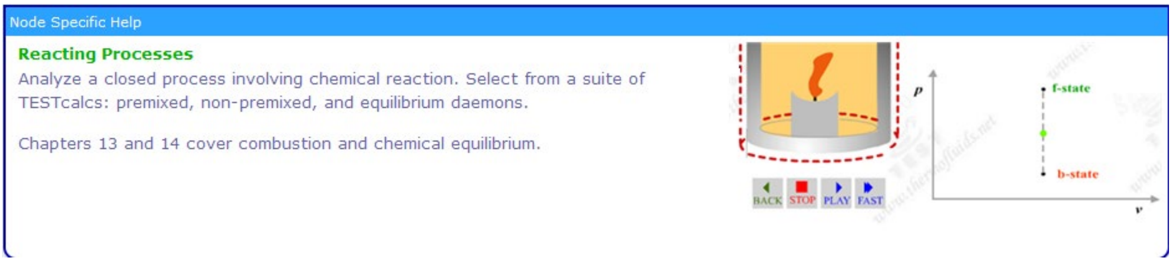
The combustion TEST Calc (or 'daemon' as it was called in earlier versions of TEST) is slightly different to operate compared to other daemons.

Following are the important points to remember:

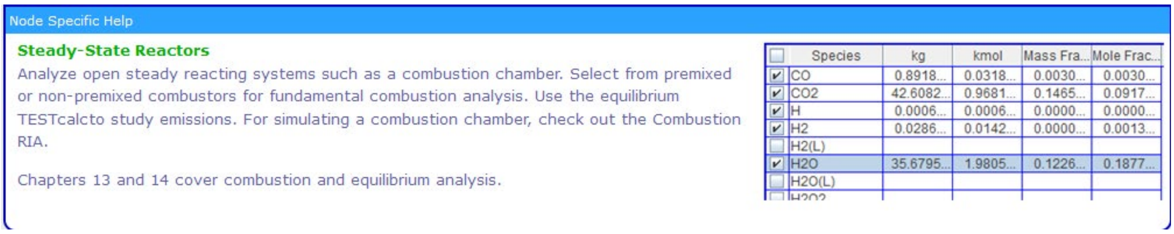
1. As with some other daemons, there are two types of combustion daemons: one for Closed systems and the other for Open systems, as shown below:



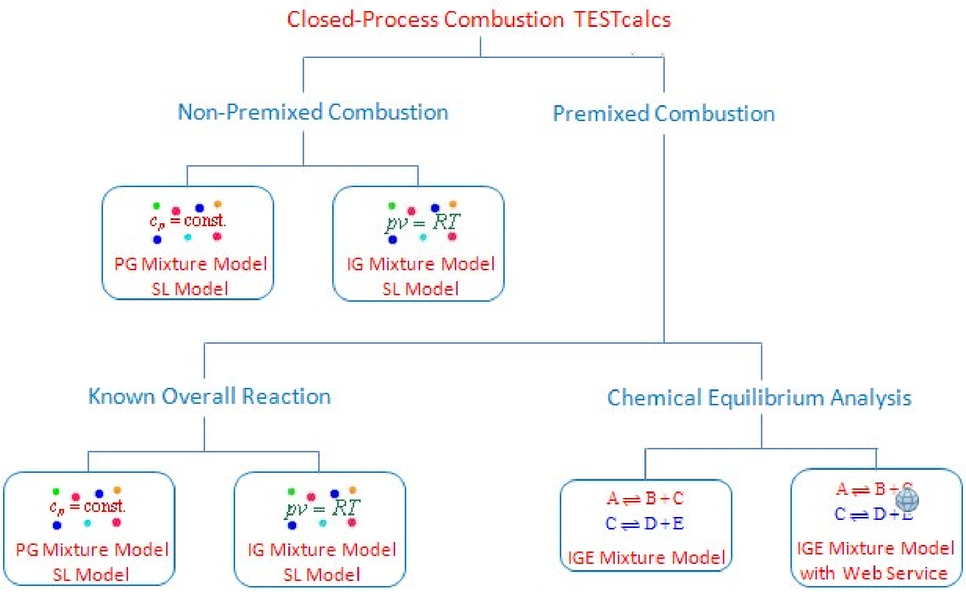
2. Hovering the mouse pointer over Closed ‘Combustion and Chemical Equilibrium’ daemon gives following explanatory pop-up:



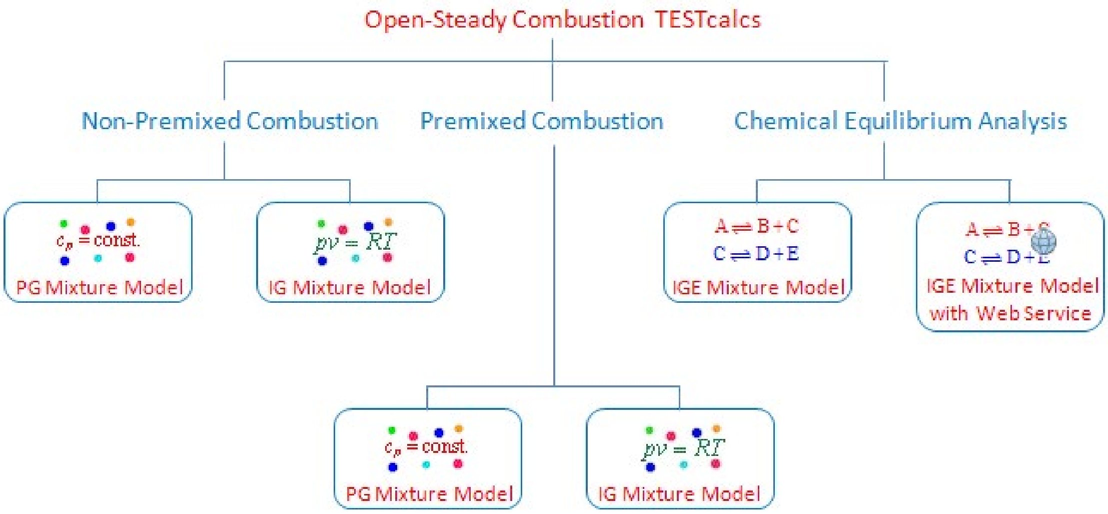
3. Similarly, hovering the mouse pointer over Open ‘Combustion and Chemical Equilibrium’ daemon gives following explanatory pop-up:



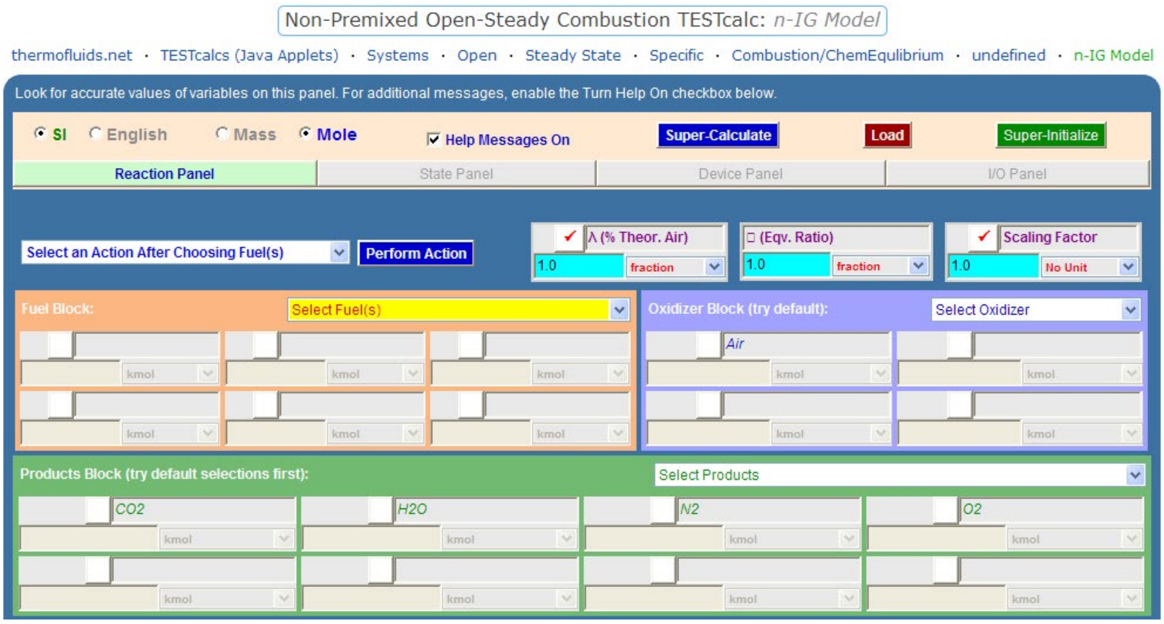
4. Clicking on Closed Process ‘Combustion and Chemical Equilibrium’ gives the following Material selection window:



5. Clicking on Open system 'Combustion and Chemical Equilibrium' gives the following Material selection window:

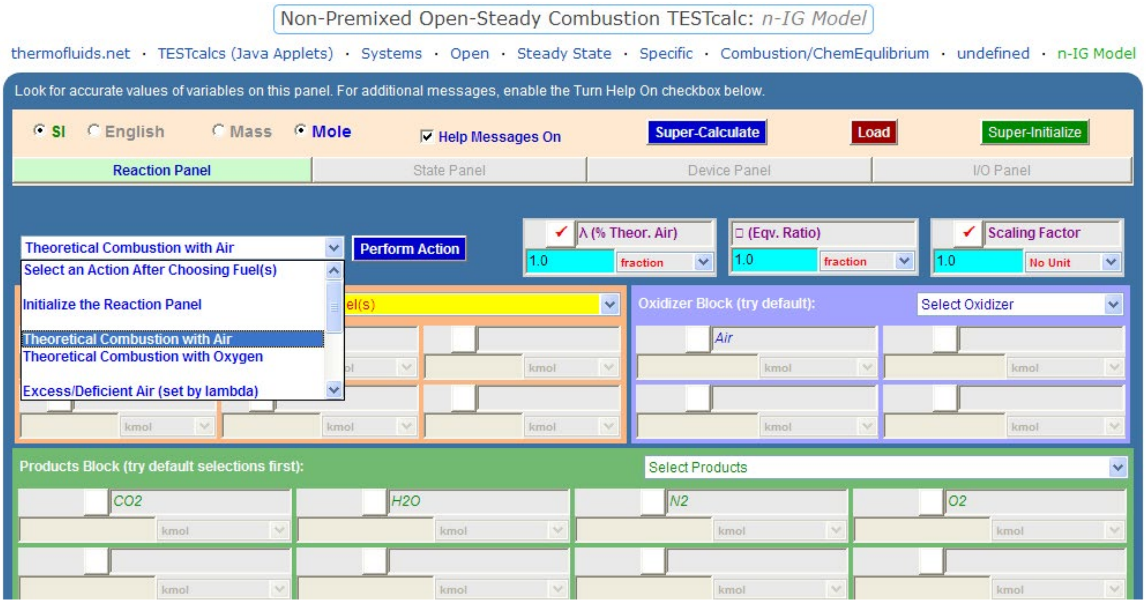


6. Combustion daemon is built on the basic panel called the **'Reaction panel'**. It has 3 sections or blocks as shown below: Fuel block, Oxidizer block and Products block:

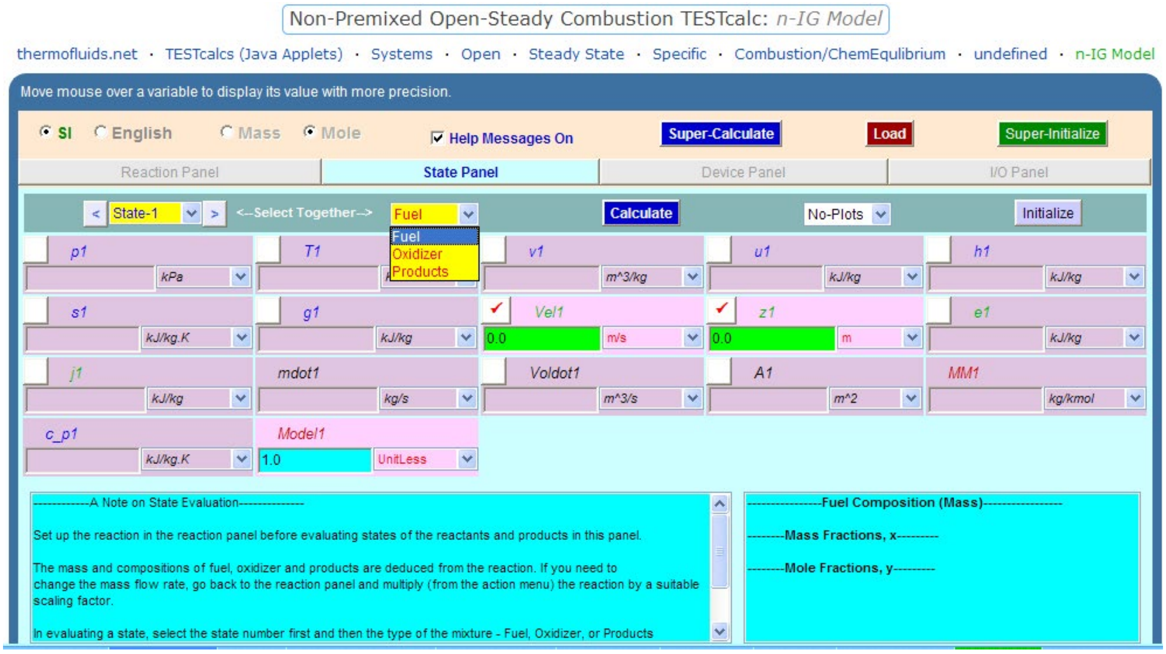


7. We can select any one or more of fuels from the 'Select Fuel(s)' widget. Similarly, any of the oxidizers and Products can be selected from Oxidizer or Products widgets.

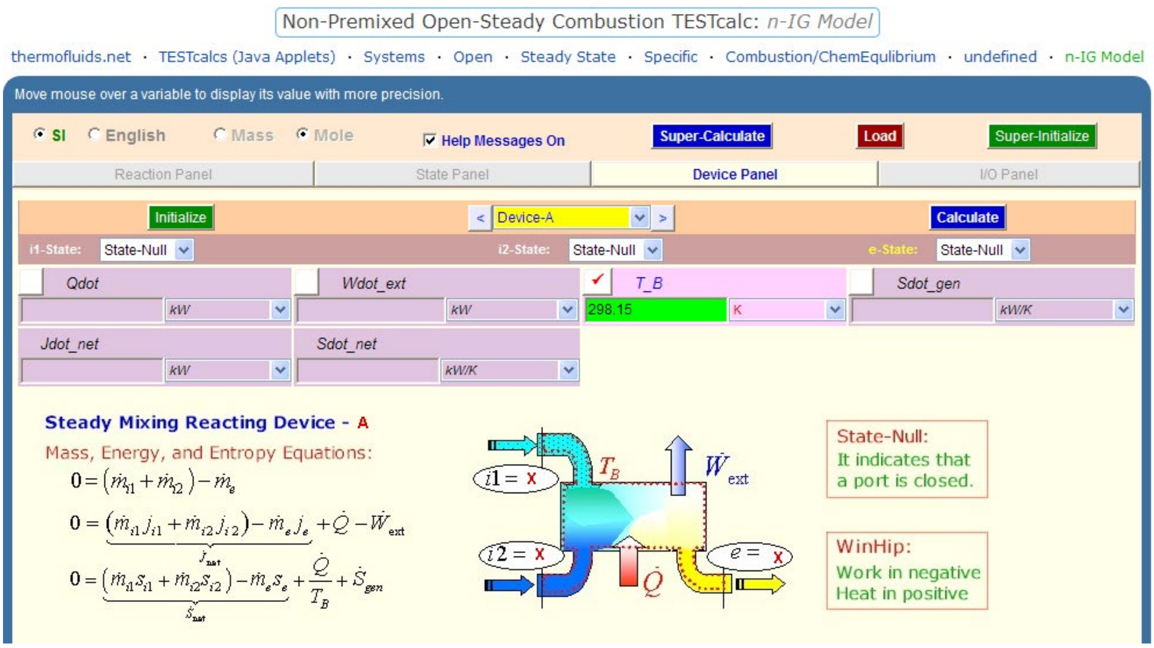
8. After selecting a fuel, choose the required action from the 'Select an action…' widget, and then perform that action by clicking on 'Perform Action':



9. State panel calculates the States of Fuel, oxidizer or Products, as per the selection:



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.



With this short introduction, now let us solve a few standard types of combustion problems:

==

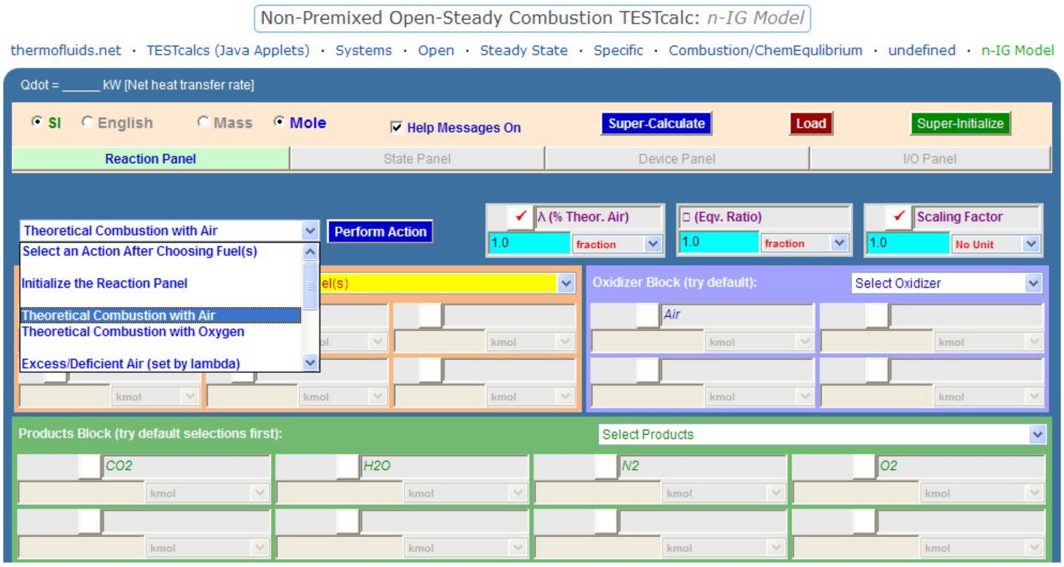
Prob. 8.4.1 Methane(gas) burns with theoretical air. Find out the AF ratio by moles and by mass.

(b) If 50% excess air is supplied, find the composition of products on mole basis, and also the Dew point temp.

