Basic Thermodynamics: Software Solutions Part III

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Basic Thermodynamics: Software Solutions-Part-III

(Engines, Refrigerators and Heat pumps, II Law, Entropy and its uses)

Basic Thermodynamics: Software Solutions-Part-III
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Could you think of 101 new things
to do with eggs and oil?

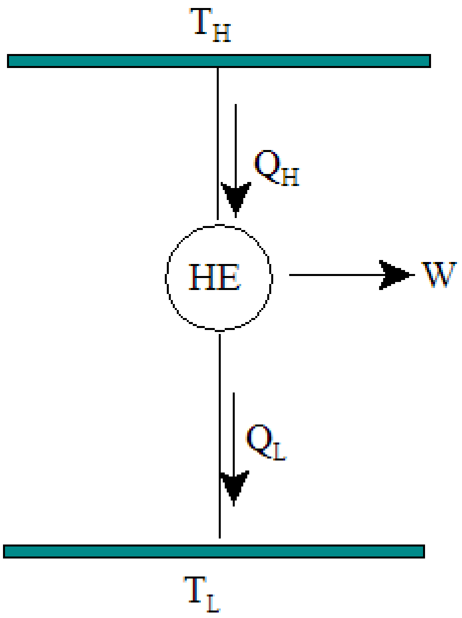
6 Second Law of Thermodynamics

Learning objectives:

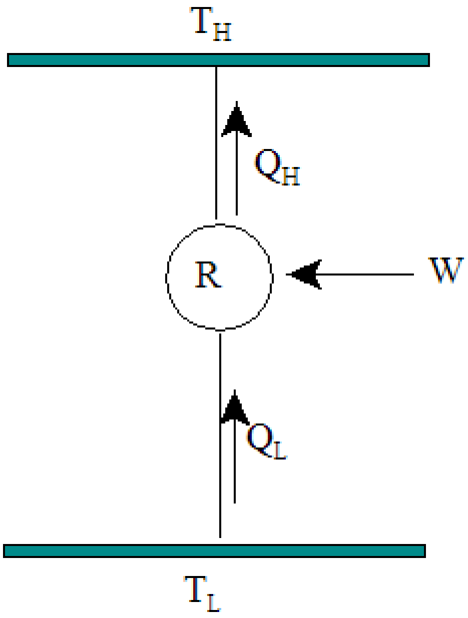
1. First Law is a Law of conservation of Energy. Satisfying the I Law, however, does not necessarily ensure that the process will actually occur.
2. Second Law dictates the direction in which the process will occur.
3. **Only when** both the I Law and II law are satisfied, will the process actually take place.
4. First, concepts of Thermal reservoir, Heat Engine, Refrigerator and Heat Pump and their efficiency / coefficient of performance (COP) are explained.
5. Then, two important statements of II Law, viz. Kelvin – Plank statement and Clausius statement are given; Clausius inequality is also mentioned.
6. Reversible and irreversible processes, Carnot cycle, its efficiency etc are explained next.

6.1 Definitions, Statements and Formulas used [1,2,4]:

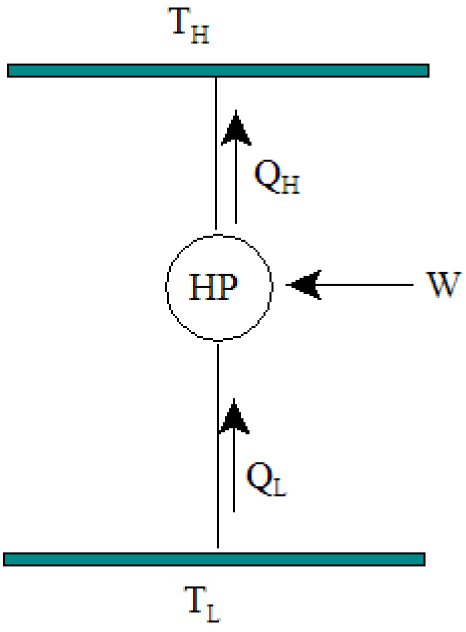
1. A **Thermal reservoir** can absorb or reject finite amounts of heat *isothermally*.
2. Work can be converted to heat directly, but heat can be converted to work only by a device called **'heat engine'**.
3. **Source** is a high temperature reservoir from which engine receives heat.
4. **Sink** is a low temperature reservoir to which the engine rejects heat.
5. **Heat engine** is a cyclically operating device which receives heat from a **'source'** and rejects heat to a **'sink'** and produces **'net work'.**
6. **Refrigerator**, whose objective is to produce low temperature, is a cyclically operating device which absorbs heat from a low temp body and rejects heat to a high temp body and work is required to be done on this device. Generally, atmosphere is the high temp reservoir.
7. **Heat Pump,** whose objective is to reject heat to a high temp reservoir, is a cyclically operating device which absorbs heat from a low temp body and rejects heat to a high temp body and work is required to be done on this device. Generally, atmosphere is the low temp reservoir.
8. Schematic diagrams of Heat Engine, Refrigerator and Heat Pump are shown below:



Heat Engine



Refrigerator



Heat Pump

9. **Kelvin – Planck statement of II Law:** No heat engine can produce a net amount of work while exchanging heat with a single reservoir only.
10. **Clausius statement of II Law:** No device can transfer heat from a cooler body to a warmer one without leaving an effect on the surroundings.
11. Any device which violates the first or the second Law is called a **perpetual motion machine**.
12. **Efficiency of a Heat Engine:**

$$\eta_{th} = \frac{W_{net}}{Q_H} = 1 - \frac{Q_L}{Q_H} \qquad \text{...eqn.6.1}$$

13. **Coefficient of Performance (COP) of a Refrigerator:**

$$COP_R = \frac{Q_L}{W_{net}} = \frac{1}{\frac{Q_H}{Q_L} - 1} \qquad \text{...eqn.6.2}$$

14. **COP of a Heat Pump:**

$$COP_{HP} = \frac{Q_H}{W_{net}} = \frac{1}{1 - \frac{Q_L}{Q_H}} \qquad \text{...eqn.6.3}$$

15. A process is said to be **reversible** if both the system and the surroundings can be restored to their original conditions. Any other process **is irreversible**.
16. Effects such as friction, non-quasi-equilibrium expansion or compression, and heat transfer through a finite temp difference render a process irreversible.
17. **Carnot cycle** is a reversible cycle consisting of four reversible processes, two isothermal and two adiabatic.
18. A **Carnot Engine** is a hypothetical device and is not practical, since it consists of reversible processes which have to proceed at very slow rate without any temp and pressure differences.
19. However, *Carnot Engine serves as a standard to compare the performance of any other engine.*
20. **The Carnot Principles** state that (i) thermal efficiencies of all reversible heat engines operating between the same two reservoirs are the same, and (ii) no heat engine is more efficient than a reversible one operating between the same two reservoirs.
21. **These principles form the basis for establishing a thermodynamic temperature scale.**
22. **Thus, efficiency of a Carnot engine and COPs of Carnot refrigerator and Carnot Heat Pump are:**

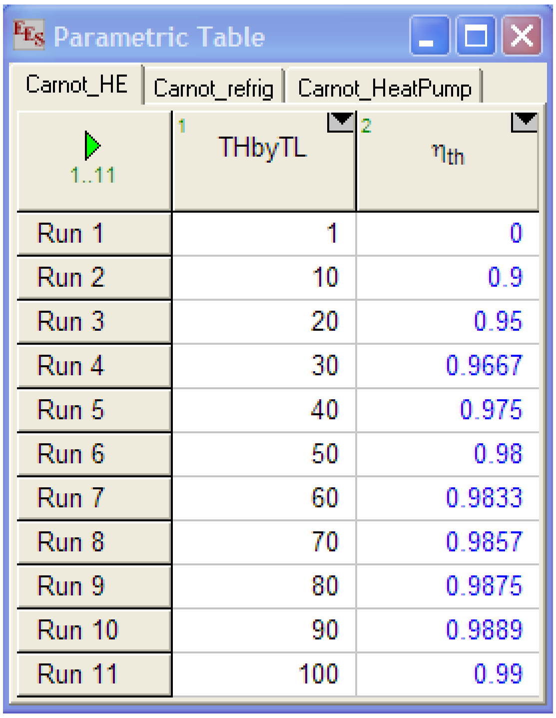
$$\eta_{th\_rev} = \frac{W_{net}}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H} \qquad \text{...eqn.6.4}$$

$$COP_{R\_rev} = \frac{Q_L}{W_{net}} = \frac{1}{\frac{Q_H}{Q_L} - 1} = \frac{1}{\frac{T_H}{T_L} - 1} \qquad \text{...eqn.6.5}$$