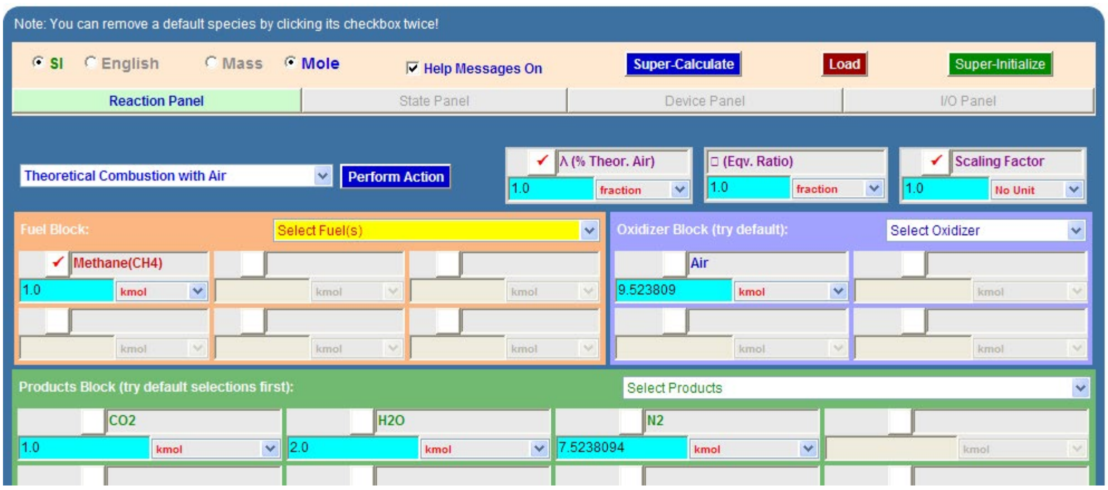
TEST Solution:

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:



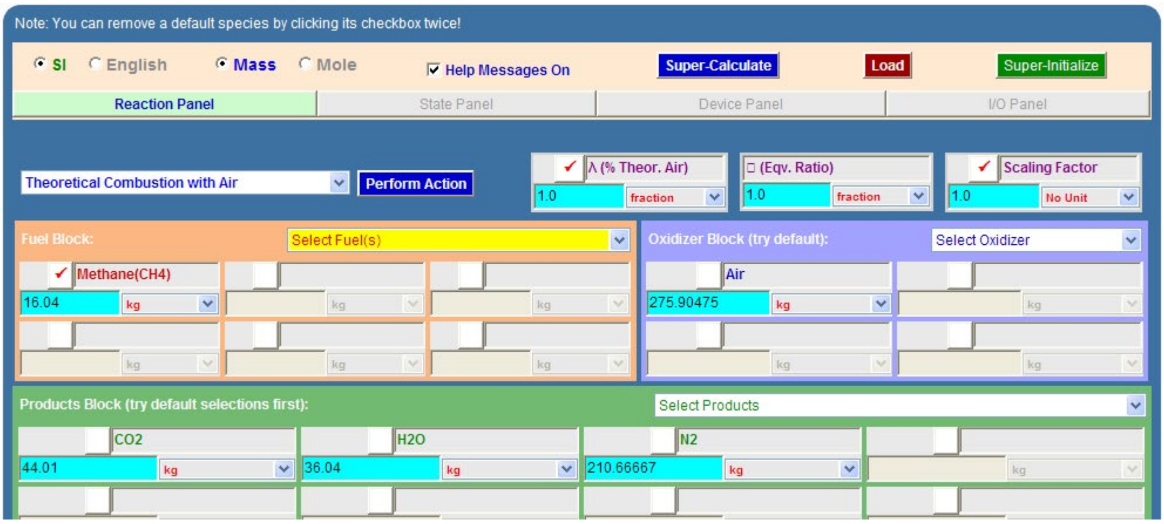
2. Select Methane (CH4) as fuel, 'Theoretical combustion with Air' from Action widget, and click on 'Perform Action'. We get:



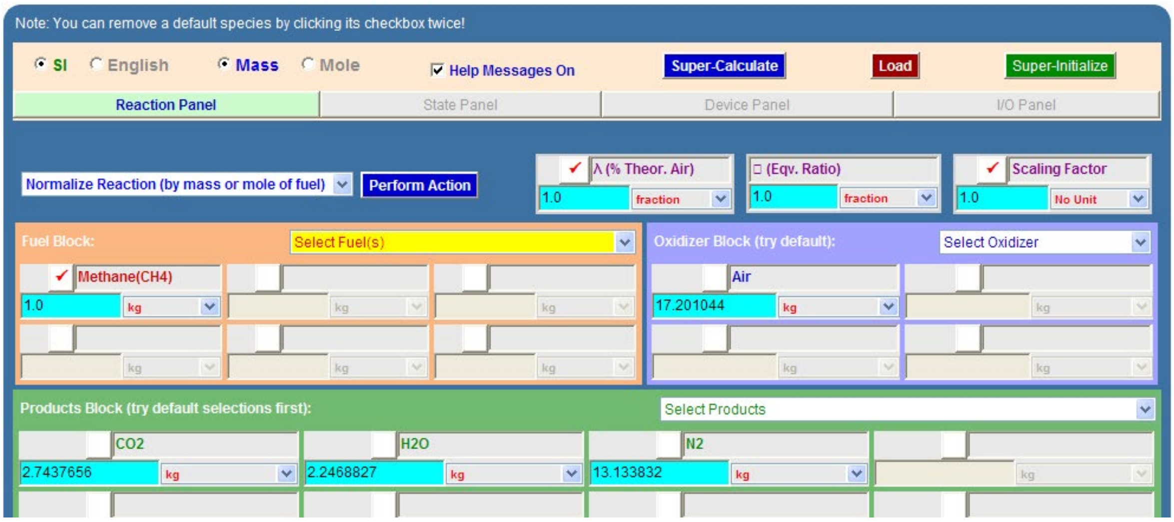
Note that in the above, **Moles** radio button was chosen by default; also ‚**Air** as oxidizer was chosen by default. And, products compositions of CO2, H2O and N2, are shown. We find that:

AF ratio on mole basis: 9.5238 …. Ans.

3. **To get AF ratio on Mass basis:** Click **Mass** radio button: immediately, screen changes to:



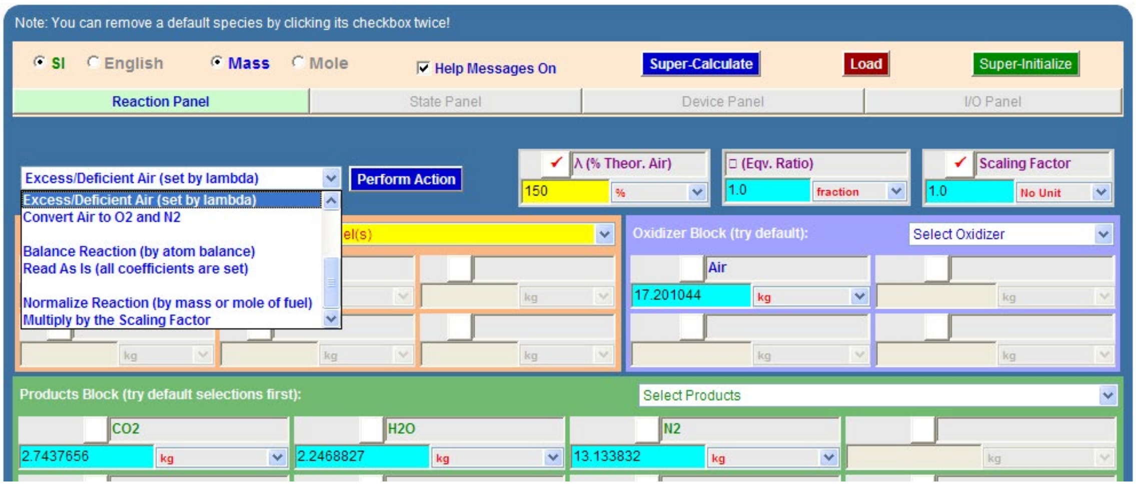
Now, **normalize reaction** to get mass of air for 1 kg of fuel:



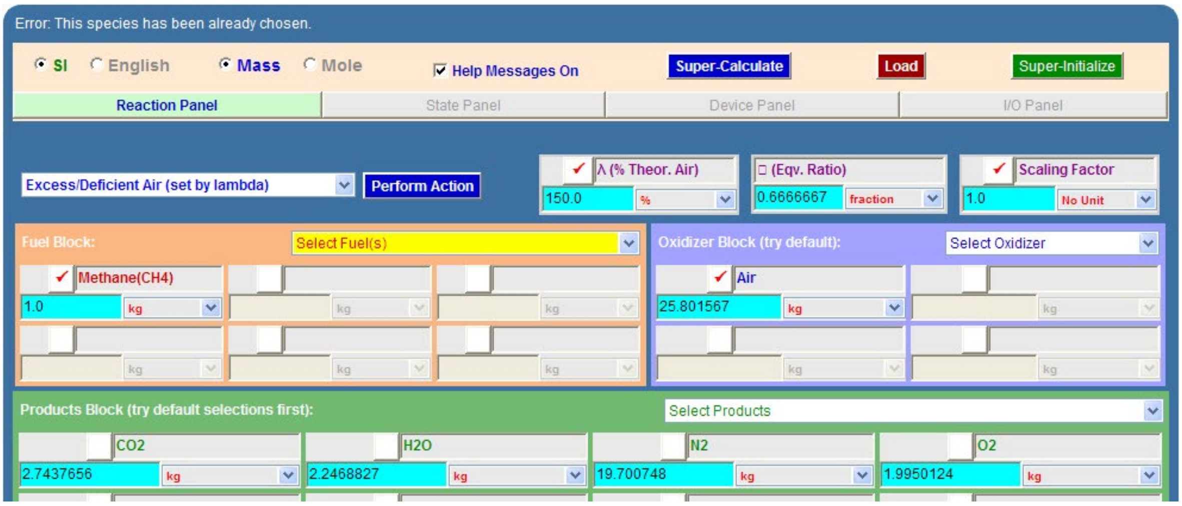
Therefore: AF ratio = 17.2 on mass basis … Ans.

4. **If 50% excess air is supplied:**

Choose λ as 150%, and, from Action widget, select Excess/Deficient Air as shown below:

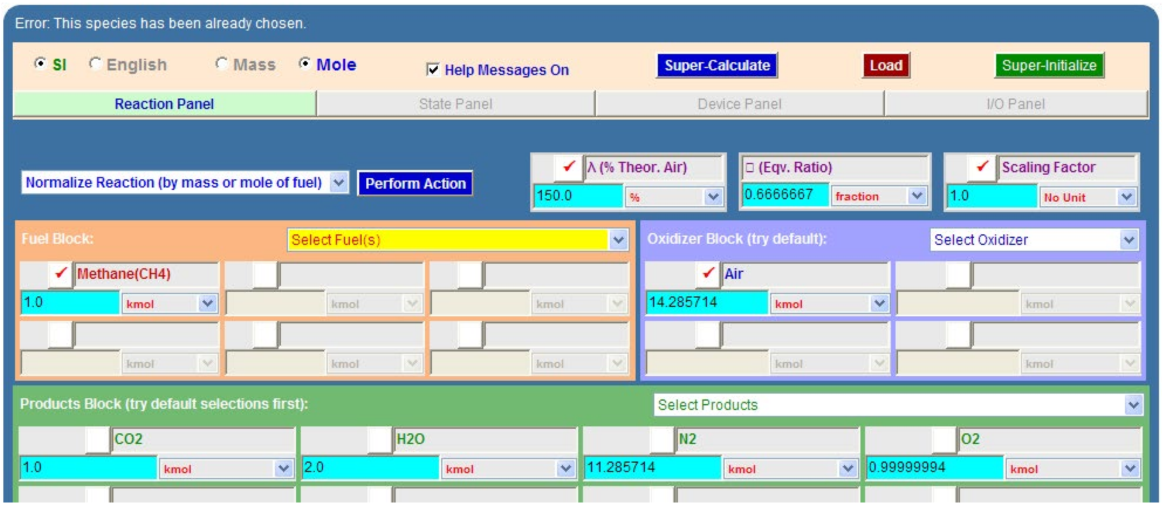


And, Click on 'Perform action'. We get:



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:



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.

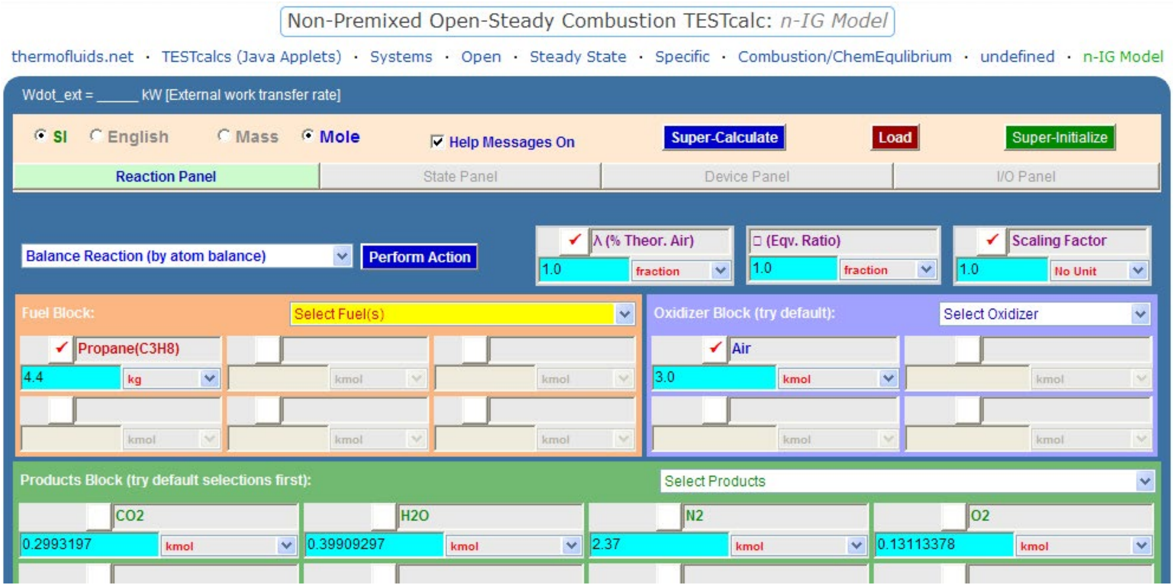
==

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]

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. 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:



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

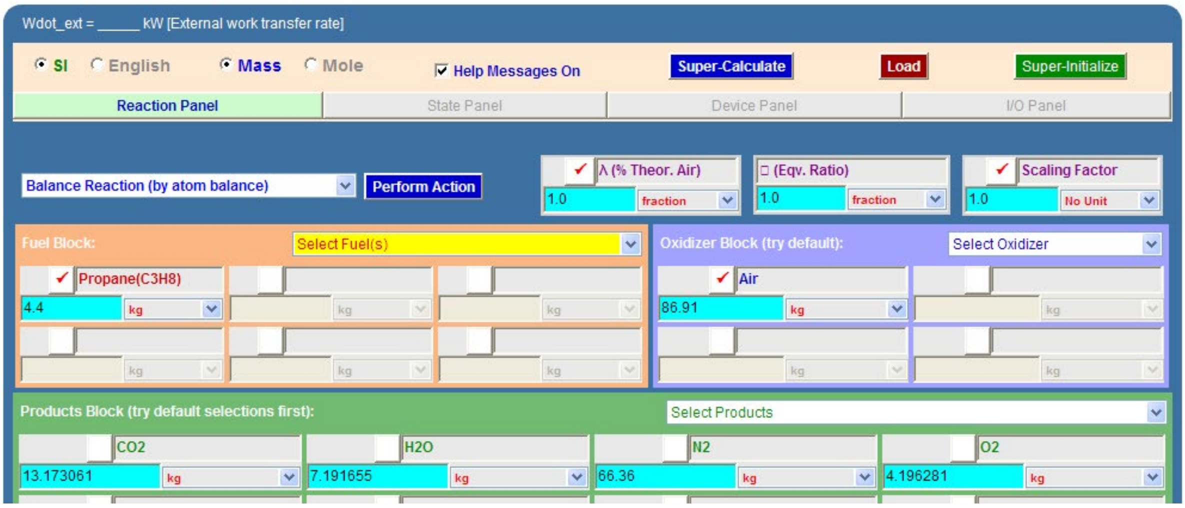
Therefore,

mole% of CO2 = 0.2993 * 100 / 2.8 = 10.689% … Ans.

mole% of N2 = 2.37 * 100 / 2.8 = 84.643% …. Ans.

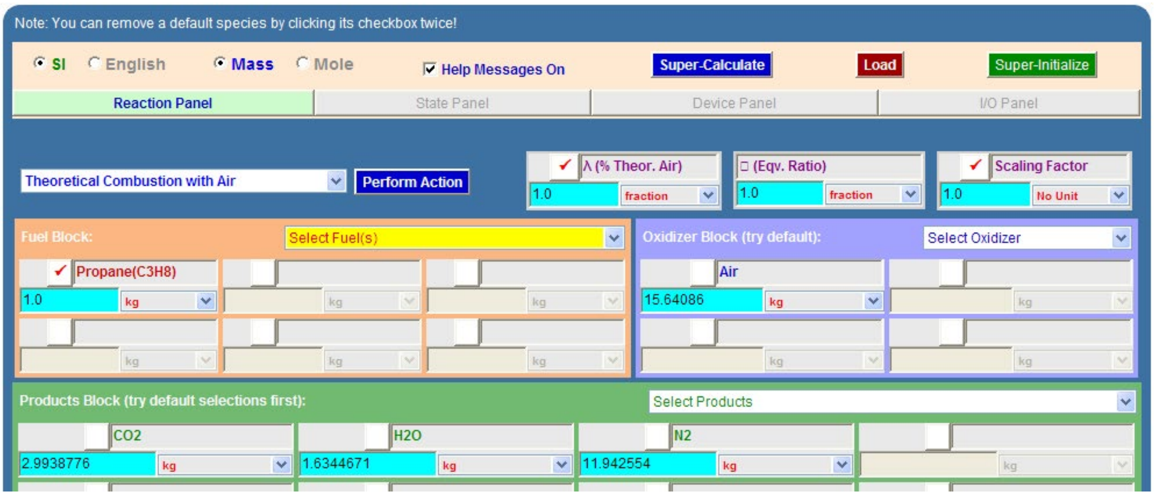
mole% of O2 = 0.1311 * 100 / 2.8 = 4.682% … Ans.

2. To get results on mass basis for this reaction, we select Mass radio button, and we get:



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:



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.

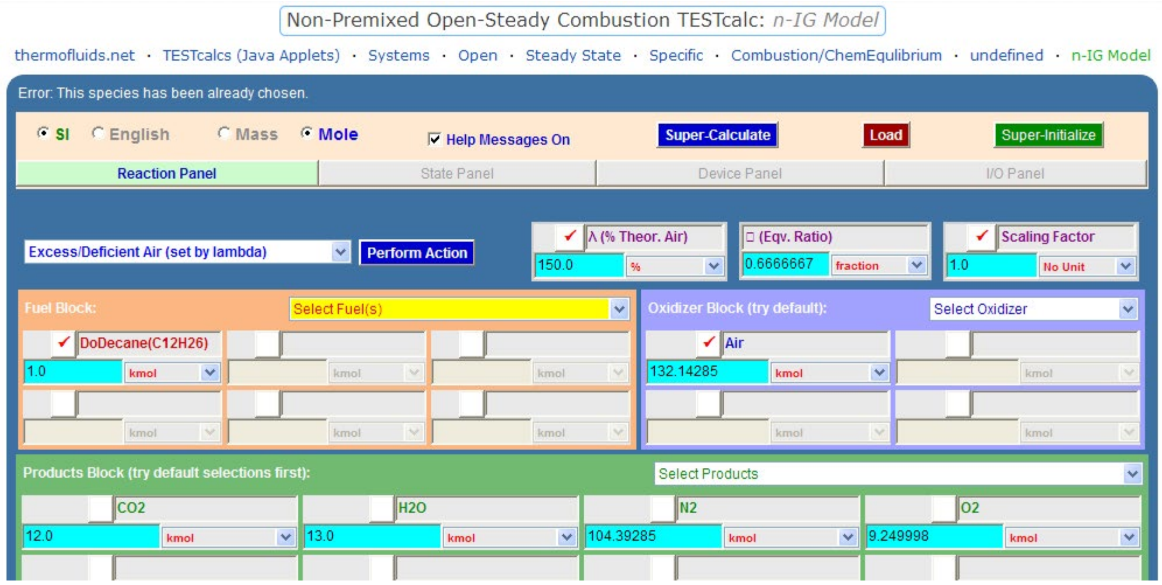
===

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:

1. 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:



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.