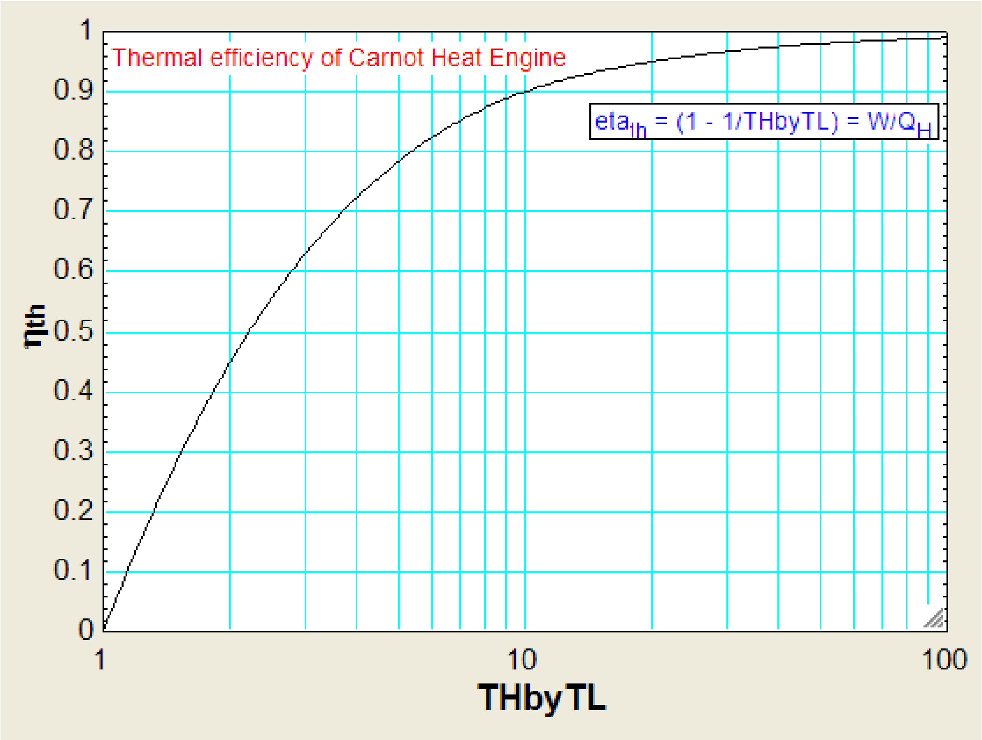
$$COP_{HP\_rev} = \frac{Q_H}{W_{net}} = \frac{1}{1 - \frac{Q_L}{Q_H}} = \frac{1}{1 - \frac{T_L}{T_H}} \qquad \text{...eqn.6.6}$$

Thermal efficiency of Carnot Engine and COP's of Carnot Refrigerator and Carnot Heat Pump as functions of the temp ratio (TH/ TL) are evaluated ad presented in graphical form, using EES:

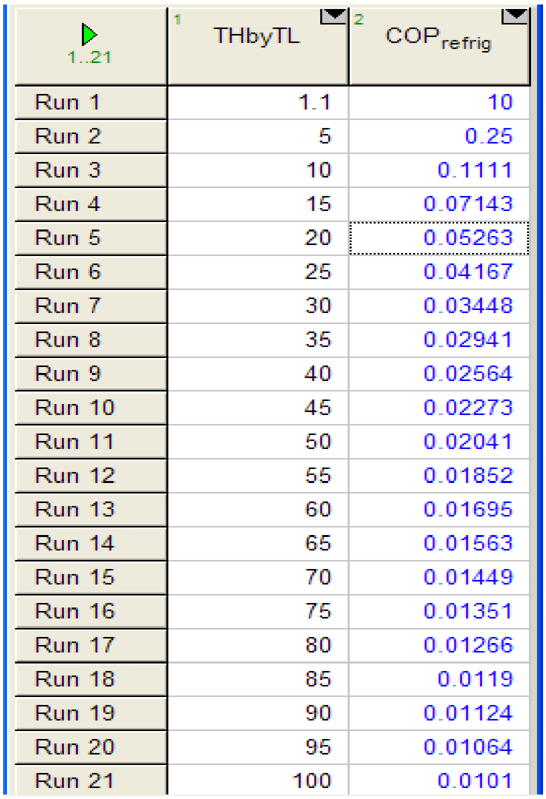
a) **Carnot Heat Engine:**



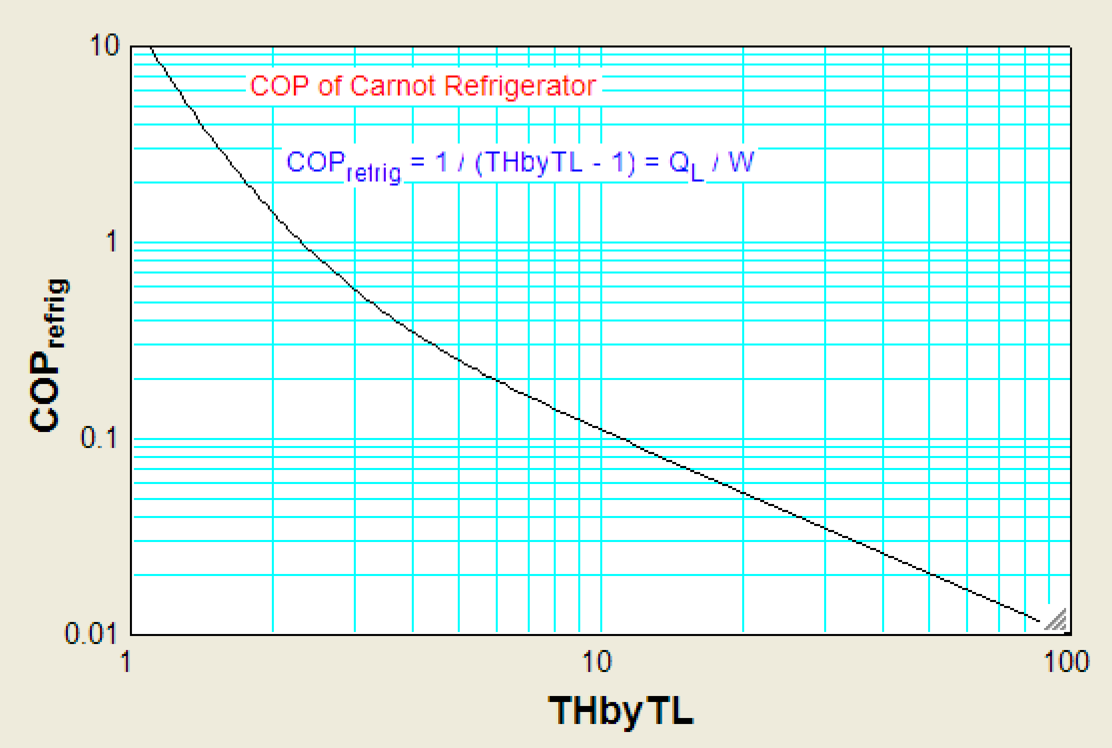
1..11	THbyTL	η_{th}
Run 1	1	0
Run 2	10	0.9
Run 3	20	0.95
Run 4	30	0.9667
Run 5	40	0.975
Run 6	50	0.98
Run 7	60	0.9833
Run 8	70	0.9857
Run 9	80	0.9875
Run 10	90	0.9889
Run 11	100	0.99