2. **Dew point temp:**

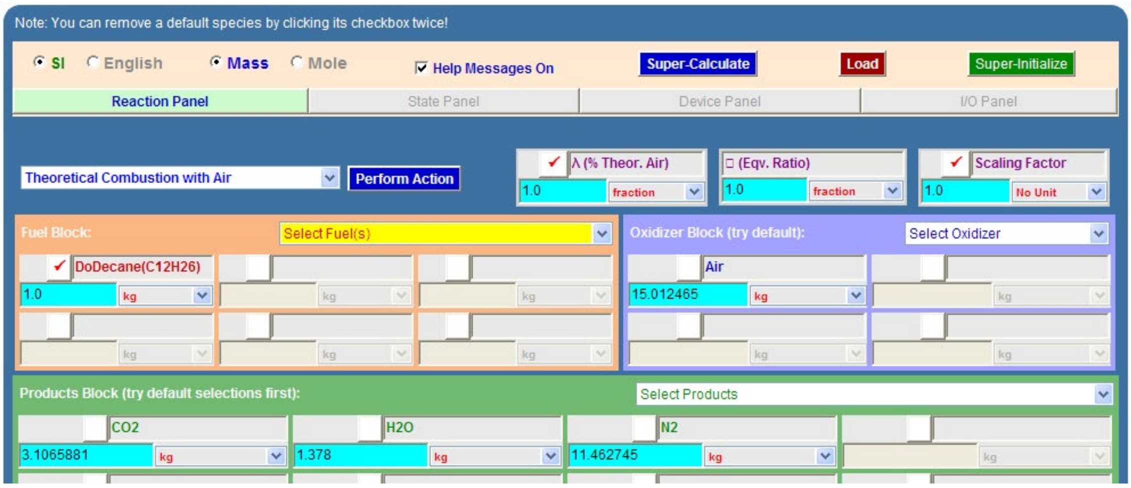
   Knowing that mole fraction of H2O is 0.09377, we get the partial pressure of water vapor in products = 101 * 0.09377 = 9.471 kPa (where P = 101 kPa = total pressure).

   Dew point temp is the sat. temp corresponding to this partial pressure:

   We get: Dew point temp = 44.642 C …. Ans.

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.

===

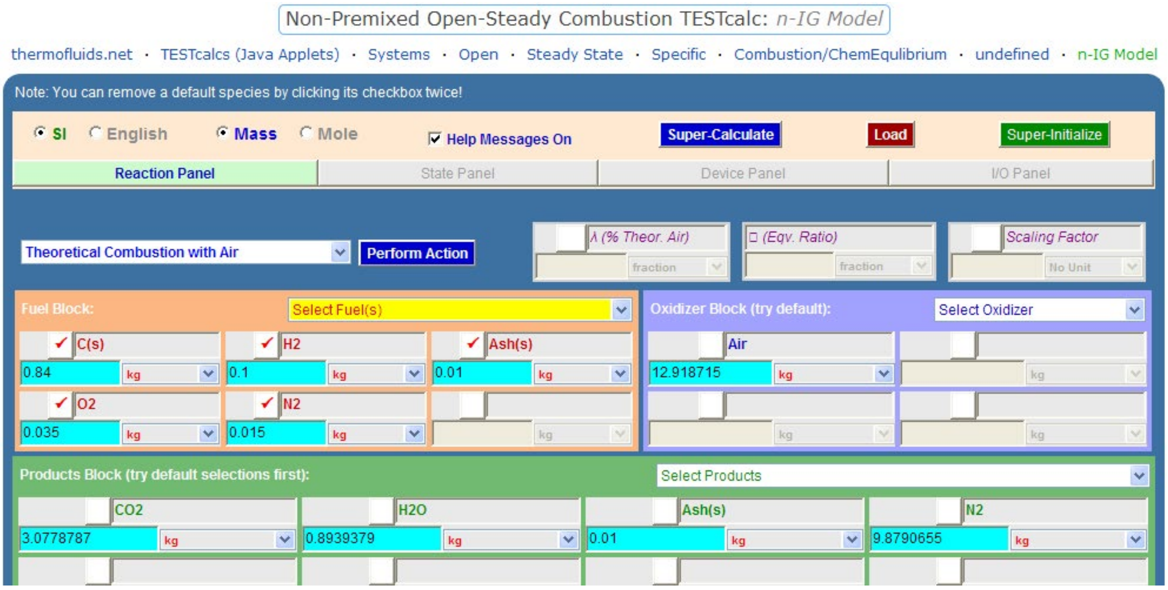
Prob. 8.4.4 A sample of fuel has following percentage composition by weight: C = 84%, O2 = 3.5%, H2 = 10%, Ash = 1%, N2 = 1.5%. Determine: (i) stoichiometric AF ratio by mass (ii) if 20% excess air is supplied, find the percentage composition of dry flue gases by volume. [VTU]

Note: This is the same as Prob.8.2.2, solved with Mathcad.

Now, let us solve it with TEST:

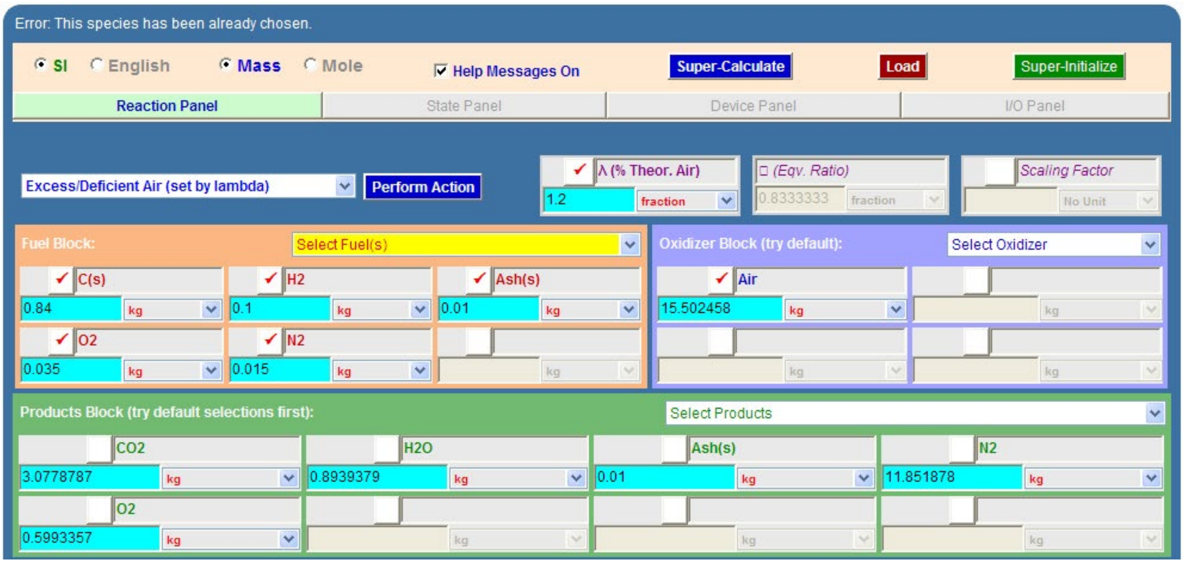
Following are the steps:

1. 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:

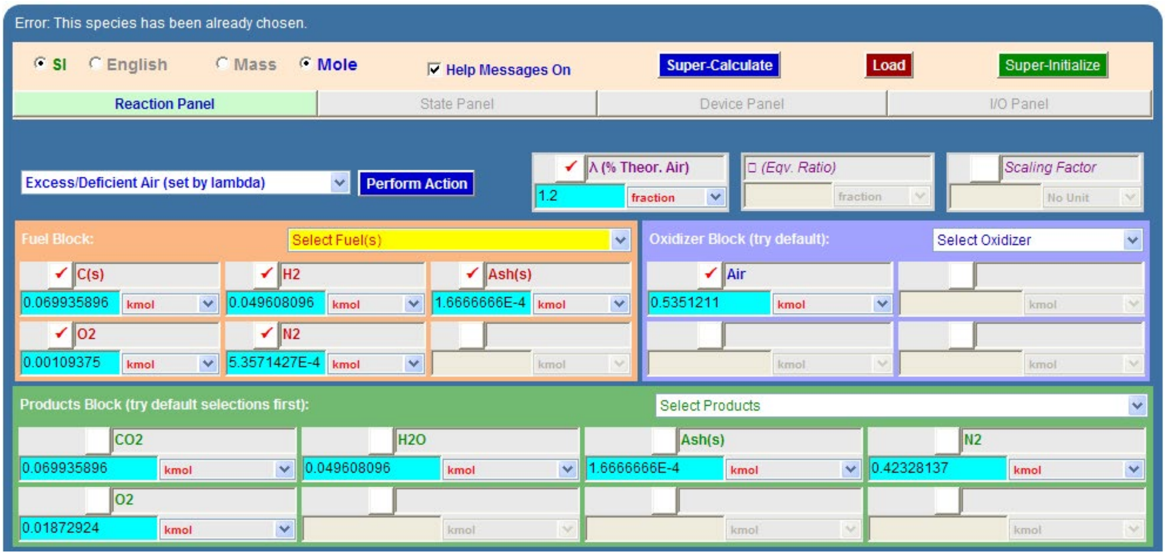


Therefore, we read: Stoichiometric AF ratio = 12.92, by mass…. Ans.

1. With 20% Excess air: Change λ 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:



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.

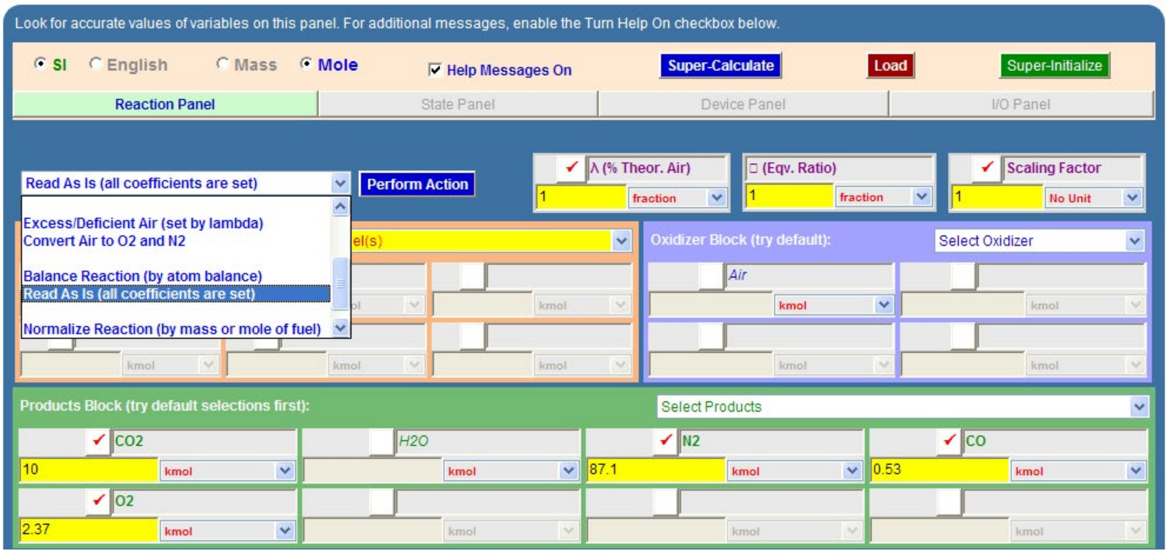
==

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]

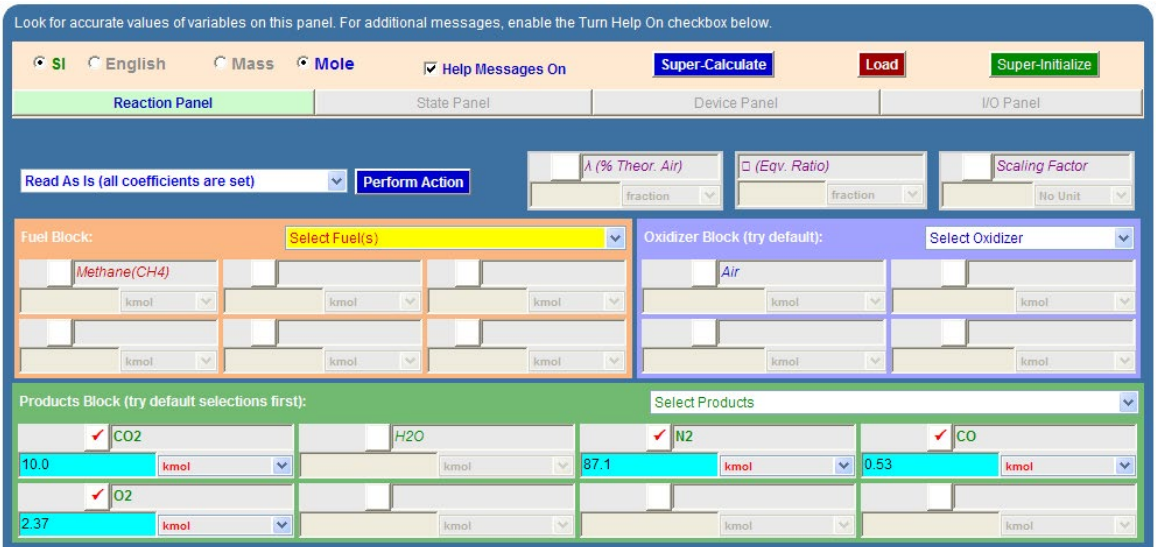
TEST Solution:

Following are the steps:

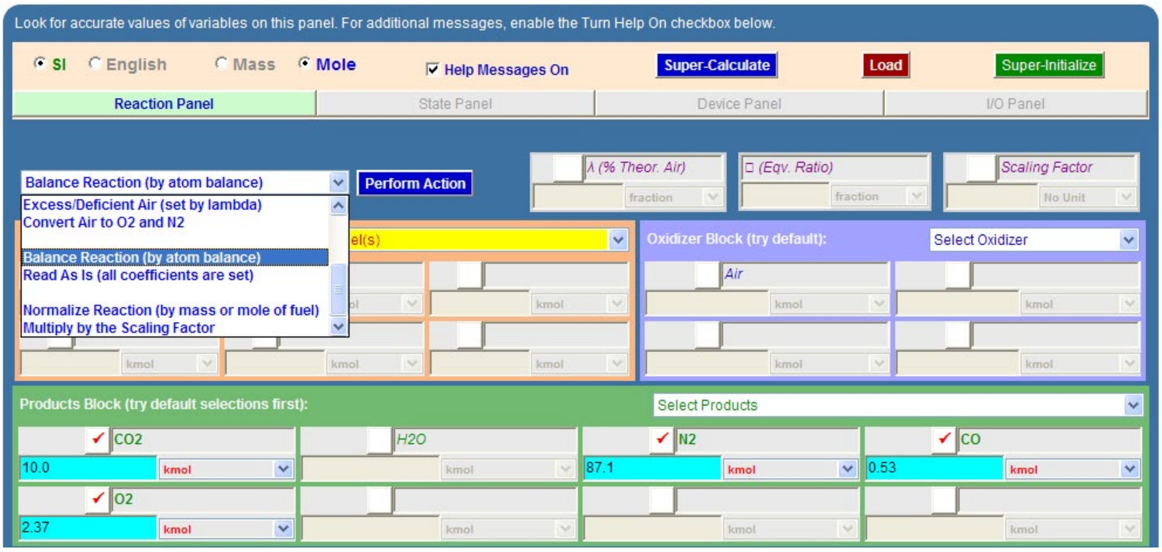
2. Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose **Mole** radio button. Select fuel: CH4, and in the Products block fill in the fractions as shown. Air is chosen as oxidizer, by default.



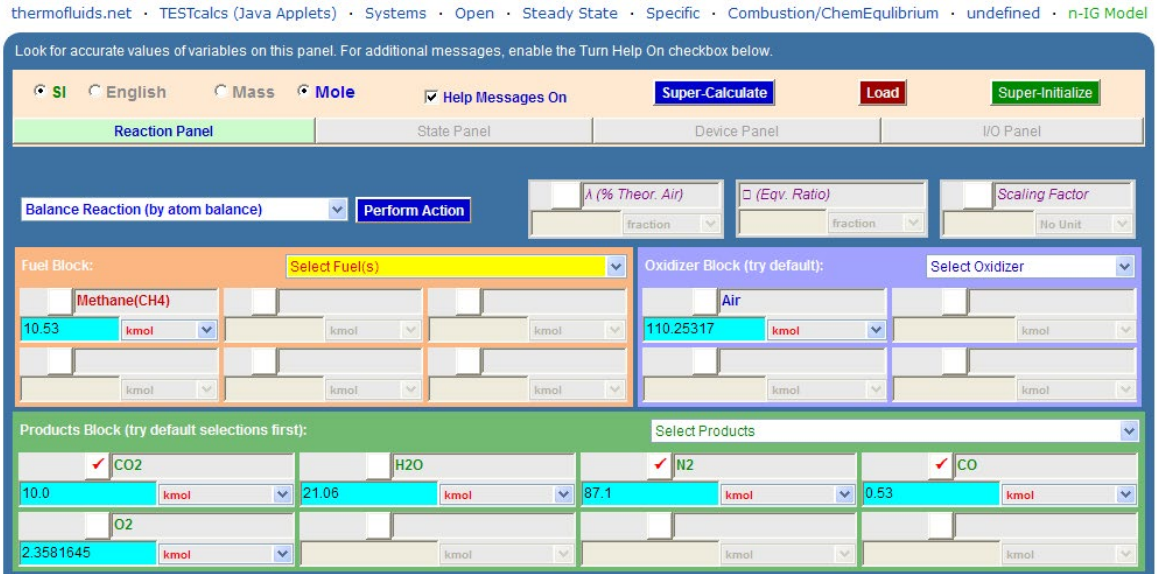
3. Select 'Read As Is' from Action widget, and click on 'Perform Action'. We get:



4. Select 'Balance Reaction (by atom balance)' from the Action widget:



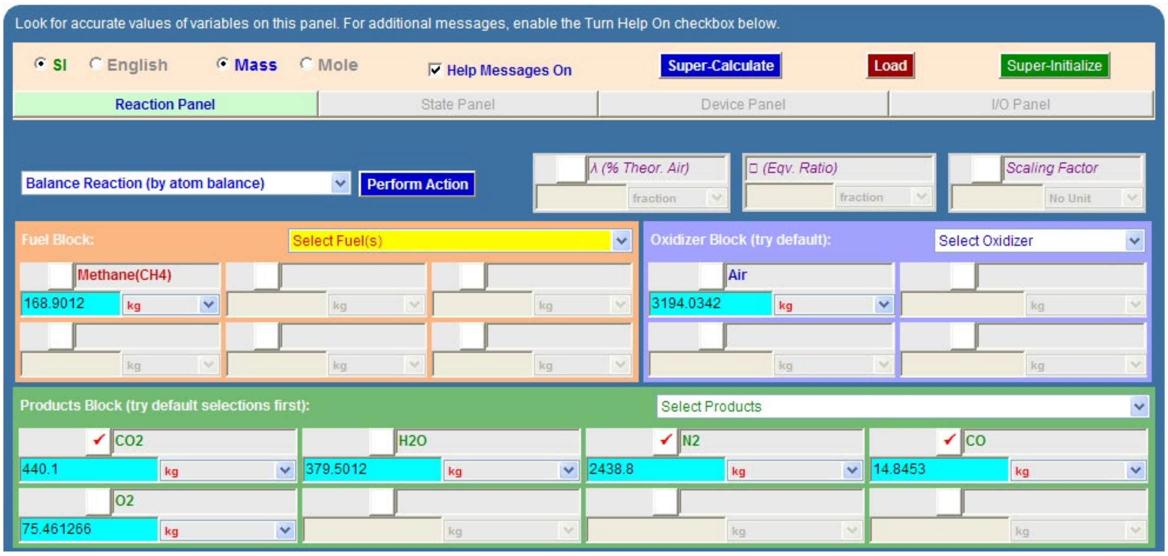
5. And, click on 'Perform Action'. We get:



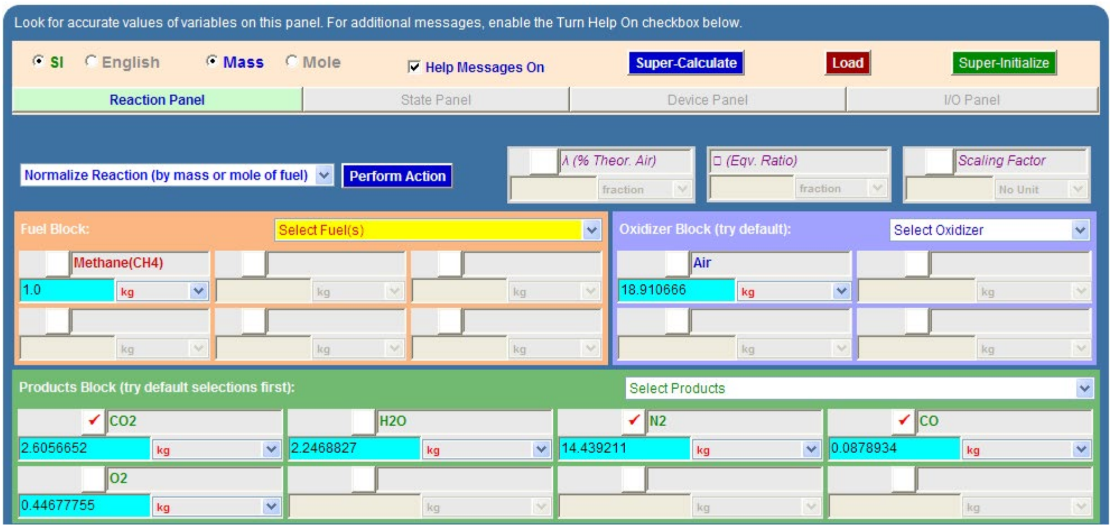
Therefore, combustion eqn is:

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:

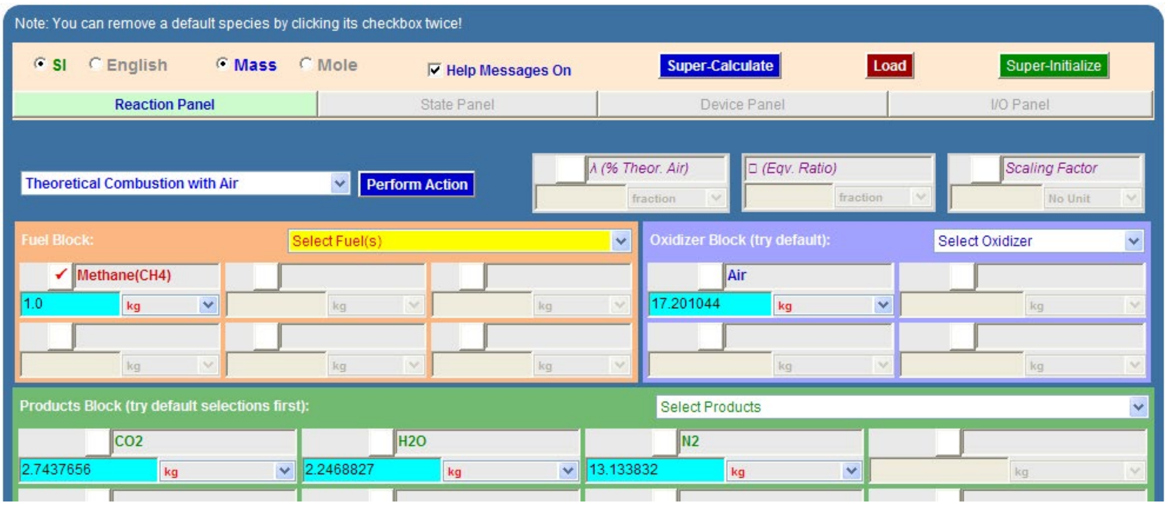


7. **To get the eqn on unit mass of fuel basis:** choose 'Normalize Reaction' in Action widget, and click on 'Perform Action'. We get:



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.

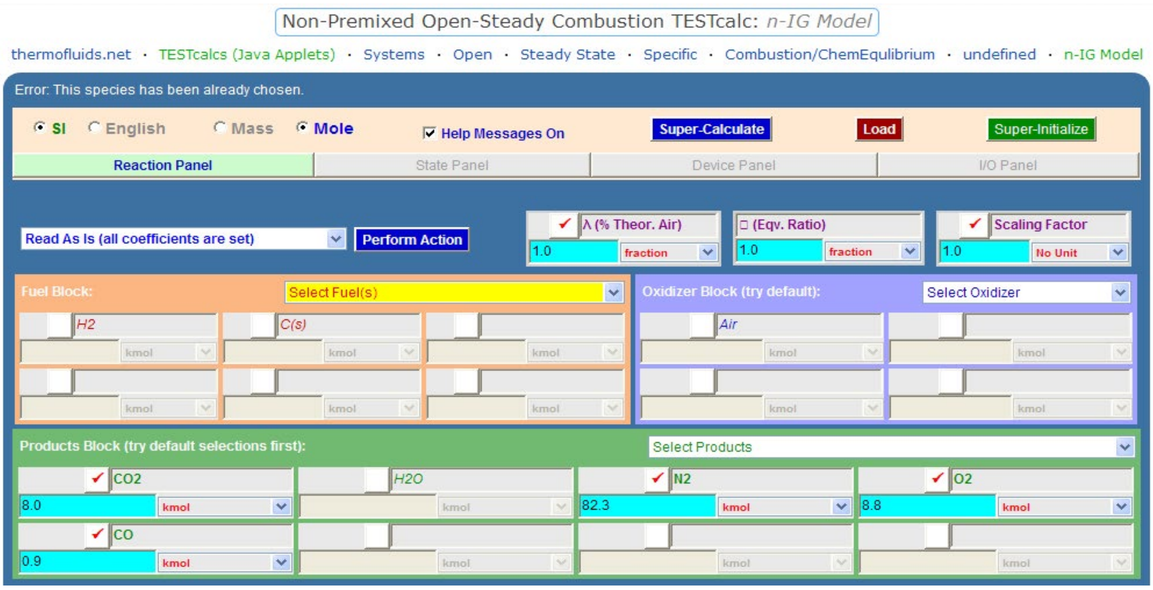
===

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]

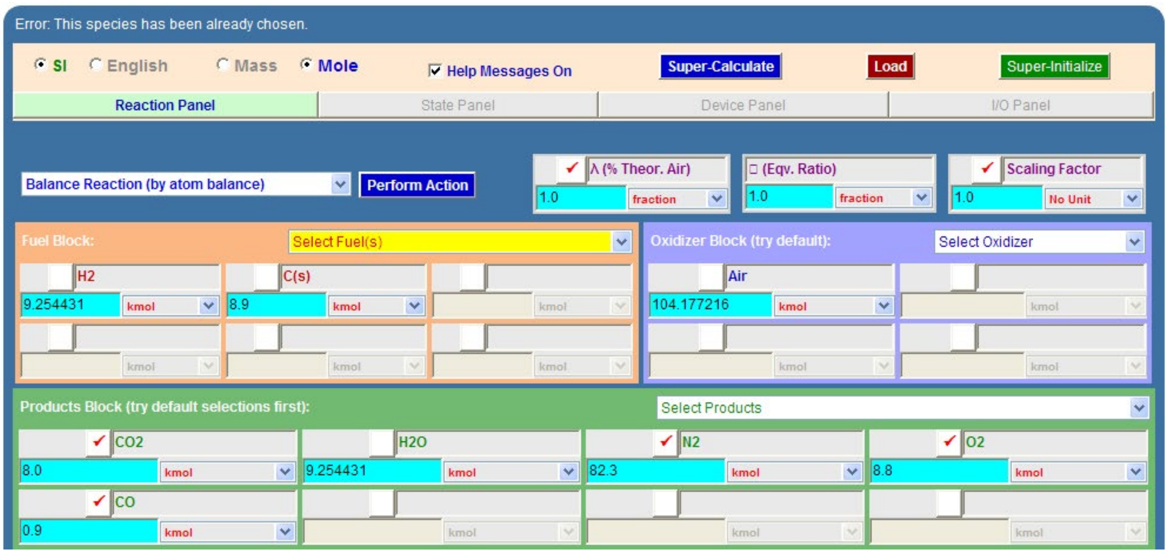
TEST Solution:

Following are the steps:

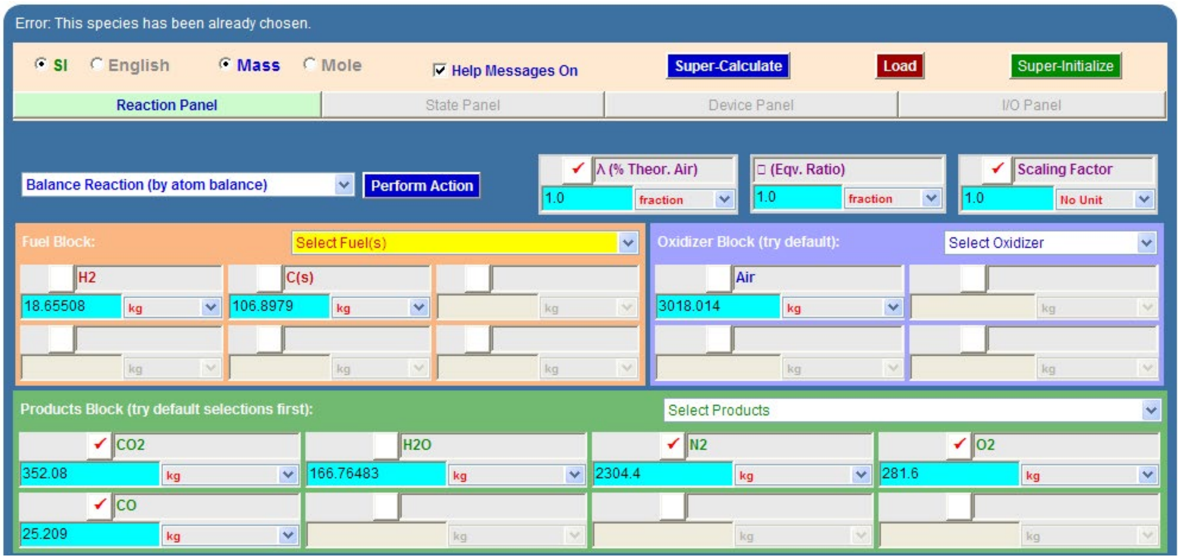
1. Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose **Mole** radio button. Select fuels: C and H2, and in the Products block fill in the fractions as shown. Air is chosen as oxidizer, by default. Select 'Read As Is' from Action widget, and click on 'Perform Action' to register the entered values:



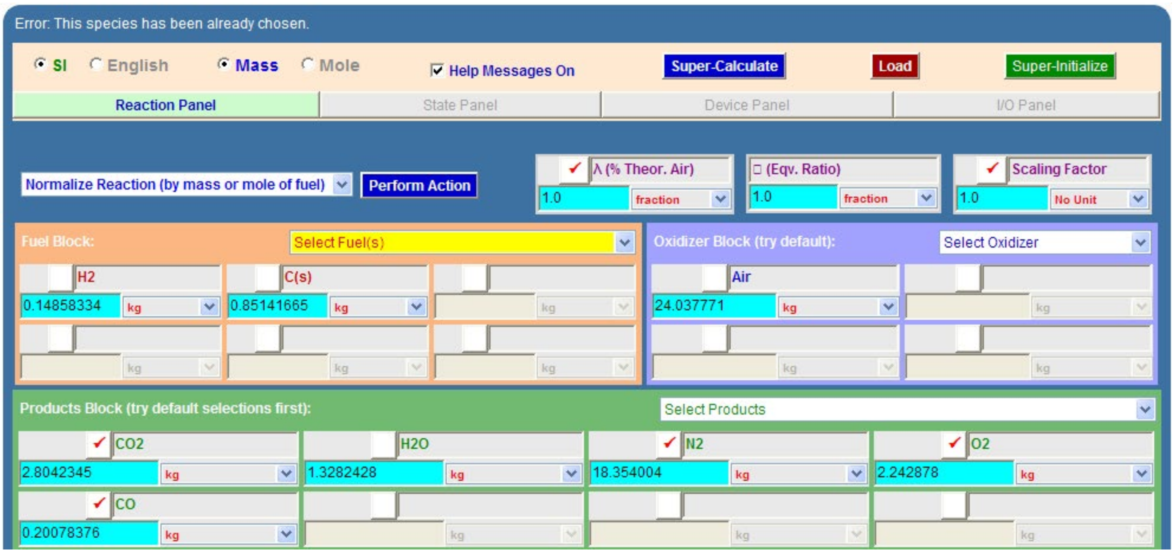
2. Next, select 'Balance Reaction (by atom balance)' and click on 'Perform Action'. Immediately, the eqn is balanced and we get:



3. **To convert on mass basis:** click on Mass radio button. Immediately, we get:



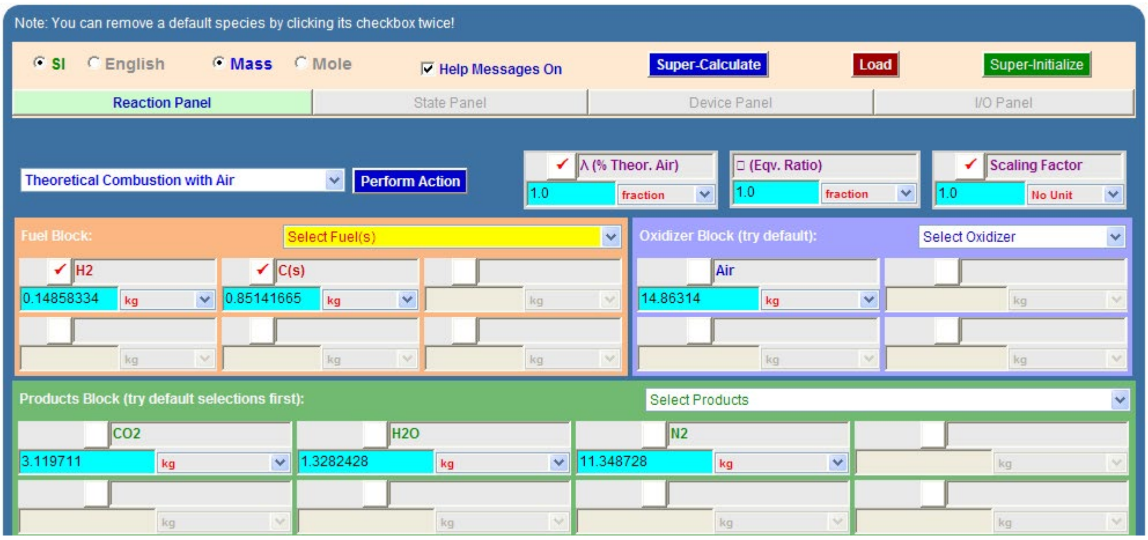
4. **To get on unit mass of fuel basis:** select 'Normalize Reaction' from Action widget, and click on 'Perform Action'. We get:



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:



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.