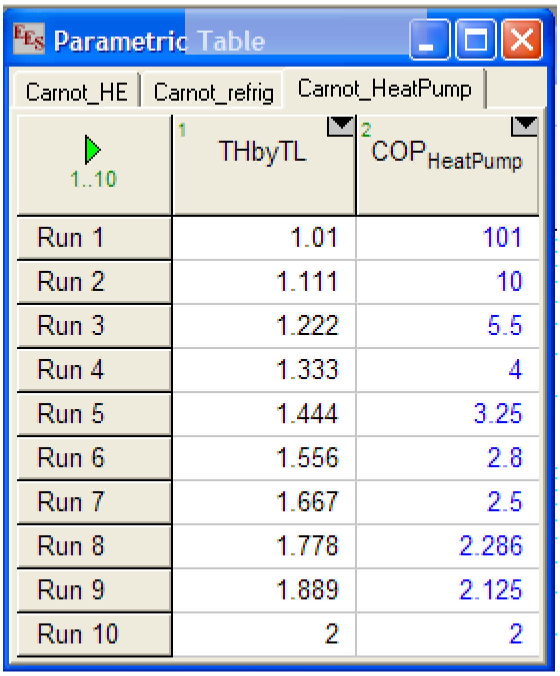
b) **Carnot Refrigerator:**



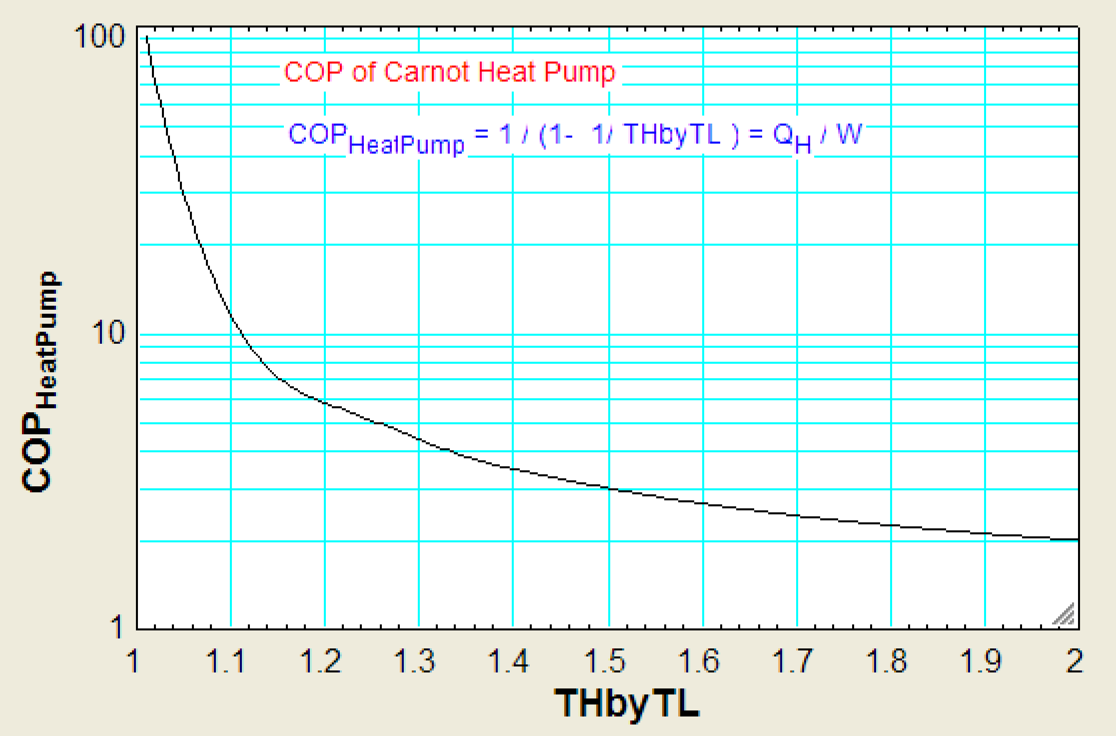
1..21	THbyTL	COP_{refrig}
Run 1	1.1	10
Run 2	5	0.25
Run 3	10	0.1111
Run 4	15	0.07143
Run 5	20	0.05263
Run 6	25	0.04167
Run 7	30	0.03448
Run 8	35	0.02941
Run 9	40	0.02564
Run 10	45	0.02273
Run 11	50	0.02041
Run 12	55	0.01852
Run 13	60	0.01695
Run 14	65	0.01563
Run 15	70	0.01449
Run 16	75	0.01351
Run 17	80	0.01266
Run 18	85	0.0119
Run 19	90	0.01124
Run 20	95	0.01064
Run 21	100	0.0101



c) **Carnot Heat Pump:**



1..10	THbyTL	$COP_{HeatPump}$
Run 1	1.01	101
Run 2	1.111	10
Run 3	1.222	5.5
Run 4	1.333	4
Run 5	1.444	3.25
Run 6	1.556	2.8
Run 7	1.667	2.5
Run 8	1.778	2.286
Run 9	1.889	2.125
Run 10	2	2



23. **Clausius Inequality:** is useful when you have to analyze many other processes in addition to Engines, Refrigerators and Heat Pumps. This is another way of stating II Law. It is stated as:

Considering the usual sign conventions for Heat and Work, (i.e. Heat going In is +ve, Work going Out is +ve)

$\sum \frac{Q}{T} = 0$ ……for a Reversible engine (Carnot Engine) ……eqn. 6.7

$\sum \frac{Q}{T} < 0$……for an Irreversible engine ……eqn. 6.8

If $\sum \frac{Q}{T} > 0$ ……It is an Impossible engine ……eqn. 6.9

==

6.2 Problems solved with EES:

"**Prob. 6.1.** The minimum power required to drive a heat pump which maintains a house at 20 C is 3 kW. If the outside temp is 3 C, estimate the amount of heat which the house loses per minute. [VTU-BTD-Dec. 06–Jan. 07:]"

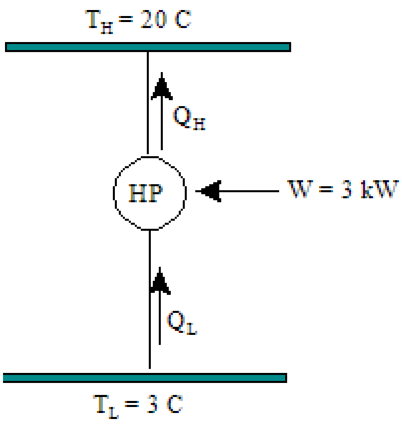
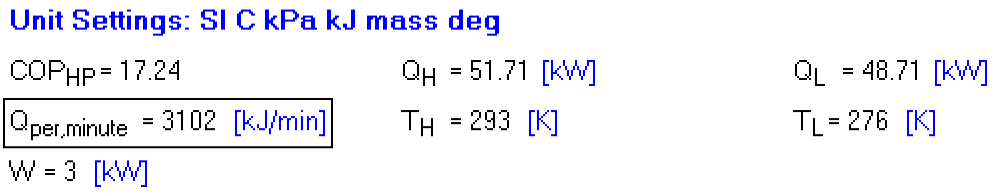


Fig.Prob.6.1

EES Solution:

```
"Data:"

T_H = 20 + 273 "K"
T_L = 3 + 273 "K"
W = 3 "kW"

"Calculations:"

COP_HP = T_H/(T_H-T_L) "determines COP"

COP_HP = Q_H/W "....determines Q_H"

Q_per_minute = Q_H* convert(kJ/s,kJ/min) "kJ/min"

Q_H = Q_L + W "kW......determines Q_L"
```

Results:



Unit Settings: SI C kPa kJ mass deg

```
COP_HP = 17.24                  Q_H = 51.71 [kW]      Q_L = 48.71 [kW]
Q_per,minute = 3102 [kJ/min]    T_H = 293 [K]         T_L = 276 [K]
W = 3 [kW]
```

Thus: Heat lost per minute = 3102 kJ/min …. Ans.

==

“**Prob. 6.2.** It is proposed to produce 1000 kg of ice per hour from liquid water at 0 C in summer when the ambient atmospheric temp is 37 C. It is planned to use a heat engine to operate the refrigeration plant. Hot water at 70 C, produced by solar heating acts as a source to the heat engine which uses the atmosphere as the sink. Calculate: (i) the power required by the refrigeration plant (ii) the ratio of energy extracted from freezing water to that absorbed by the heat engine, and (iii) the rate of rejection of heat by both the devices. Take enthalpy of fusion of water at 0 C as 333.43 kJ/kg. [VTU-BTD-Dec. 08–Jan. 09]”

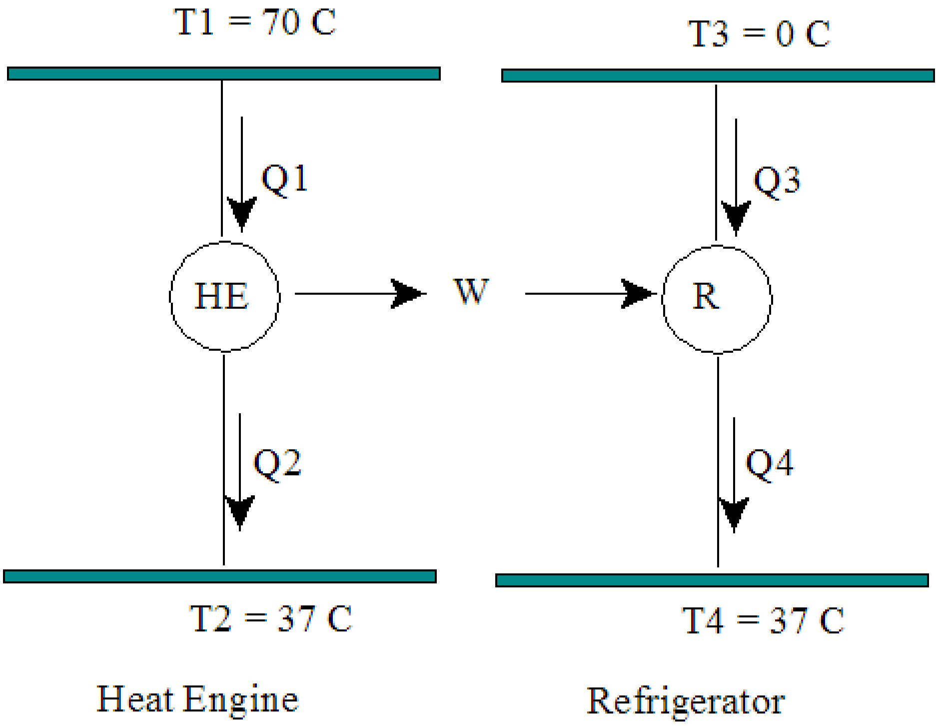
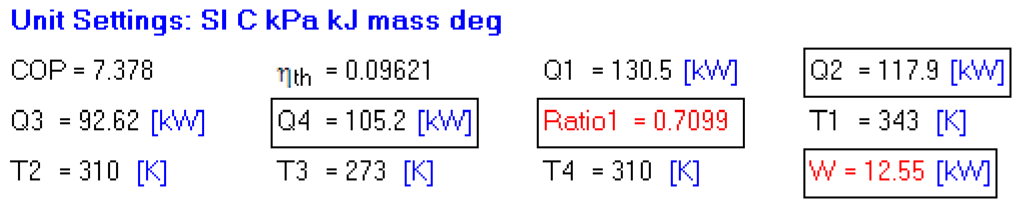