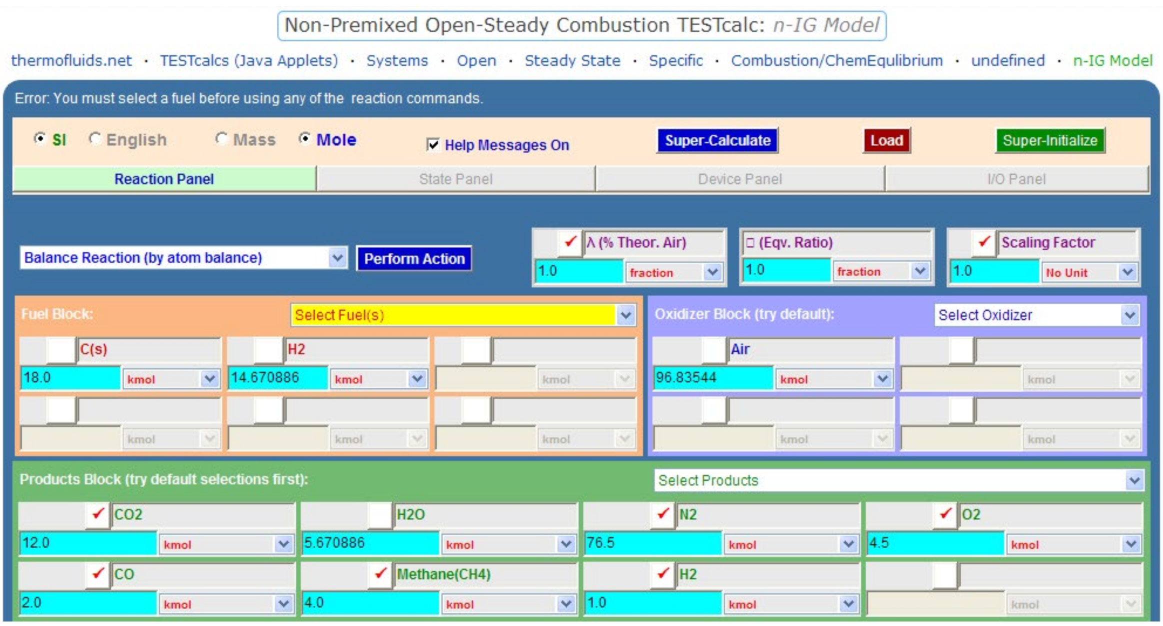
==

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]

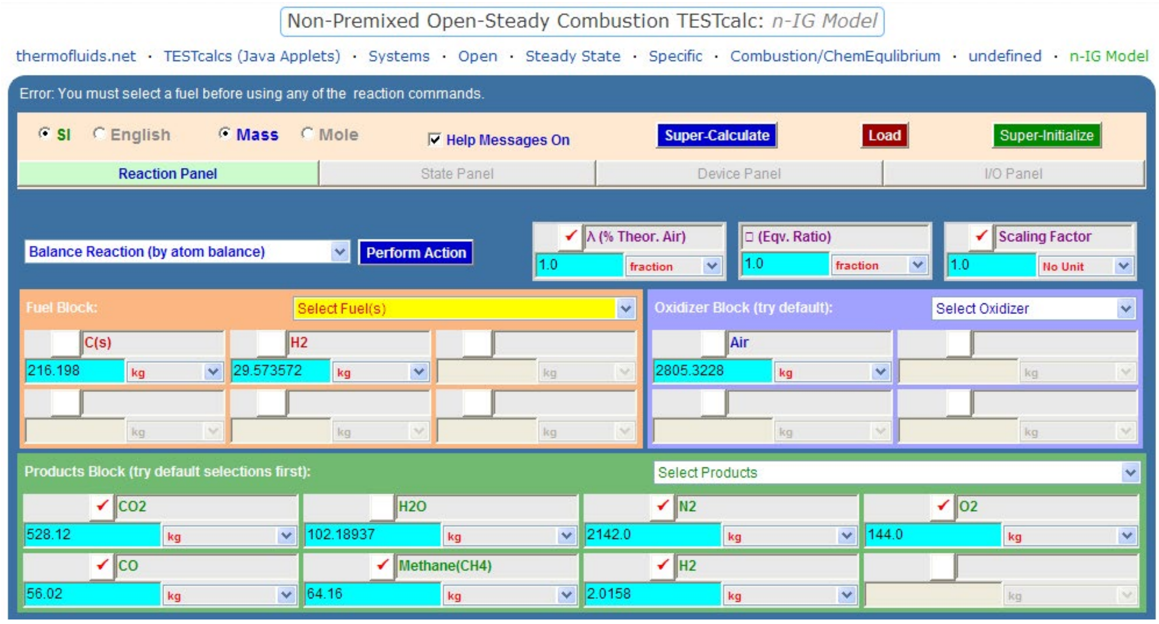
TEST Solution:

Following are the steps:

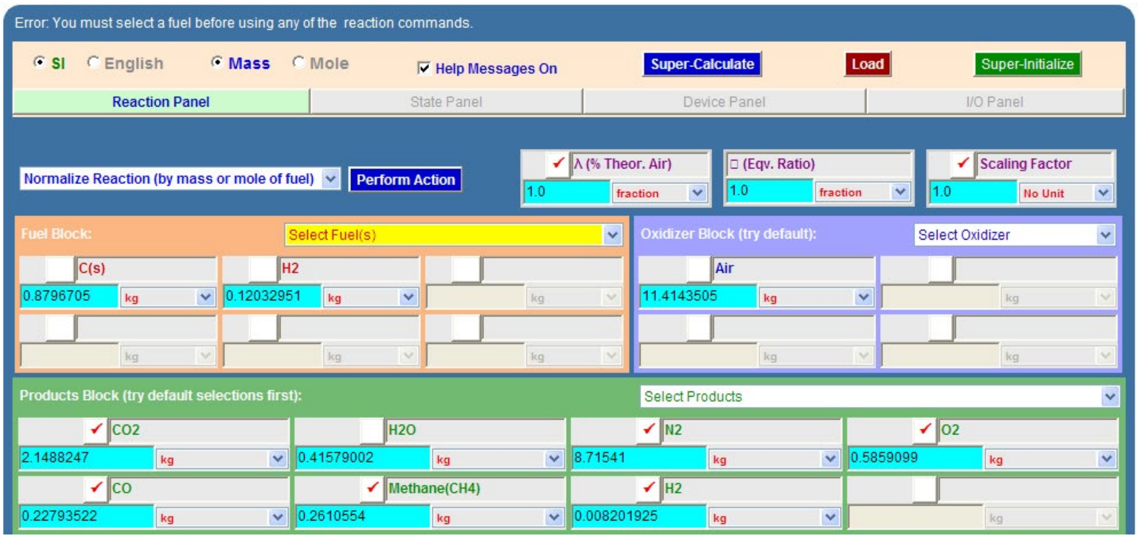
1. Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose **Mole** radio button. Select fuels: C and H2, and in the Products block, fill in the fractions as shown. Air is chosen as oxidizer, by default. Select 'Read 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:



2. **To convert it on mass basis,** simply select the **Mass** radio button. Immediately, we get:



3. **Now, to get it for unit mass of fuel,** select 'Normalize Reaction' from ction widget, and click on 'Perform Action'. We get:



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.

==

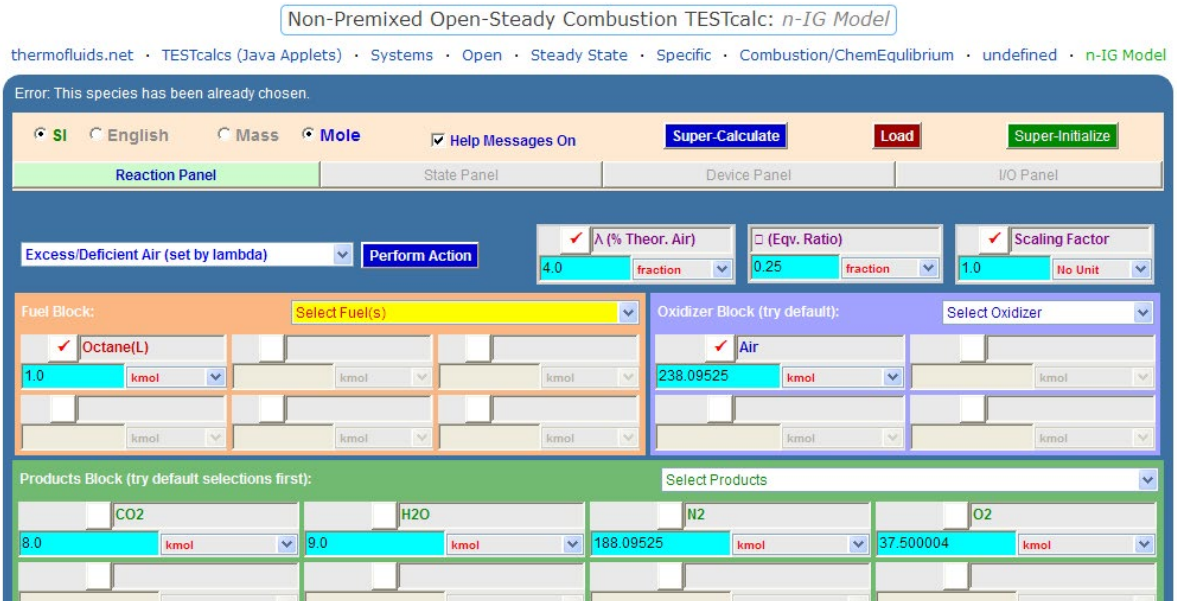
Prob. 8.4.8 Liquid Octane (C_8H_{18}) at 25 C is burnt with 400 % theoretical air at 101 kPa, 25 C in a steady flow process. Determine the adiabatic flame temp.

(b) Plot adiabatic flame temp vs percent excess air.

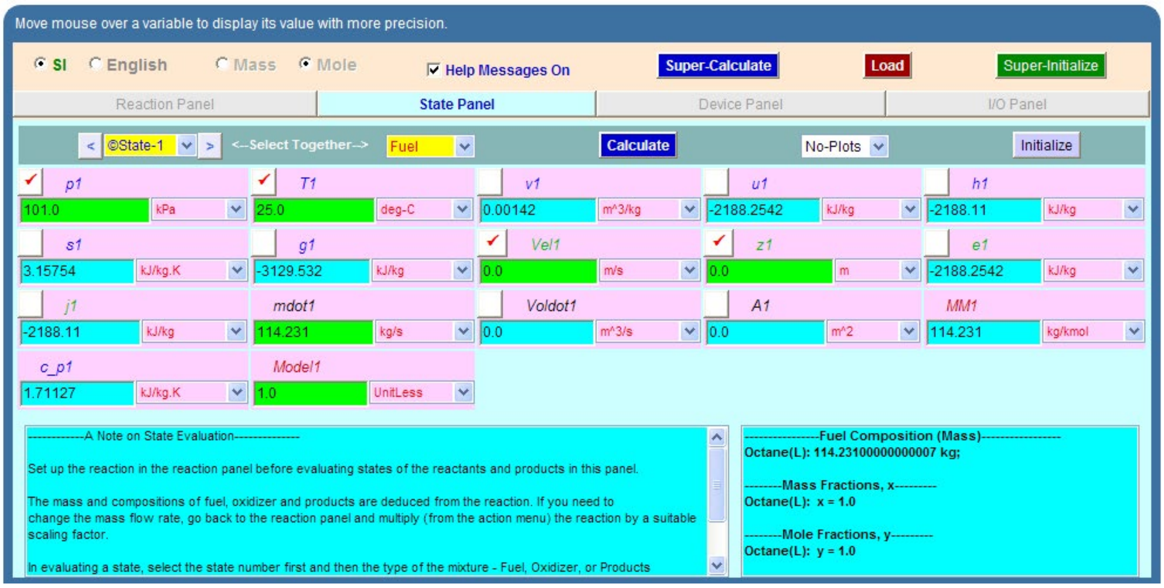
TEST Solution:

Following are the steps:

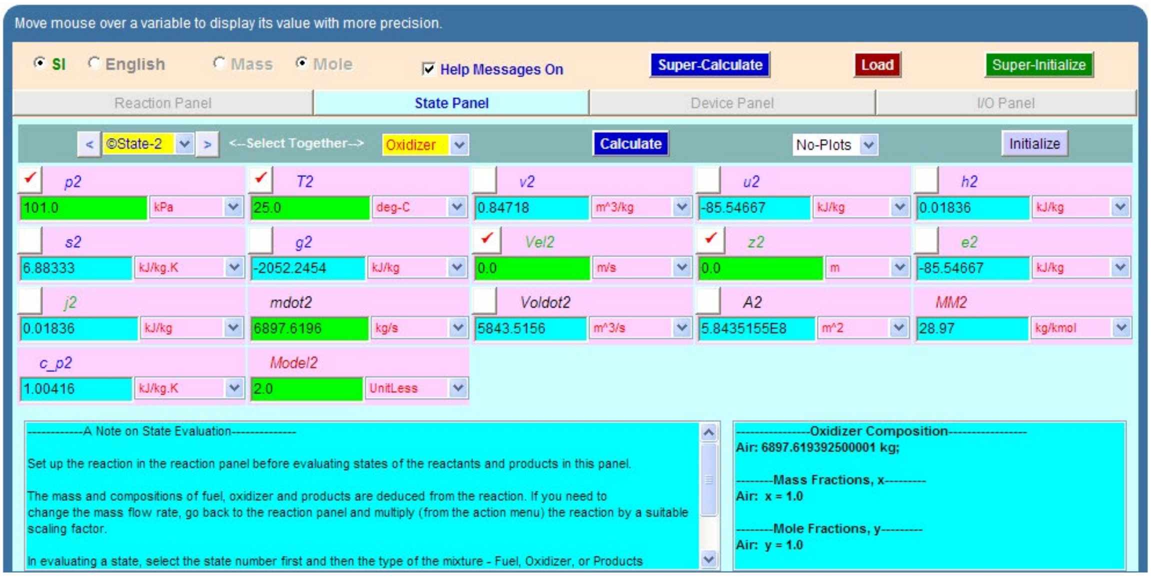
1. Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose **Mole** radio button. Select Octane (L) for fuel, and select λ as 4 (fraction) i.e. 400%. Air is chosen as oxidizer, by default. Select 'Excess/Deficient Air' from Action widget, and click on 'Perform Action'. We get:



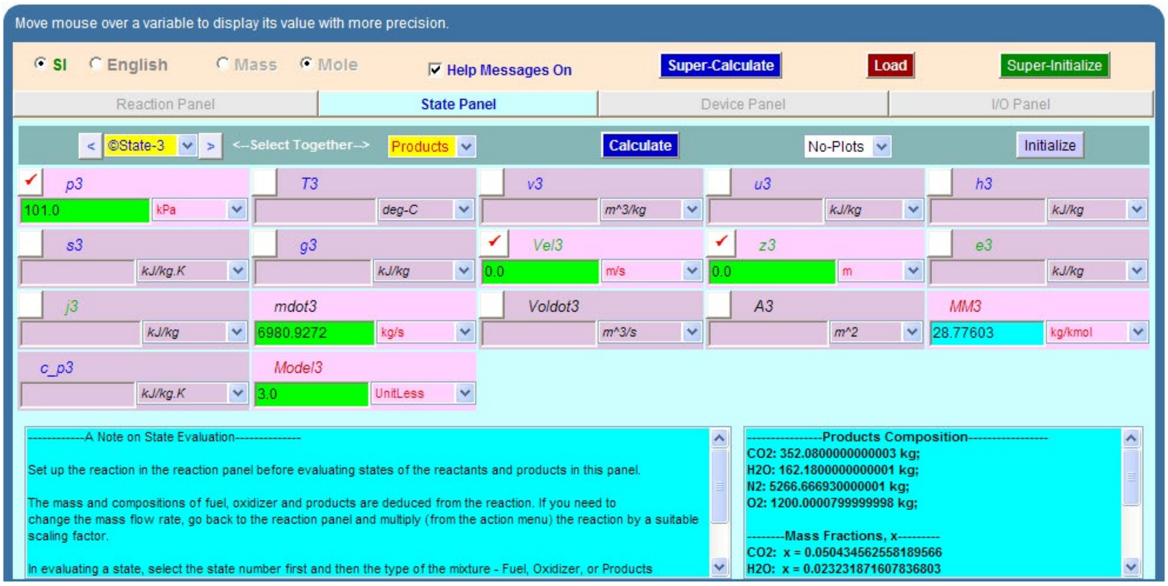
2. Now, go to States panel. For State 1, Fuel is chosen by default. Fill in P and T as 101 kPa and 25 C respectively. Click on Calculate. Immediately, State 1 is calculated:



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:

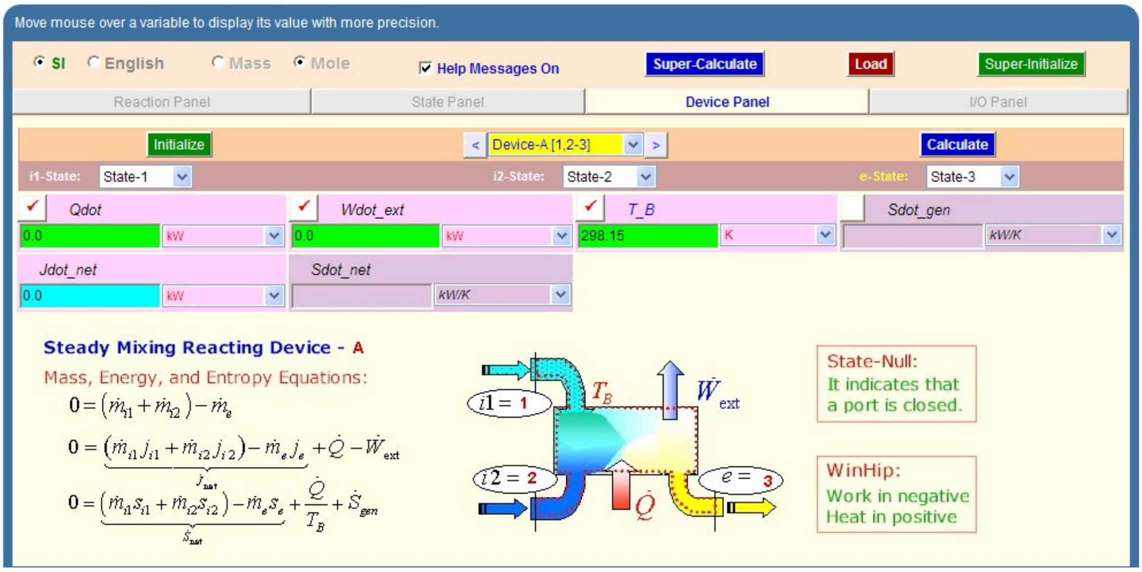


4. State 3 is for Products. Here temp is the unknown. Fill in the known value of P as shown, press Enter. We get:

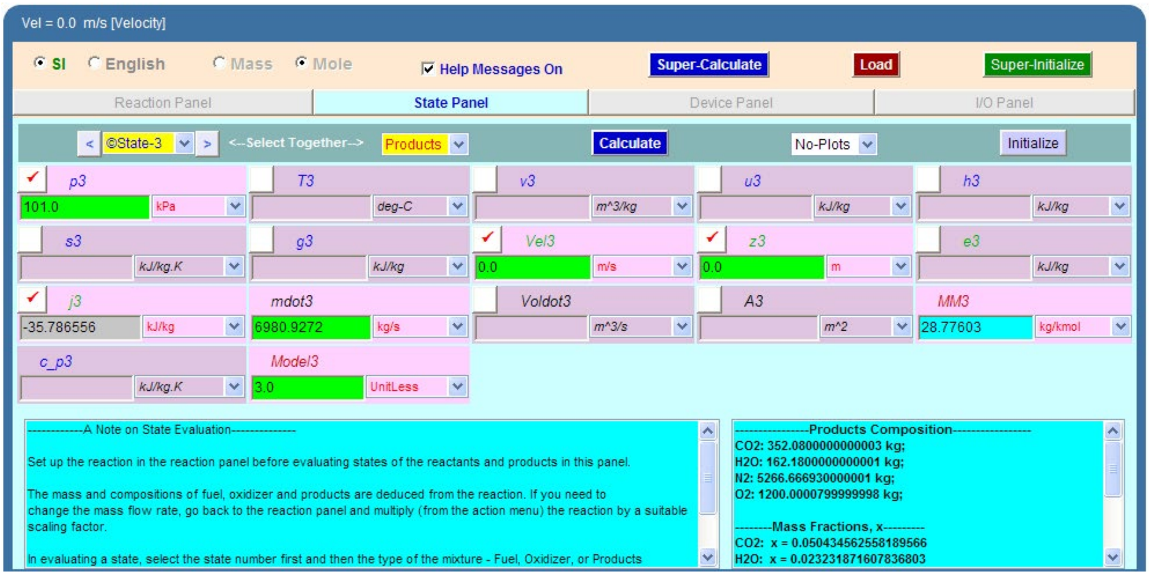


Of course, State 3 is not completely calculated since data is not enough. We will revisit this State after completing the Device panel.