Fig.Prob.6.2

EES Solution:

```
"Data:"

T1 = 70+273"K"
T2 = 37+273 "K"
T3 = 0+273 "K"
T4 = T2

"Calculations:"

Q3 = 333.43*1000/3600 "kJ/s.... heat extracted from freezing water at 0 C"
COP = T3/(T4-T3)"...finds COP of refrigerator"
COP = Q3/W"...finds W"
Q4 = Q3 + W "kJ/s ... heat delivered to ambient by refrigerator"
eta_th = 1 - (T2/T1) "...finds eta of heat engine"
eta_th = W/Q1 "...finds Q1"
Q2 = Q1 - W"kJ/s .... heat rejected to ambient by the heat engine"
"Therefore:"
Ratio1=Q3/Q1
```

Results:



```
Unit Settings: SI C kPa kJ mass deg
COP = 7.378        ηth = 0.09621       Q1 = 130.5 [kW]     Q2 = 117.9 [kW]
Q3 = 92.62 [kW]    Q4 = 105.2 [kW]     Ratio1 = 0.7099     T1 = 343 [K]
T2 = 310 [K]       T3 = 273 [K]        T4 = 310 [K]        W = 12.55 [kW]
```

Thus:

Power required by refrigerator = W = 12.55 kW … Ans.

Ratios of energy extracted from freezing water to that absorbed by heat engine = Q3/Q1 = Ratio1 = 0.7099 …Ans.

Rate of heat rejected by heat engine = Q2 = 117.9 kW … Ans.

Rate of heat rejected by refrigerator = Q4 = 105.2 kW … Ans.

==

“**Prob.6.3.** A household refrigerator is maintained at 2 C. Every time the door is opened, warm material is placed inside, introducing an average of 420 kJ of heat but making only small changes in the temp of the refrigerator. The door is opened 20 times in a day and the refrigerator COP is 15% of the ideal COP. The cost of operating the refrigerator is 32 paise for 1 kWh. What is the monthly bill of this refrigerator? Take ambient temp to be 30 C. [VTU-BTD-Dec. 08–Jan. 09-2002 Scheme]”

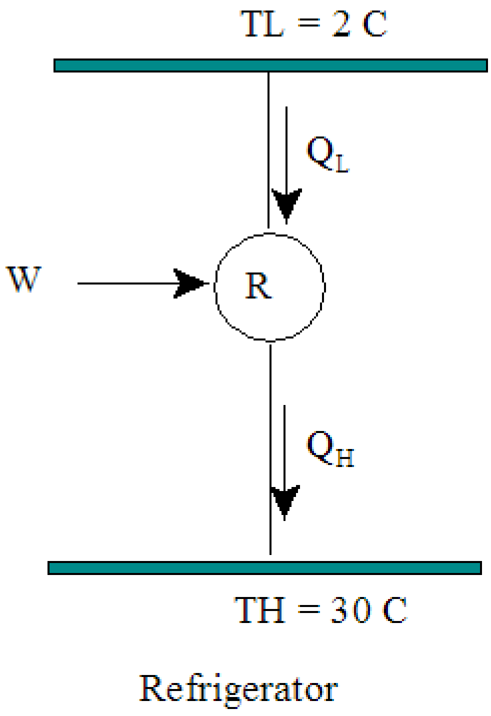


Fig.Prob.6.3

EES Solution:

```
"Data:"

TH = 30+273 "K"
TL = 2+273 "K"

"Calculations:"

Q_L = 420 * 20 / (24 * 3600) "kJ/s"

COP_ideal = TL/(TH-TL)

COP_actual = 0.15*COP_ideal

COP_actual = Q_L / W"...kW...finds W"

cost = 0.32 "Rs/kWh"

"Therefore, monthly bill:"

Monthlybill = W * (24*30) * cost "....Rs.    for 30 days."
```

Results:

```
Unit Settings: SI C kPa kJ mass deg
COPactual = 1.473          COPideal = 9.821          cost = 0.32 [Rs]
Monthlybill = 15.2 [Rs]    QL  = 0.09722 [kW]        TH = 303  [K]
TL  = 275  [K]             W = 0.06599 [kW]
```

Thus: Monthly bill = 15.2 Rs…..Ans.

===

"**Prob.6.4.** A reversible heat engine operates between two reservoirs at temperatures of 600 C and 40 C. The engine drives a reversible refrigerator, which operates between 40 C and -20 C. The heat transfer to the engine is 2000 kJ and net work output from the combined engine and refrigerator system is 360 kJ. Calculate heat transfer to the refrigerator and the net heat transfer to the reservoir at 40 C. [VTU-BTD-June–July-2009]"

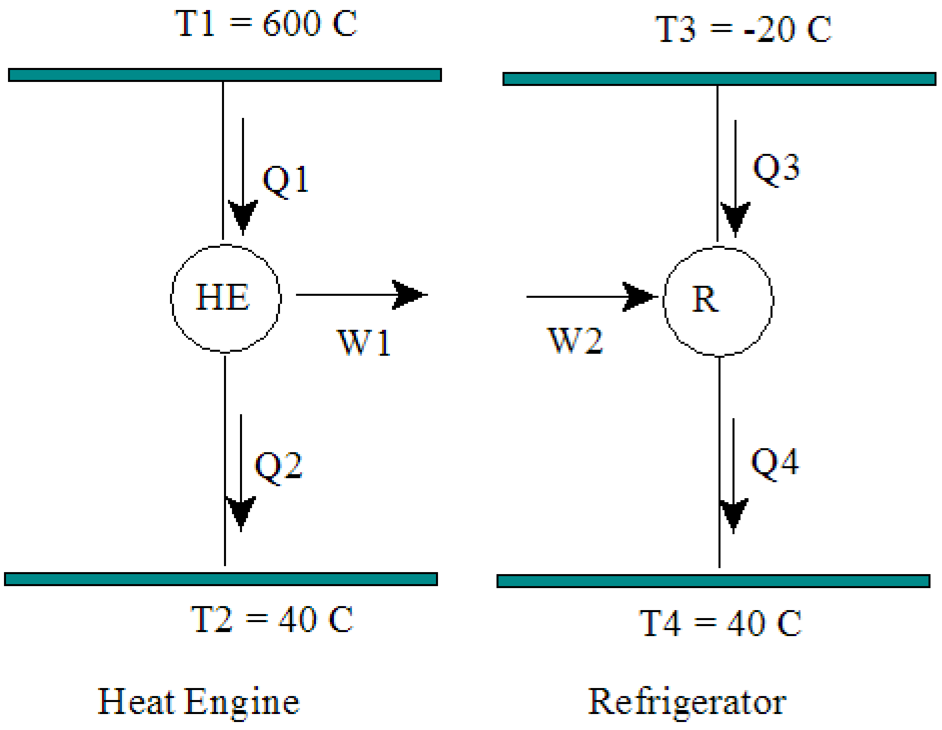
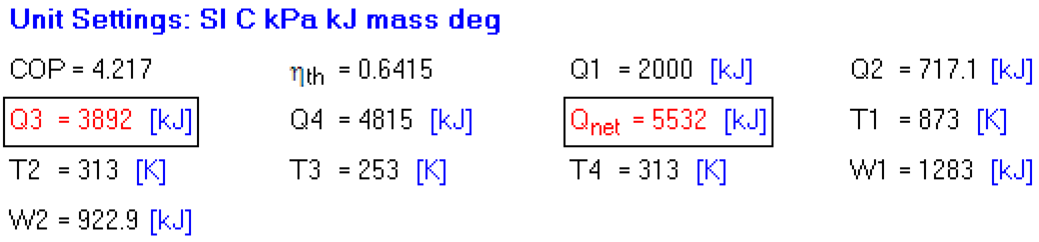


Fig.Prob.6.4

EES Solution:

```
"Data:"

T1 = 600+273 "K"
T2 = 40 + 273 "K"
T3 = -20 + 273 "K"
T4 = T2
Q1 = 2000 "kJ"

"Calculations:"

eta_th = 1 -T2/T1"....effcy. of rev. heat engine"

eta_th = W1/Q1"..finds W1, work output of rev. engine"

Q2 = Q1 - W1"....heat rejected by rev. engine"

W2 = W1 - 360 "kJ... work input to refrigerator"

COP = T3 / (T4 - T3) "...finds COP of rev. refrigerator"

COP = Q3 / W2"...finds Q3, heat transfer to the refrigerator"

Q4 = Q3 + W2 "...heat rejected by refrigerator to reservoir at 40 C"

Q_net = Q2+Q4 "...net heat transfer to the reservoir at 40 C"
```

Results:



```
Unit Settings: SI C kPa kJ mass deg

COP = 4.217          ηth = 0.6415        Q1 = 2000 [kJ]      Q2 = 717.1 [kJ]
Q3 = 3892 [kJ]       Q4 = 4815 [kJ]      Qnet = 5532 [kJ]    T1 = 873 [K]
T2 = 313 [K]         T3 = 253 [K]        T4 = 313 [K]        W1 = 1283 [kJ]
W2 = 922.9 [kJ]
```

Thus:

Heat transfer to refrigerator, Q3 = 3892 kJ … Ans.

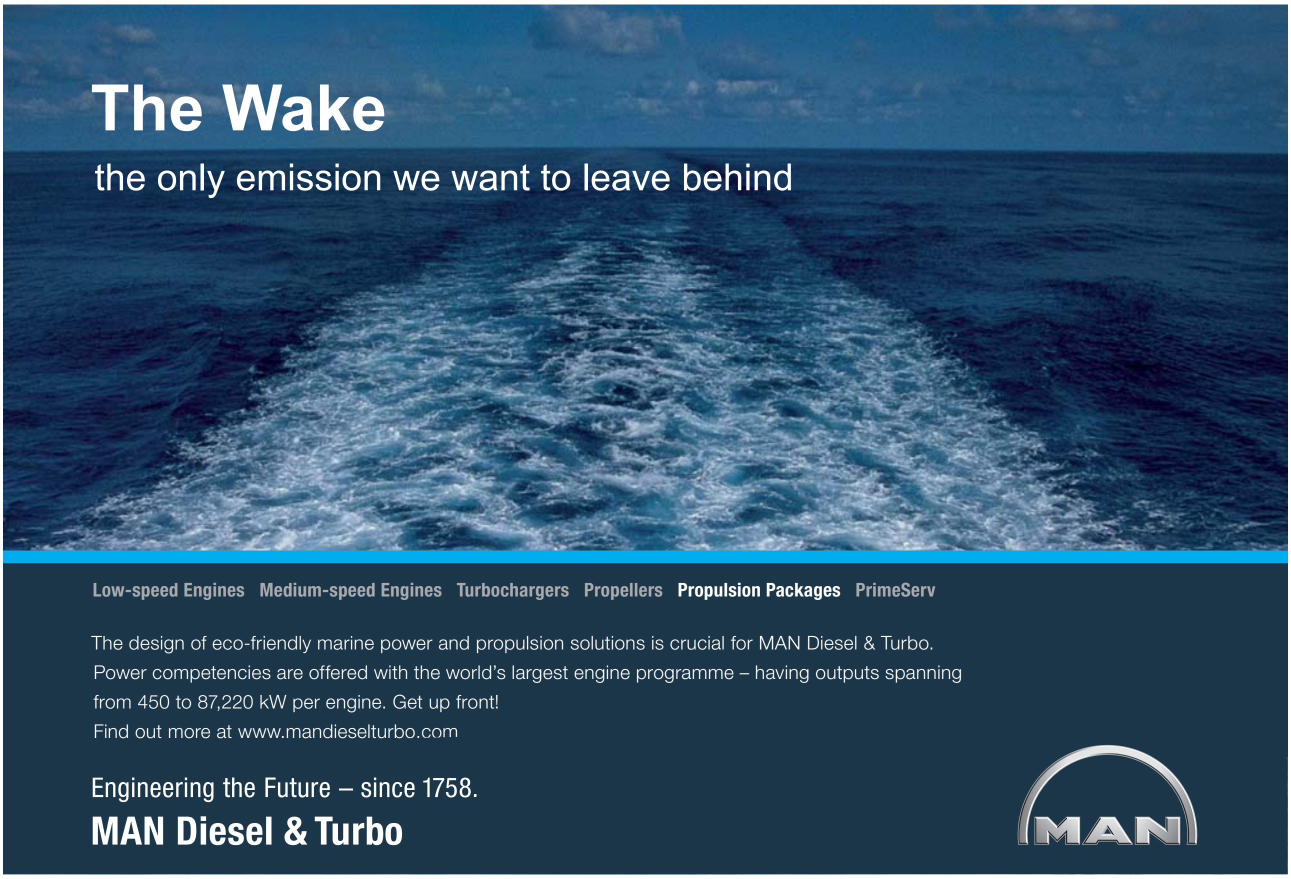
Net heat transfer to the reservoir at 40 C = Q_net = 5532 kJ … Ans.

==

“**Prob.6.5.** Two reversible heat engines A and B are arranged in series, A rejecting heat to B through an intermediate reservoir. Engine A receives 200 kJ at a temp of 421 C from a hot source, while engine B is in communication with a cold sink at a temp of 4.4 C. If the work output of A is twice that of B, find: (i) the intermediate temp between A and B (ii) efficiency of each engine, and (iii) heat rejected to the cold sink. [VTU-BTD-June–July-2008]”

EES Solution:

```
"Data:"

T1 = 421+273 "K"
T3 = 4.4 + 273 "K"
Q1 = 200 "kJ"

W_A = 2 * W_B "by data, W_A is two times W_B"
```



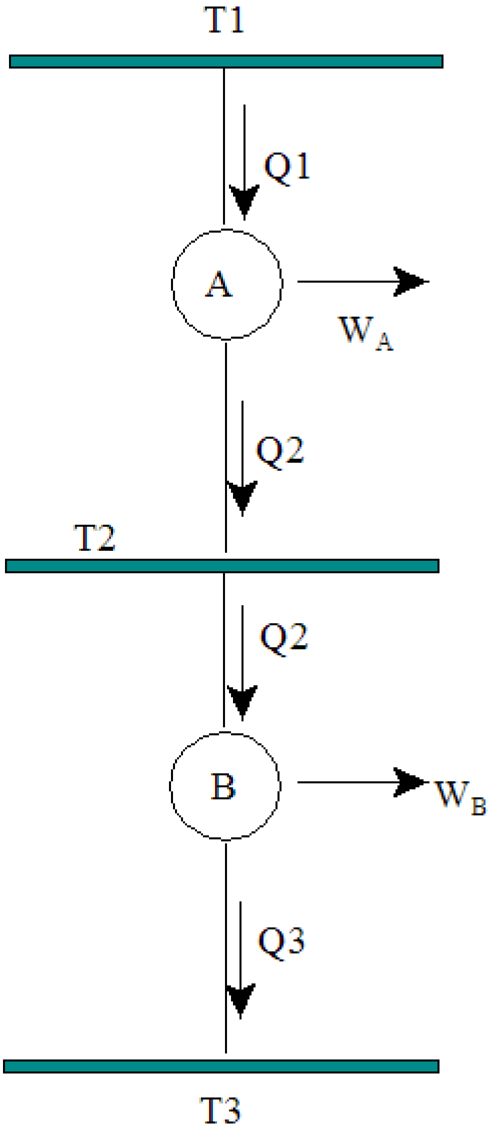


Fig.Prob.6.5

"Calculations:"

eta_A = 1 - T2 / T1"...effcy of rev. engine A"

W_A = Q1 * eta_A "...work output of A"

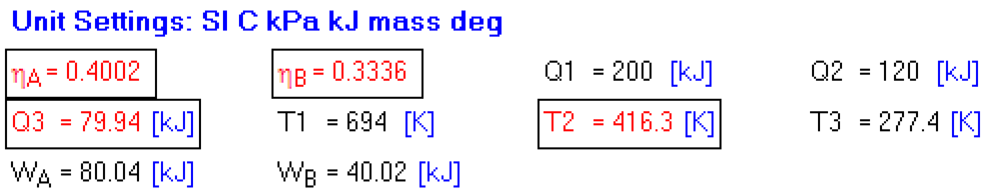
Q2 = Q1 - W_A "..heat input to engine B"

eta_B =1 - T3 / T2 "..effcy of rev. engine B"

eta_B = W_B / Q2 "...effcy of rev. engine B"

Q3 = Q2 - W_B "..heat rej. by engine B"

Results:



```
Unit Settings: SI C kPa kJ mass deg
ηA = 0.4002          ηB = 0.3336          Q1  = 200  [kJ]      Q2  = 120  [kJ]
Q3  = 79.94 [kJ]     T1  = 694  [K]       T2  = 416.3 [K]      T3  = 277.4 [K]
WA = 80.04 [kJ]      WB = 40.02 [kJ]
```

Thus:

Intermediate temp = T2 = 416.3 K … Ans.
Efficiencies of engines: eta_A = 0.4002, eta_B = 0.3336 …. Ans.
Heat rejected to the cold sink = Q3 = 79.94 kJ … Ans.