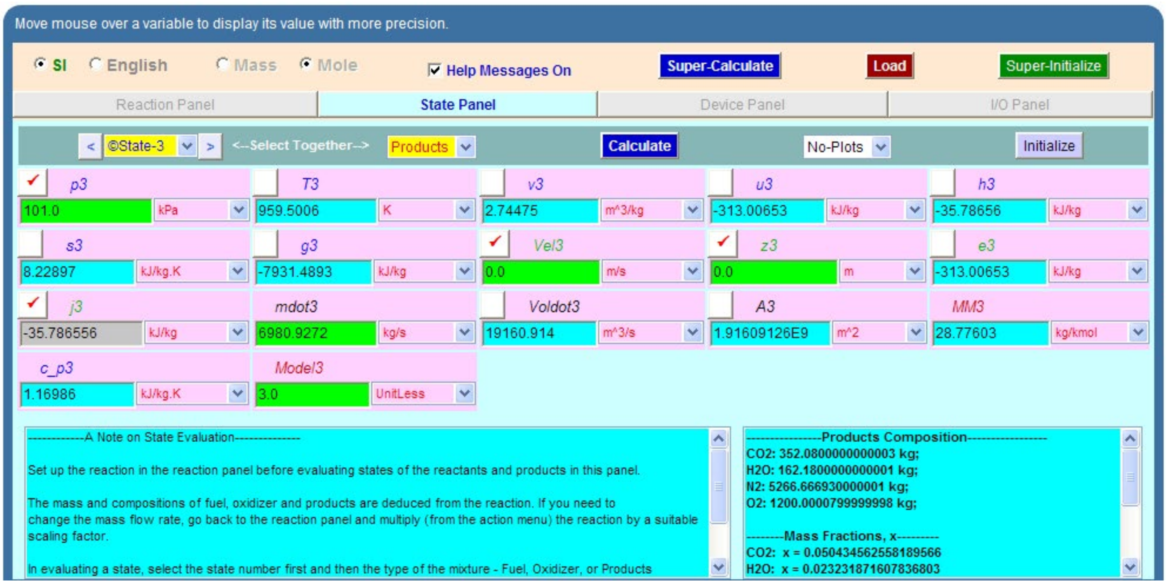
5. Now, go to Device panel. Fill in State 1 and State 2 for i10-state and i2-state, and State 3 for e-state. Also, enter Wdot_ext = 0 and Qdot = 0. Click on 'Calculate':



6. Now, go back to State 3. Observe that j3 is posted (with a grey background) there:

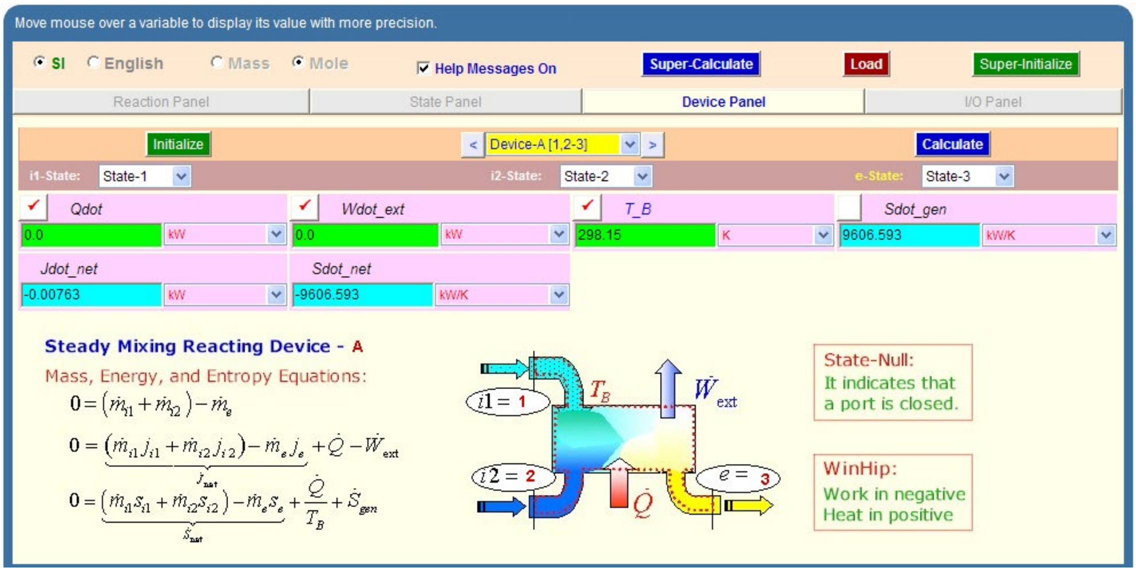


7. Now, click on 'Calculate', and, immediately calculations of State 3 are completed as shown below:



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:

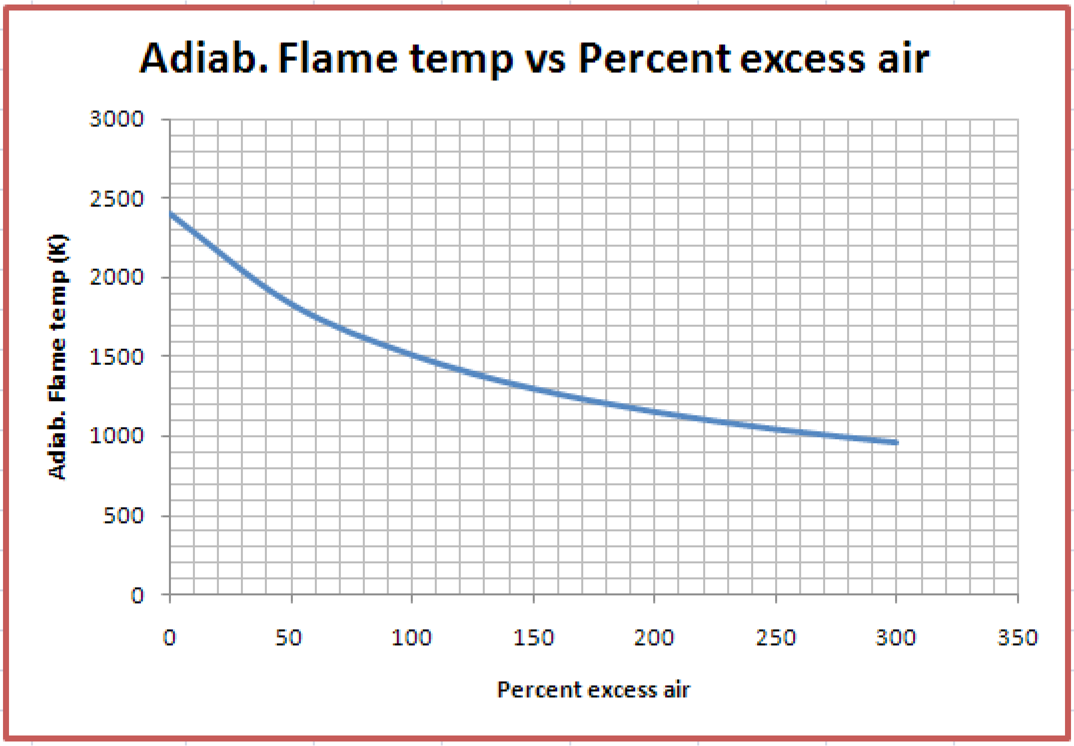
   i. Go to Reaction panel, change λ to 3.5 (i.e. 350% theor. Air or 250% excess air), Select 'Excess/Deficient Air' from Action widget, and click on 'Perform Action'. And, click on SuperCalculate. Immediately, all calculations are updated. Go to State 3, and read T3, the adiabatic Flame temp.

   ii. Repeat this procedure for desired values of λ, and tabulate the results as shown below:

Adiabatic flame temp vs excess air:

% Theoretical air, λ	% Excess air	Adiab. Flame temp (K)
400	300	959.5
350	250	1043.63
300	200	1152.54
250	150	1299.25
200	100	1507.97
150	50	1829.43
100	Stoichio.	2396.17

Now, plot the results in EXCEL:



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= -9606.593 kW/K;

==

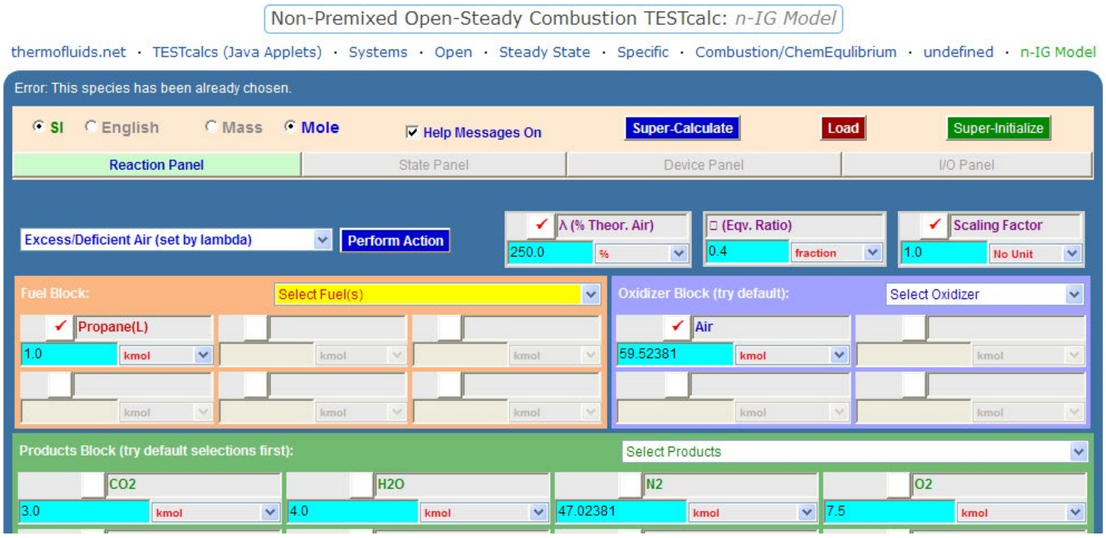
Prob. 8.4.9 Liquid propane (C3H8) enters a steady flow combustion chamber at 25 C and 1 atm at a rate of 0.4 kg/min where it is mixed anf burned with 150% excess air that enters the combustion chamber at 12 C. If the combustion products leave at 1200 K and 1 atm, determine: (i) mass flow rate of air, (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]

TEST Solution:

Following are the steps:

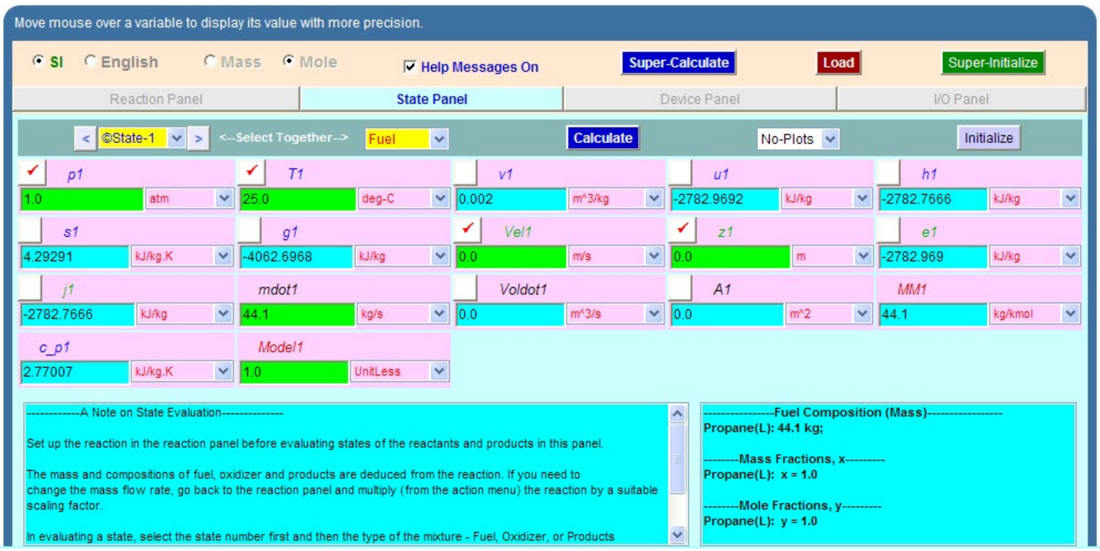
1. Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose **Mole** radio button. Select Propane (L) for fuel, and select λ as 250% i.e. 150% excess air. Air is chosen as oxidizer, by default. Select 'Excess/Deficient Air' from Action widget, and click on 'Perform Action'. We get:



Therefore: Flow rate of air for a flow rate of 0.4 kg/min of fuel:

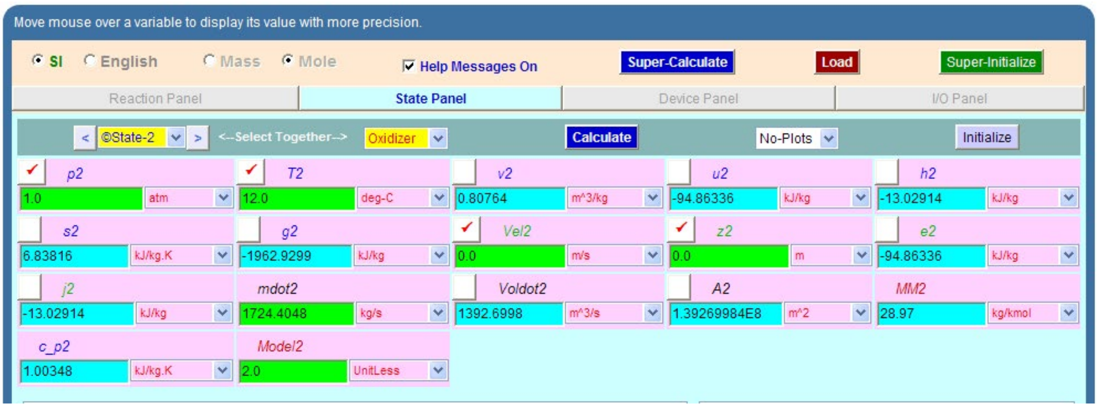
$\frac{59.5238 \cdot 29}{44.1} \cdot 0.4 = 15.657$ kg/min air for 0.4 kg/min of fuel ...Ans.

2. Go to State 1, i.e. Fuel: enter p1 = 1 atm, T1 = 25 C, hit Enter. We get:

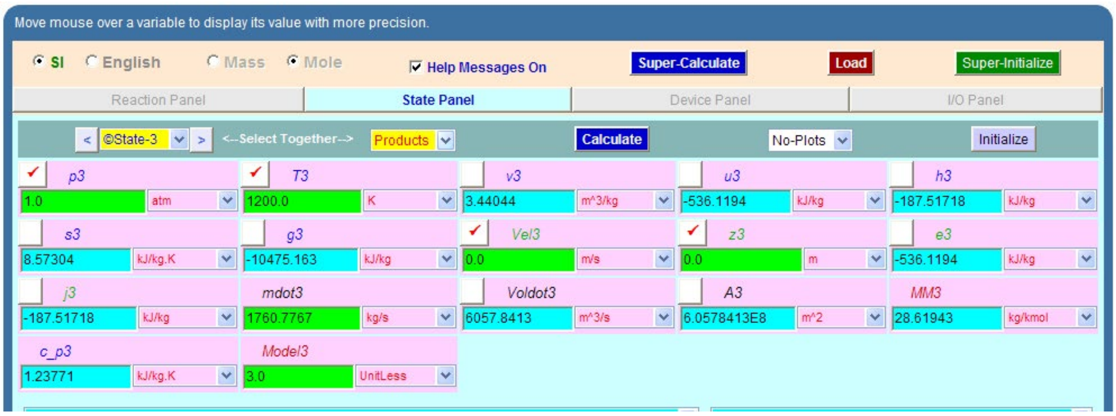


Note that mdot1 = 44.1 kg/s is automatically selected, since 1 kmol of fuel was entered in the Reaction panel.

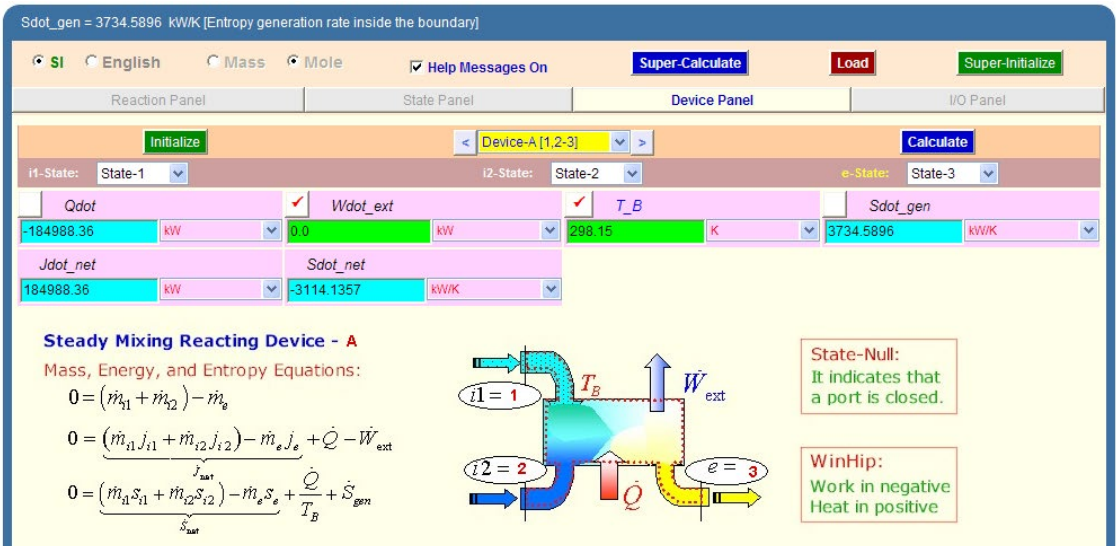
3. State 2: Enter p2, T2 for oxidizer. Hit Enter. We get:



4. State 3, for Products. Again, enter p3, T3 and hit Enter. We get:



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

$-4195 \cdot 0.4 = -1.678 \times 10^{3}$ 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} :

$298.15 \cdot 33.874 = 1.01 \times 10^{4}$ 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; }