===

"**Prob.6.6.** A direct heat engine operating between two reservoirs at 327 C and 27 C drives a refrigerator operating between 27 C and 13 C. The efficiency of heat engine and the COP of the refrigerator are each 70% of their max. values. The heat transferred to the direct heat engine is 500 kJ. The net heat rejected by the engine and the refrigerator to the reservoir at 27 C is 400 kJ. Find the net work output of the engine-refrigerator combination. Draw the schematic representation. [VTU-BTD-July-2006]"

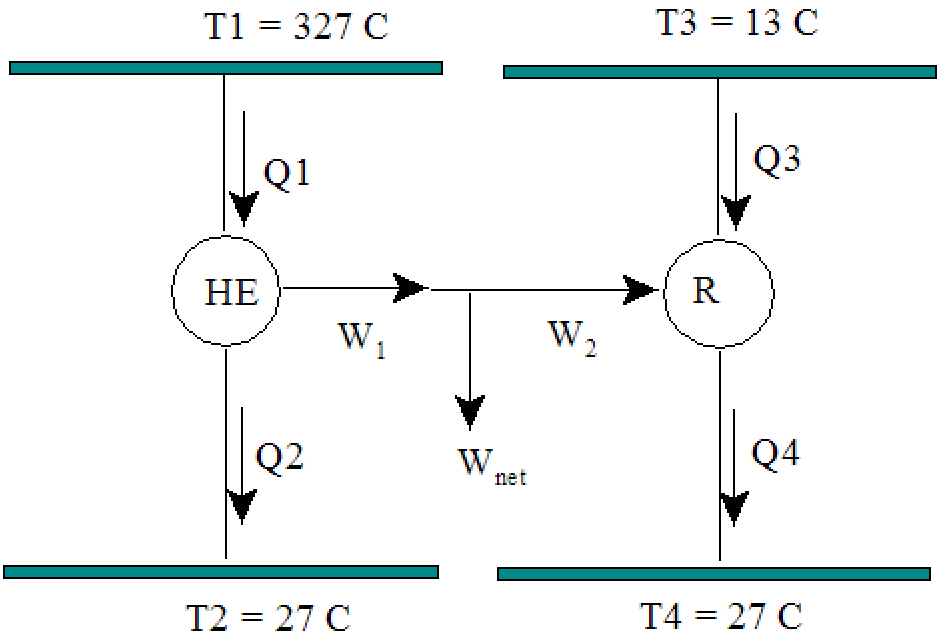
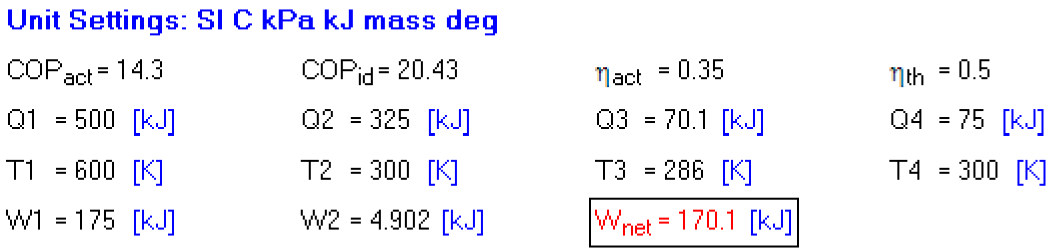


Fig.Prob.6.6

EES Solution:

```
"Data:"

T1 = 327+273 "K"
T2 = 27 + 273 "K"
T3 = 13 + 273 "K"
T4 = T2
Q1 = 500 "kJ"

"Calculations:"

eta_th = 1 -T2/T1 "..effcy of rev. engine, i.e. ideal effcy."

eta_act=0.7*eta_th "..effcy of actual engine"

eta_act = W1/Q1"..finds W1 from the formula for actual effcy."

Q2 = Q1 - W1"...heat rej. by engine"

COP_id = T3 / (T4 - T3) "...COP of ideal or reversible refrigerator"

COP_act = 0.7 * COP_id "...COP of actual refrigerator"

COP_act = Q3 / W2  "....COP of actual refrigerator"

Q2 + Q4 = 400 "...finds Q4, the heat rej. by the refrig."

Q3 + W2 = Q4 “…First Law for refrig.”

W_net = W1 - W2 "...net work output from the combination of engine and refrigerator"
```

Results:



```
Unit Settings: SI C kPa kJ mass deg

COPact = 14.3        COPid = 20.43       ηact = 0.35          ηth = 0.5
Q1  = 500  [kJ]      Q2  = 325  [kJ]     Q3  = 70.1  [kJ]     Q4  = 75  [kJ]
T1  = 600  [K]       T2  = 300  [K]      T3  = 286  [K]       T4  = 300  [K]
W1 = 175  [kJ]       W2 = 4.902 [kJ]     Wnet = 170.1  [kJ]
```

Thus: Net work output of the combination = W_net = 170.1 kW … Ans.

==

"**Prob. 6.7.** A reversible engine working in a cycle takes 4800 kJ/min of heat from a source at 800 K and develops 20 kW power. The engine rejects heat to two reservoirs at 300 K and 360 K. Determine the heat rejected to each sink. [VTU-BTD-Dec. 2011]"

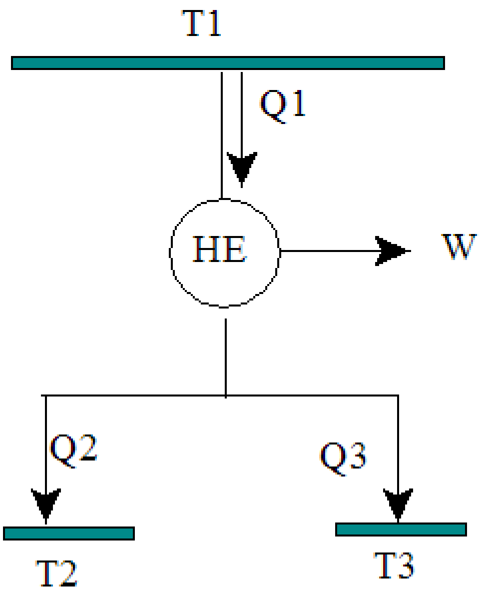
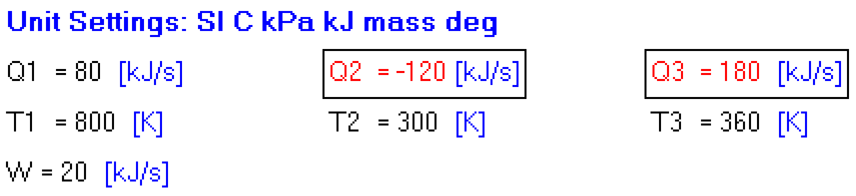


Fig.Prob.6.7

EES Solution:

```
"Data:"

Q1 = 80 "kJ/s"
T1 = 800 "K"
W = 20 "kJ/s"
T2 = 300 "K"
T3 = 360 "K"

"Calculations:"

Q1 = W + Q2 + Q3 "...by First Law"
Q1/T1 - Q2/T2 - Q3/T3 = 0 "...for rev. engine, by Clausius inequality form of Second Law"
```

Results:



Unit Settings: SI C kPa kJ mass deg

Q1 = 80 [kJ/s]	Q2 = -120 [kJ/s]	Q3 = 180 [kJ/s]
T1 = 800 [K]	T2 = 300 [K]	T3 = 360 [K]
W = 20 [kJ/s]		

Thus:

Q2 = heat rejected to sink at T2 (=300 K) = -120 kW, i.e. since sign is opposite to what we assumed, it means that 120 kJ/s heat is actually supplied to the rev. engine at 300 K, not rejected!
Q3 = heat rejected to sink at T3 (=360 K) = 180 kJ/s ….Ans.

==

"**Prob.6.8**. A reversible heat engine works between two reservoirs at 1400 K and 350 K respectively. A reversible heat pump receives heat from the reservoir at 250 K and rejects the heat to a reservoir at 350 K to which the heat engine also rejects the heat. The work output from the engine is used to drive the heat pump. If the total heat supplied to the reservoir at 350 K is to be 100 kW, find the heat to be received by the heat engine. [VTU-BTD-July-2007]"

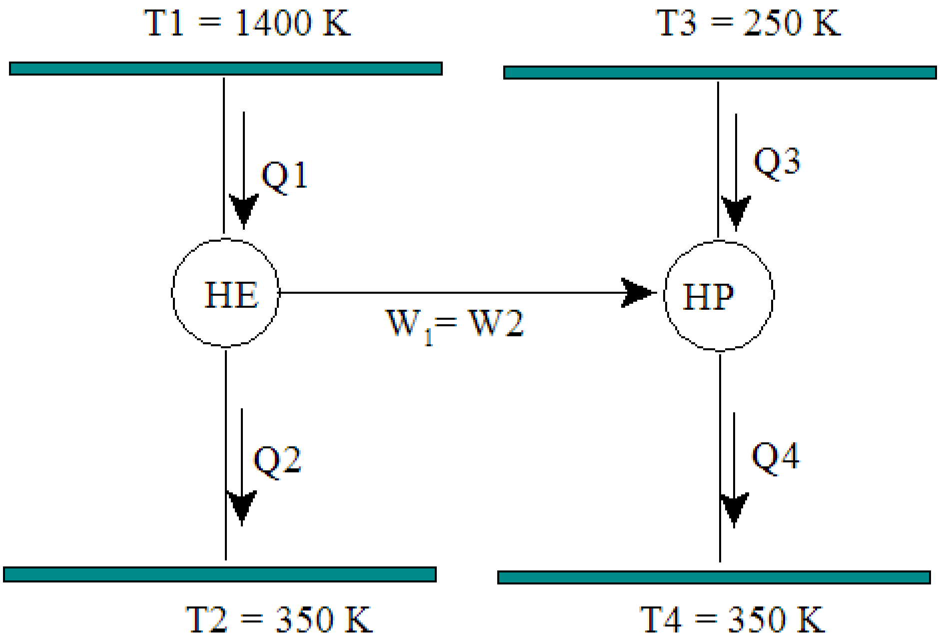
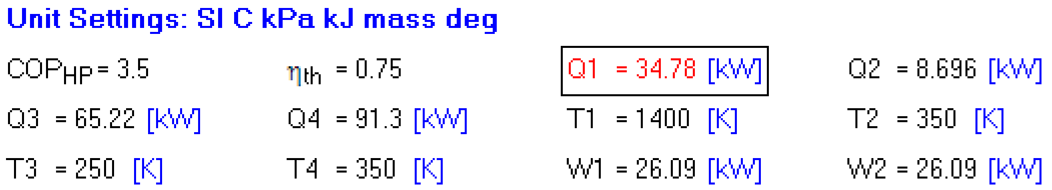


Fig.Prob.6.8

EES Solution:

```
"Data:"

T1 = 1400"K"
T2 = 350"K"
T3 = 250"K"
T4 = T2

"Calculations:"

eta_th = 1 -T2/T1"...effcy of rev. engine"

eta_th = W1 / Q1"....effcy of the rev. engine"

Q2 = Q1 - W1"....heat rej. by the engine"

COP_HP = T4 / (T4-T3) "...COP of rev. heat pump"

COP_HP = Q4 / W2"...COP of rev. heat pump"

W1= W2 "...works are equal, by data"

Q2 + Q4 = 100"... total heat rej....finds Q4"

Q3 + W2 = Q4 "...work rej. by heat pump"
```

Results:



```
Unit Settings: SI C kPa kJ mass deg
COPHP = 3.5          ηth = 0.75        Q1 = 34.78 [kW]    Q2 = 8.696 [kW]
Q3 = 65.22 [kW]      Q4 = 91.3 [kW]    T1 = 1400 [K]      T2 = 350 [K]
T3 = 250 [K]         T4 = 350 [K]      W1 = 26.09 [kW]    W2 = 26.09 [kW]
```

Thus:

Heat received by heat engine = Q1 = 34.78 kW …. Ans.

==

"**Prob.6.9.** A reversible engine is supplied with heat from two constant temperature sources at 900 K and 600 K, and rejects heat to a constant temp sink at 300 K. The engine develops work equivalent to 90 kJ/s and rejects heat at the rate of 56 kJ/s. Estimate: (i) heat supplied by each source, and (ii) thermal efficiency of the engine. [VTU-BTD-June/July 2008]"

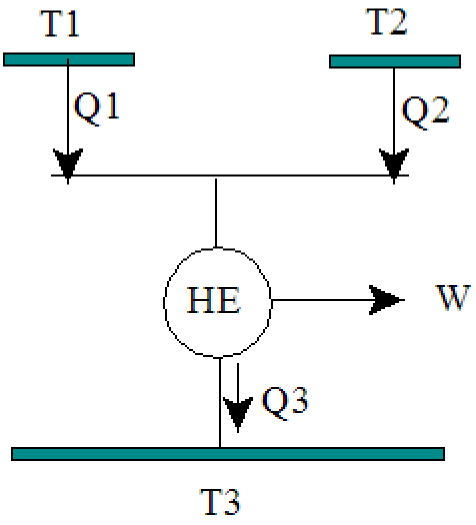


Fig.Prob.6.9

Recollect that Clausius inequality form of Second Law is:

Considering the usual sign conventions for Heat and Work, (i.e. Heat going In is +ve, Work going Out is +ve)

$\sum \frac{Q}{T} = 0$ ……for a Reversible engine (Carnot Engine) ……eqn. 6.7

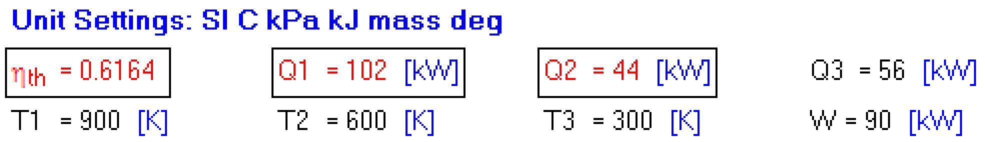
$\sum \frac{Q}{T} < 0$ ……for an Irreversible engine ……eqn. 6.8

If If $\sum \frac{Q}{T} > 0$ ……It is an Impossible engine ……eqn. 6.9

EES Solution:

```
"Data:"

T1 = 900 "K"
T2 = 600 "K"
T3 = 300 "K"
Q3 = 56 "kW"
W = 90 "kW"

"Calculations:"

"Let Q1, Q2 be the heat supplied from the heat sources at 900 K and 600 K respectively."

"Then, for any process to take place, both the First and Second Laws must be satisfied simultaneously:"

Q1 + Q2 - Q3 = W "....First Law"

Q1/ T1 + Q2 / T2 - Q3 / T3 = 0 "...Second Law for a reversible engine, in Clausius Inequality form"

eta_th = W/(Q1+Q2) "...Thermal efficiency of engine"
```

Results:



```
Unit Settings: SI C kPa kJ mass deg
ηth = 0.6164        Q1 = 102 [kW]      Q2 = 44 [kW]       Q3 = 56 [kW]
T1 = 900 [K]        T2 = 600 [K]       T3 = 300 [K]       W = 90 [kW]
```

Thus:

Heat supplied from Source at 900 K = Q1 = 102 kW … Ans.

Heat supplied from Source at 600 K = Q2 = 44 kW … Ans.

Thermal efficiency of engine = eta_th = 0.6164 … Ans.