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 -----------------------

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 kJ/kg; Voldot1= 0.0 m^3/s; A1= 0.0 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; Sdot_net= -3114.1357 kW/K;
```

(b) Plot the rate of exergy destruction for the surrounding temp varying from 0 to 38 C:

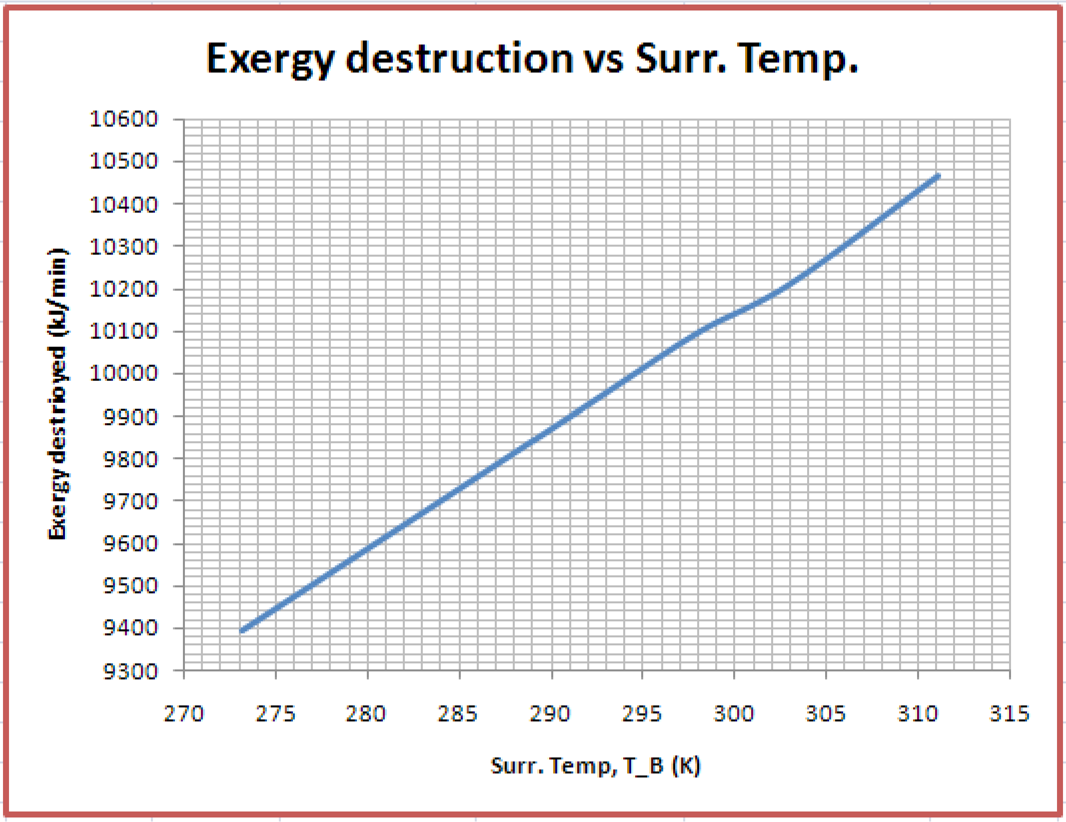
Procedure is quite simple:

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.

T_B (K)	**Sdot_gen (kW/K)**	**Sdot_gen. for 0.4 kg/min of fuel = Col. 2 * 0.4 / 44.1 (kJ/min.K)**	**Exergy destroyed = T0 * Sdot_gen = 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

Now, plot the Results:



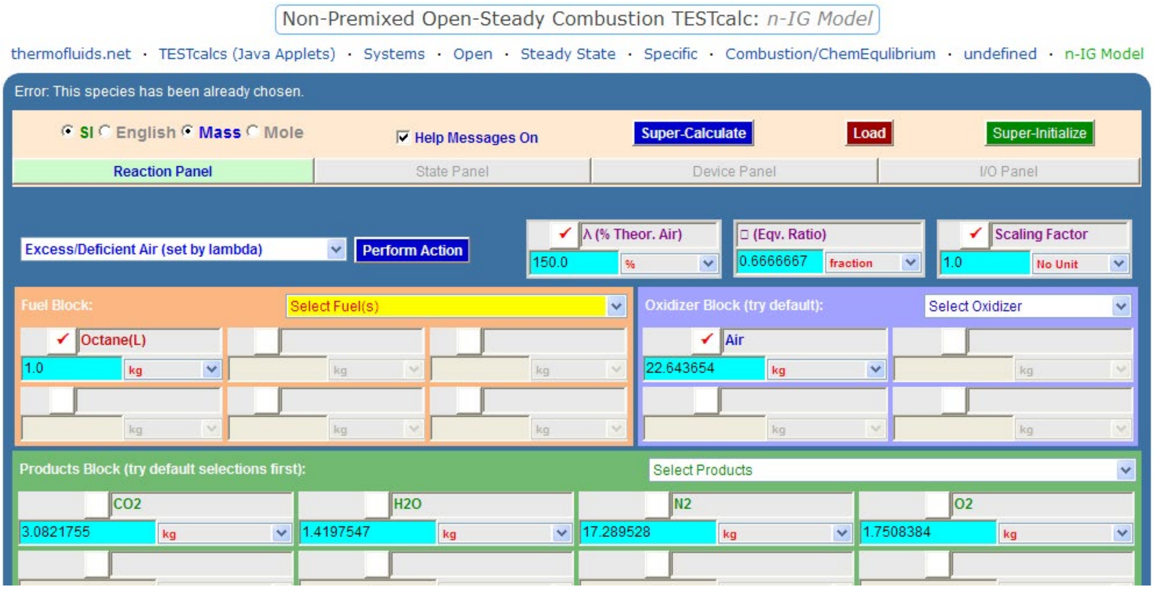
==

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.

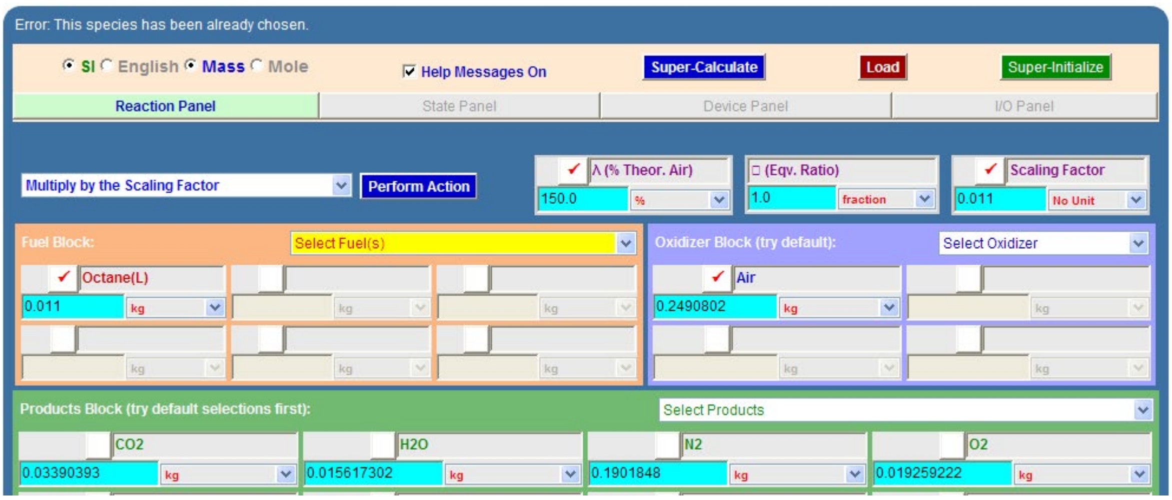
TEST Solution:

Following are the steps:

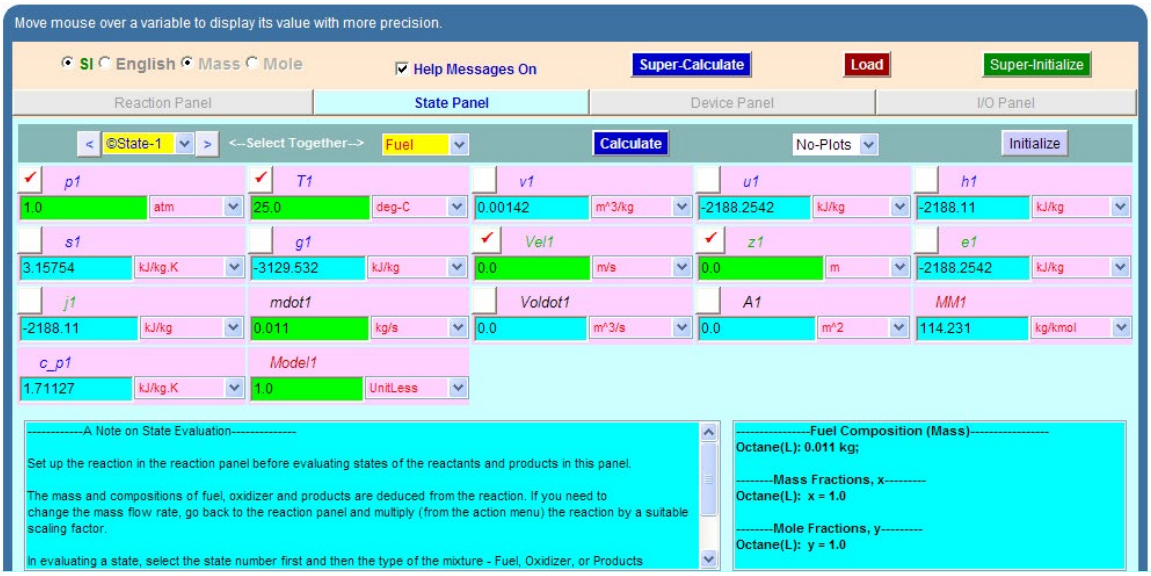
1. Select the Open, Steady combustion daemon, choose non-premixed (i.e. fuel and oxidizer come in separate streams) Ideal Gas (IG) model. Choose **Mass** radio button. Select Octane(L) for fuel, and select λ as 150%. Air is chosen as oxidizer, by default. Select 'Excess/Deficient Air' from Action widget, and click on 'Perform Action'. We get:



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:

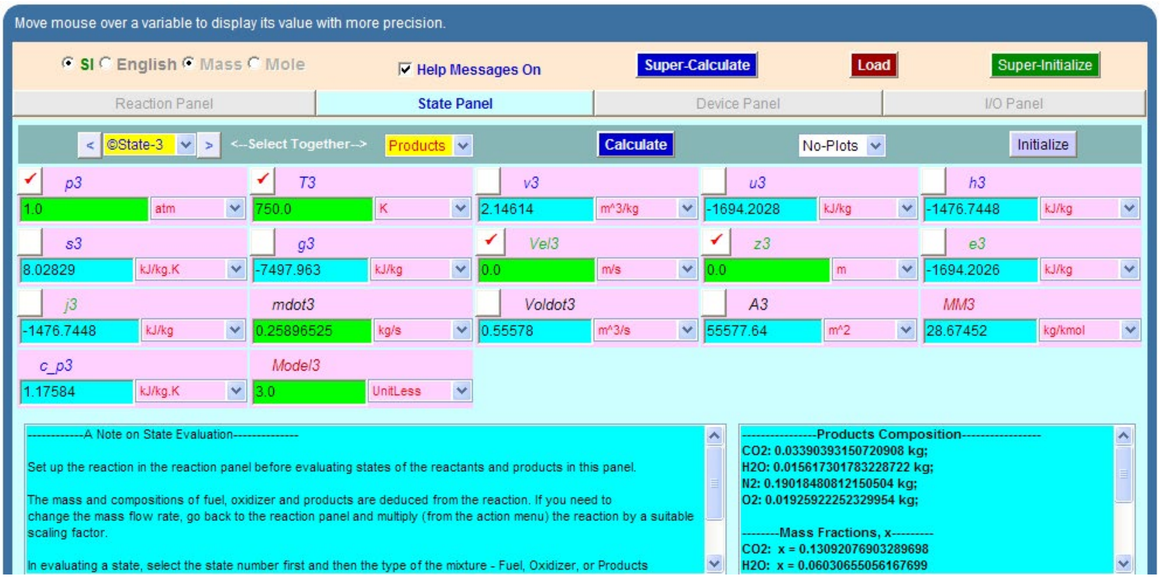


3. Now, go to States panel. Here, mass flow rates are chosen automatically, with reference to the Reaction panel. So, flow rate of fuel is 0.011 kg/s. For State 1 (i.e. fuel), enter p1, T1 as shown and hit Enter. We get:

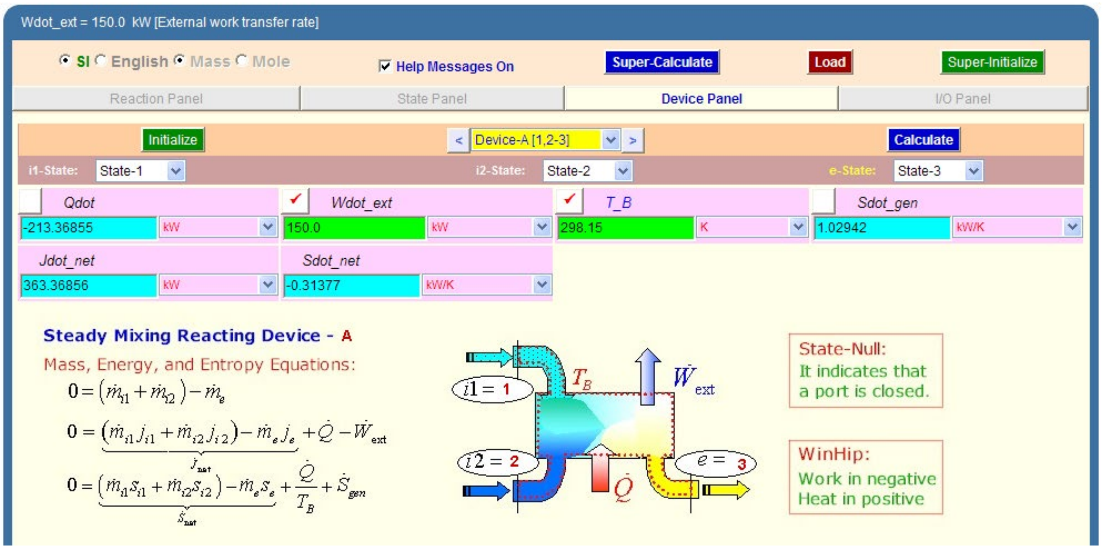


4. Similarly, for State 2, (i.e. Oxidizer) enter p2, T2 and hit Enter. We get:

5. And, for State 3: enter p3, T3 and hit Enter. We get:



6. 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; }

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 -----------------------

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 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= 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, 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: **Qdot= -213.36855 kW;** Sdot_gen= 1.0294154 kW/K; Jdot_net= 363.36856 kW; Sdot_net= -0.31377375 kW/K;

==

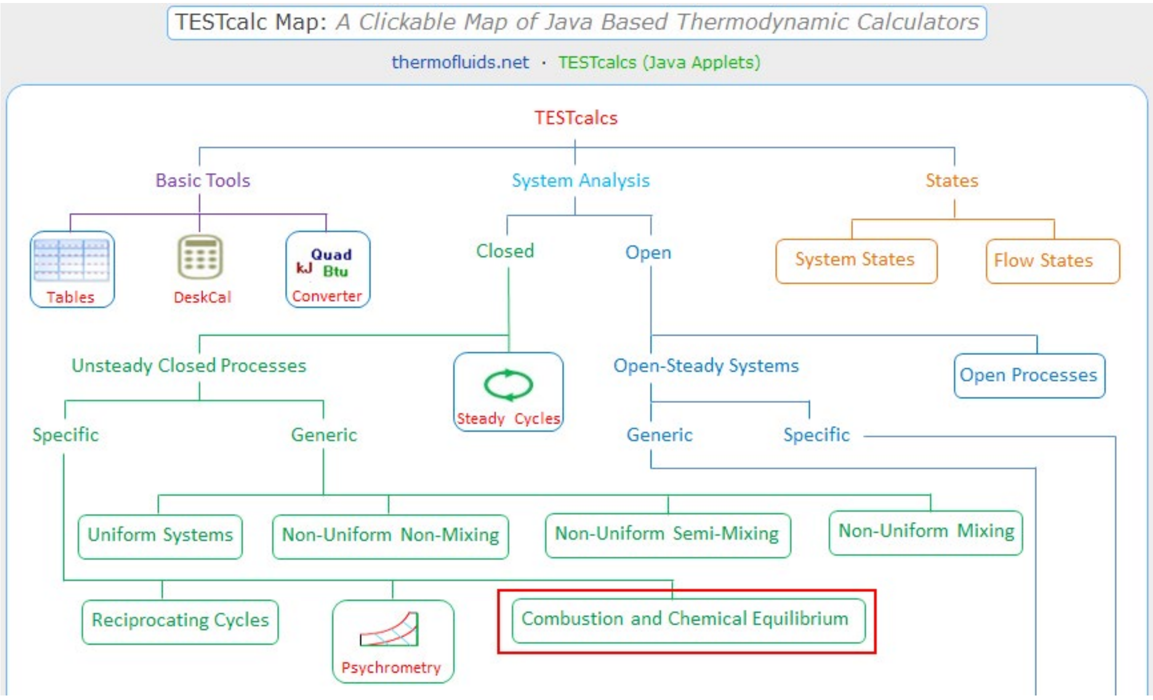
Prob. 8.4.11 One kmol of Methane (CH4) gas undergoes complete combustion with stoichiometric amount of air in a rigid container. Initially, the air and methane are at 100 kPa and 25 C. The products of combustion are at 567 C. How much heat is rejected from the container, in kJ/kmol fuel? Also, find the 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]

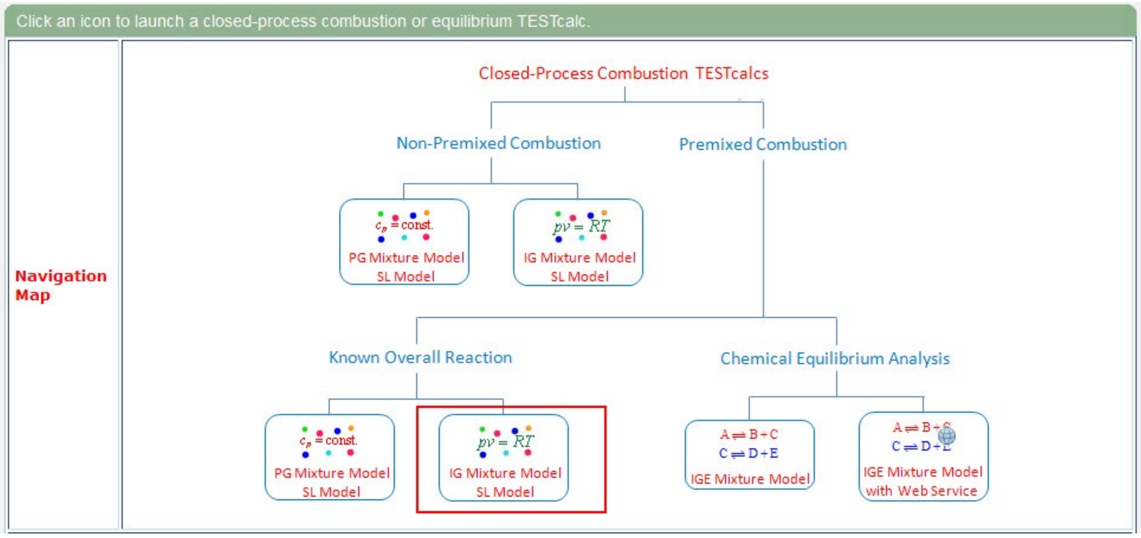
TEST Solution:

Following are the steps:

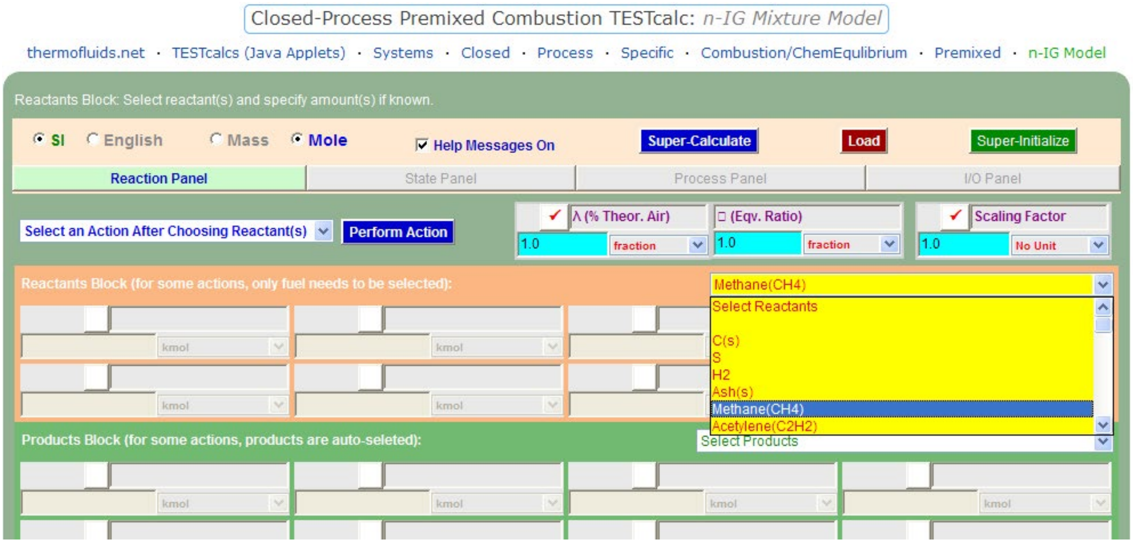
1. Select the Closed system, Combustion daemon, since the reaction occurs in a closed vessel, as shown below:



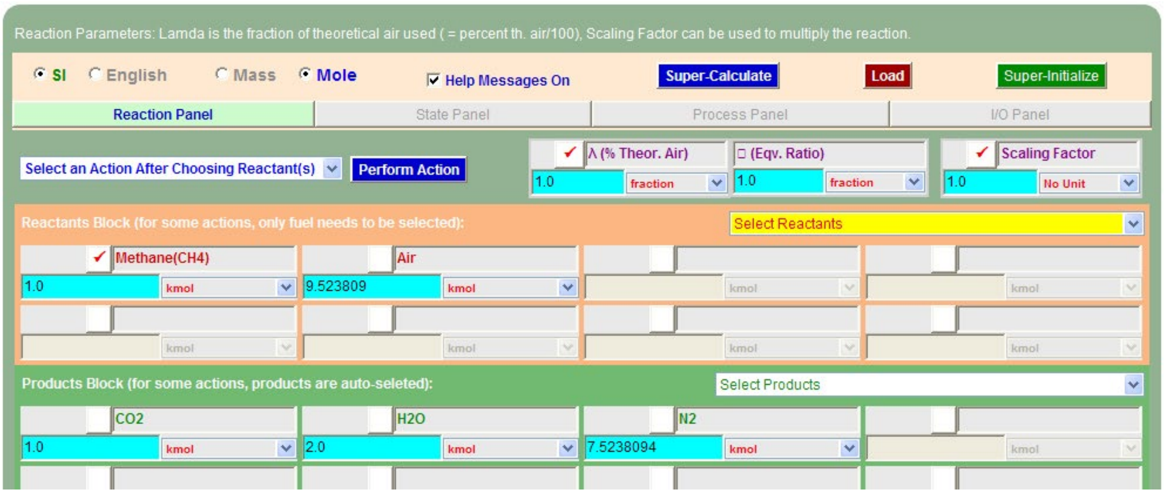
2. Select Pre-mixed, Ideal Gas (IG) for Material selection:



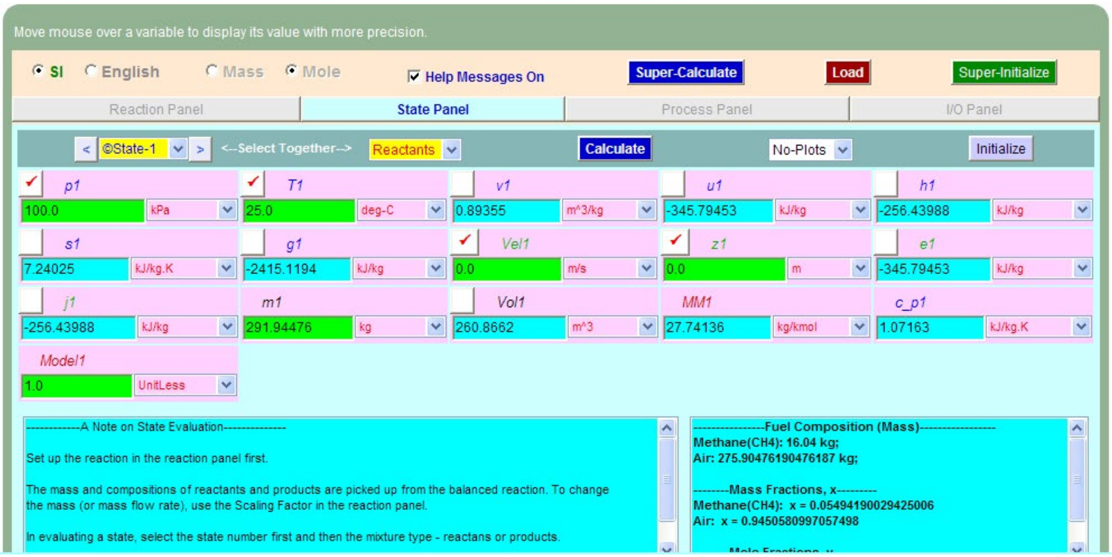
3. Clicking on IG mixture model gives the following window, where we have to choose the reactants, i.e. Methane and Air, in the present case:



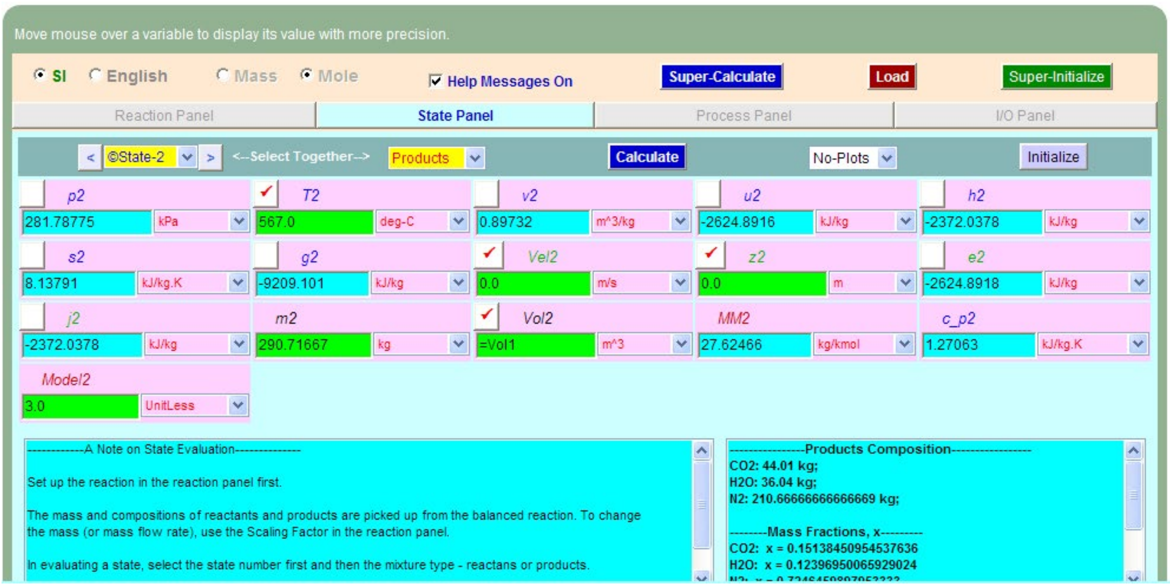
4. After choosing Methane and Air, choose 'Theoretical reaction with Air' from the Action widget, and click on 'Perform Action'. We get:



5. Now, go to State panel. For State 1, enter p1 = 100 kPa, T1 = 25 C, as shown and hit Enter. We get:

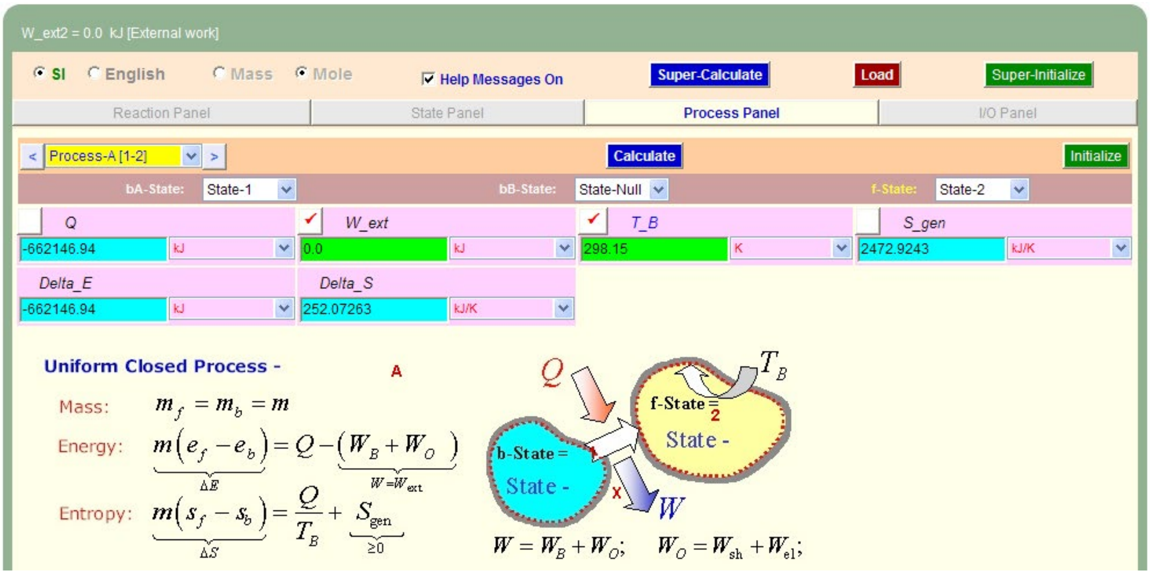


6. For State 2, enter T2 = 567 C, Vol2 = Vol1 (since it is a rigid vessel). Hit Enter. We get:



Note that p2 is 281.79 kPa … Ans.

7. 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 kJ … 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:

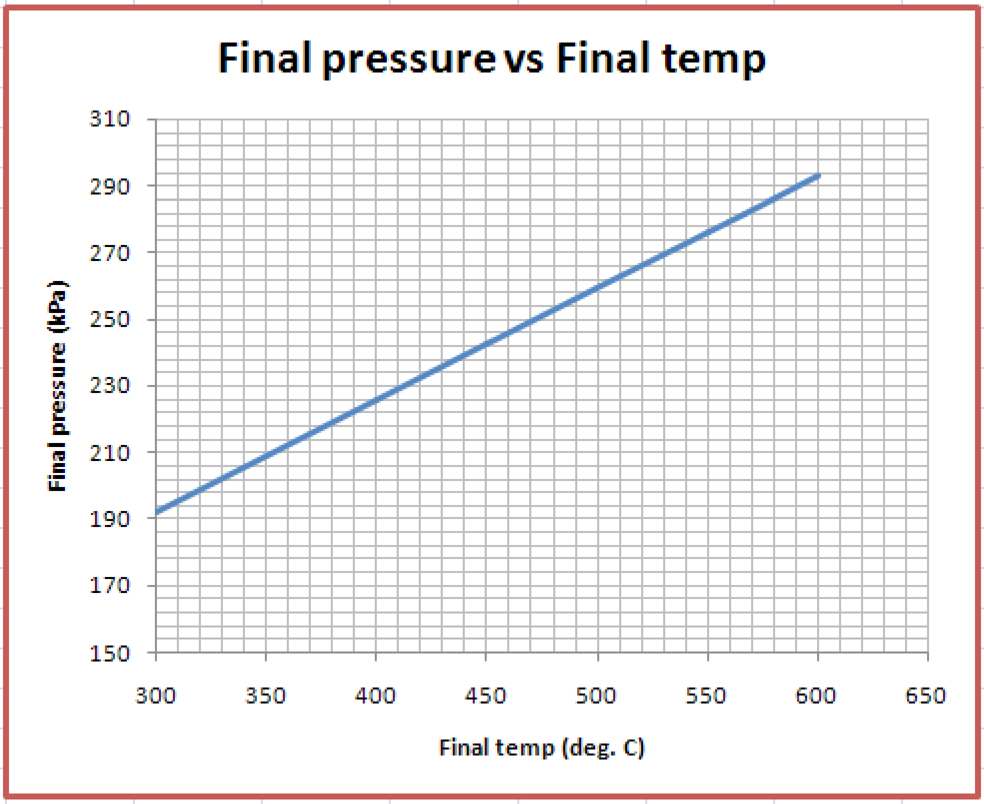
Go to State panel, and in State 2, change the T2 to desired value, hit Enter, observe new value of p2, and click on SuperCalculate. Then, go to Process panel, and note new values of Q and S_gen.

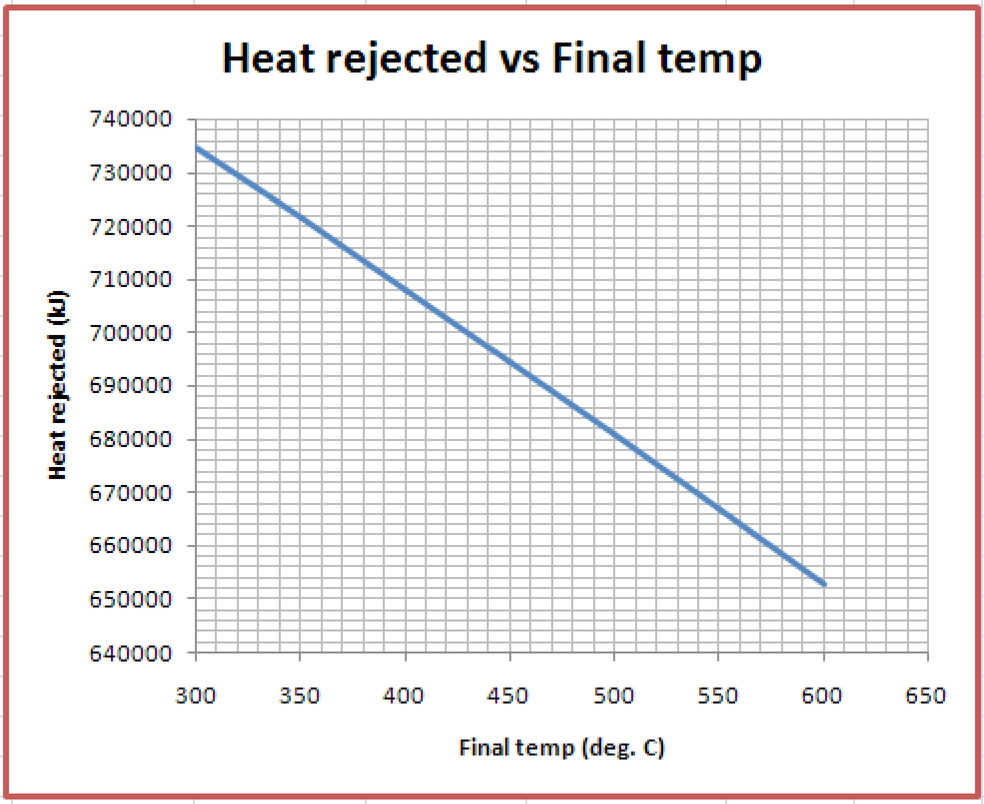
Tabulate values of p2, Q, S_gen against T2. Complete the Table as shown below, remembering that Exergy destroyed = T_B * Sdot_gen:

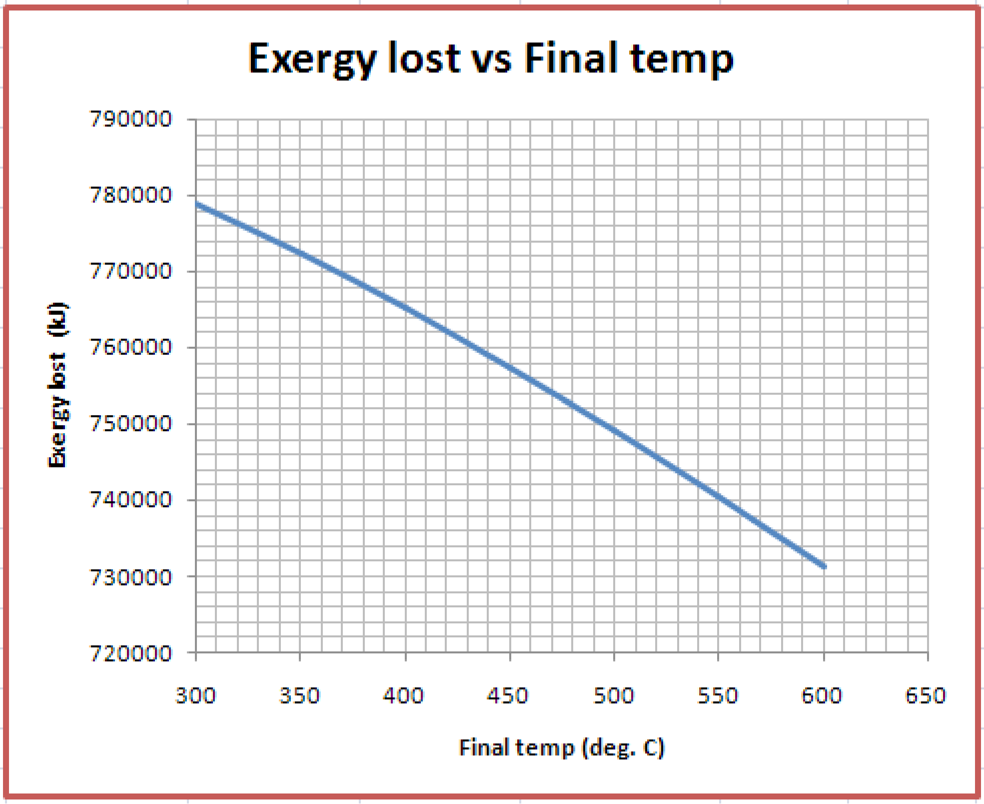
T_B = 298.15 K

T2 (C)	Heat rejected, Q (kJ)	S_gen (kJ/K)	Exergy loss = T_B * S_gen (kJ)	p2 (kPa)
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:




Heat rejected vs Final temp
Heat rejected (kJ)
740000
730000
720000
710000
700000
690000
680000
670000
660000
650000
640000
300
350
400
450
500
550
600
650
Final temp (deg. C)


Exergy lost vs Final temp
Exergy lost (kJ)
790000
780000
770000
760000
750000
740000
730000
720000
300
350
400
450
500
550
600
650
Final temp (deg. C)

==

8.5 References:

1. *Yunus A. Cengel & Michael A. Boles*, Thermodynamics, An Engineering Approach, 7th Ed. McGraw Hill, 2011.
2. *Sonntag, Borgnakke & Van Wylen*, Fundamentals of Thermodynamics, 6th Ed. John Wiley & Sons, 2005.
3. *Michel J. Moran & Howard N. Shapiro*, Fundamentals of Engineering Thermodynamics, 4th Ed. John Wiley & Sons, 2000.
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7. http://www.conservationphysics.org/atmcalc/atmoclc2.pdf "Equations describing the physical properties of moist air"
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11. Y.V.C. Rao, Engineering Thermodynamics through examples, Khanna Book Publishing Company, Delhi, 1999.

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