==

"**Prob.6.10.** A reversible engine operates between 3 heat reservoirs at 1000 K, 800 K, and 600 K and rejects heat to a reservoir at 300 K. The engine develops 10 kW and rejects 412 kJ/min. If heat supplied by the reservoir at 1000 K is 60% of heat supplied by the reservoir at 600 K, find the quantity of heat supplied by each reservoir. [VTU-BTD-March 2001]"

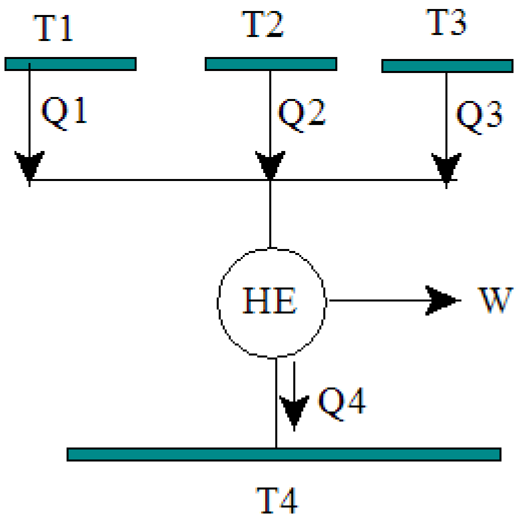


Fig.Prob.6.10

Again, recollect that:

Clausius inequality form of Second Law is:

Considering the usual sign conventions for Heat and Work, (i.e. Heat going In is +ve, Work going Out is +ve)

$\sum \frac{Q}{T} = 0$ ……for a Reversible engine (Carnot Engine) ……eqn. 6.7

$\sum \frac{Q}{T} < 0$ ……for an Irreversible engine ……eqn. 6.8

If $\sum \frac{Q}{T} > 0$ ……It is an Impossible engine ……eqn. 6.9

EES Solution:

```
"Data:"

T1 = 1000"K"
T2 = 800 "K"
T3 = 600 "K"
T4 = 300 "K"

W = 10 "kW"

Q4 = 412 / 60"kW"

Q1 = 0.6 * Q3 "by data"

"Calculations:"
```

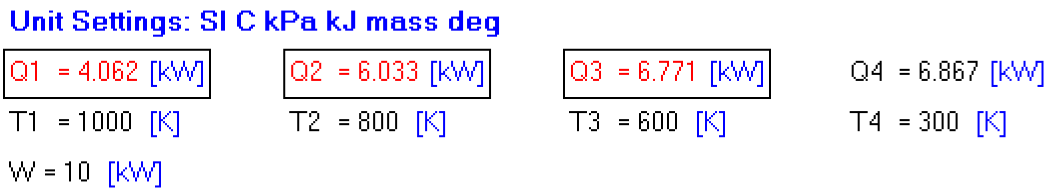
"By I Law:"

Q1 + Q2 + Q3 - Q4 = W

"By II Law...Clausius' inequality:"

Q1/ T1 + Q2 / T2 + Q3 / T3 - Q4 / T4 = 0

Results:



```
Unit Settings: SI C kPa kJ mass deg
Q1  = 4.062 [kW]     Q2  = 6.033 [kW]     Q3  = 6.771 [kW]     Q4  = 6.867 [kW]
T1  = 1000  [K]      T2  = 800  [K]       T3  = 600  [K]       T4  = 300  [K]
W = 10  [kW]
```

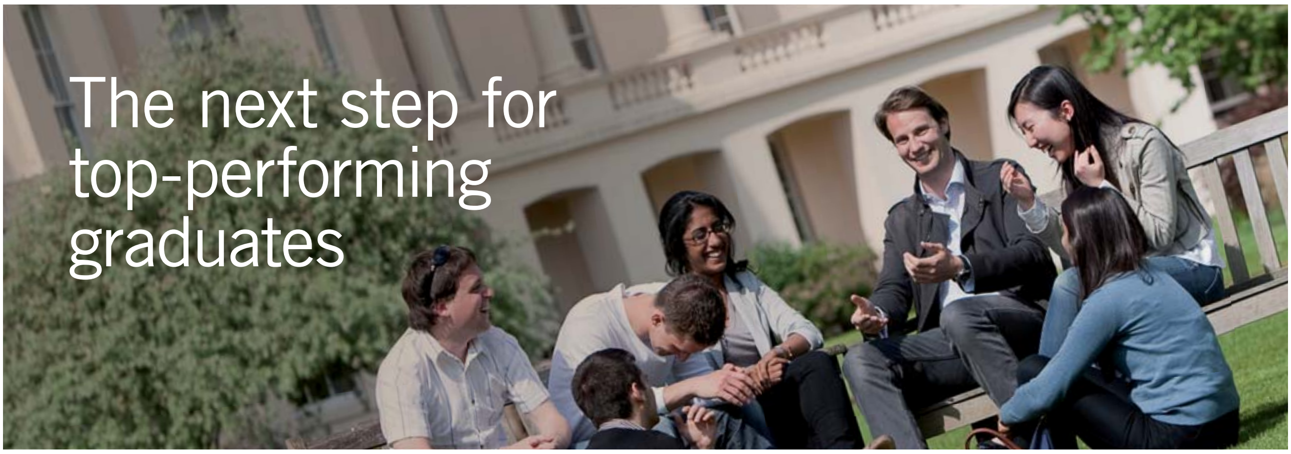
Thus:

Heat supplied from Source at 1000 K = Q1 = 4.062 kW … Ans.

Heat supplied from Source at 800 K = Q2 = 6.033 kW … Ans.

Heat supplied from Source at 600 K = Q3 = 6.771 kW … Ans.

==



"**Prob.6.11**. A heat engine receives reversibly 300 kJ/min of heat per cycle from a source at 327 C and rejects heat reversibly to a sink at 27 C. There are no other heat transfers. Three hypothetical heat rejections are given below: (i) 200 kJ/min (ii) 150 kJ/min (iii) 100 kJ/min. From these results, state which of these cases is a reversible cycle, an irreversible cycle or an impossible cycle. [VTU-BTD-Dec. 2007–Jan. 2008]"

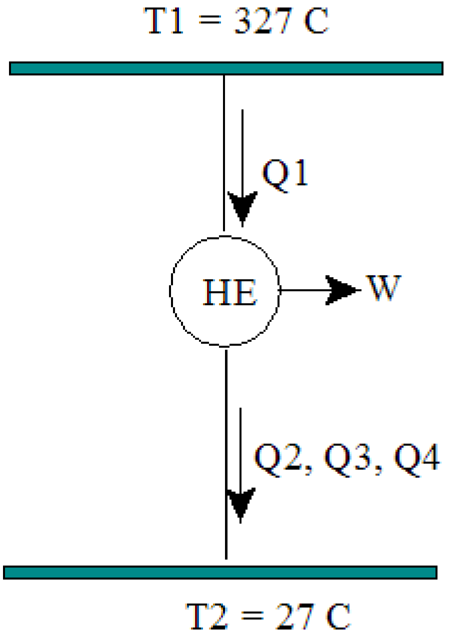


Fig.Prob.6.11

Recollecting that:

Clausius inequality form of Second Law is:

Considering the usual sign conventions for Heat and Work, (i.e. Heat going In is +ve, Work going Out is +ve)

$\sum\frac{Q}{T} = 0$ ……for a Reversible engine (Carnot Engine) ……eqn. 6.7

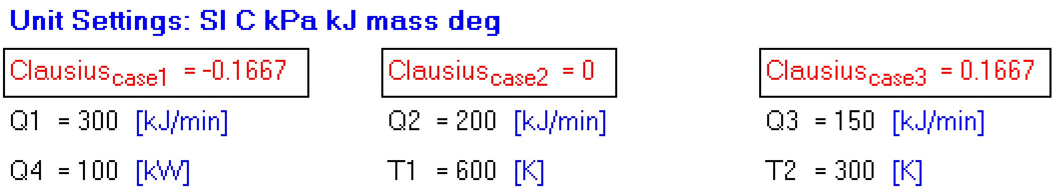
$\sum\frac{Q}{T} < 0$ ……for an Irreversible engine ……eqn. 6.8

If $\sum\frac{Q}{T} > 0$ ……It is an Impossible engine ……eqn. 6.9

EES Solution:

```
"Data:"

T1 = 327 + 273 "K"
T2 = 27 + 273 "K"

Q1 = 300 "kJ/min...by data"

Q2 = 200 "kJ/min....case 1"
Q3 = 150 "kJ/min....case 2"
Q4 = 100 "kJ/min....case 3"


"Calculations:"

"By II Law...Clausius' inequality:"

Clausius_case1 = Q1 / T1 - Q2 / T2 "...Clausius inequality for case 1"

Clausius_case2 = Q1 / T1 - Q3 / T2 "...Clausius inequality for case 1"

Clausius_case3 = Q1 / T1 - Q4 / T2 "...Clausius inequality for case 1"
```

Results:



```
Unit Settings: SI C kPa kJ mass deg
Clausius_case1 = -0.1667    Clausius_case2 = 0        Clausius_case3 = 0.1667
Q1 = 300 [kJ/min]           Q2 = 200 [kJ/min]         Q3 = 150 [kJ/min]
Q4 = 100 [kW]               T1 = 600 [K]              T2 = 300 [K]
```

Thus:

For case 1: Sum of (Q/T) = -ve, so it is an irreversible cycle …. Ans.
For case 2: Sum of (Q/T) = 0, so it is a reversible cycle … Ans.
For case 3: Sum of (Q/T) = +ve, so, it is an impossible cycle….. Ans.

==

“**Prob.6.12.** A reversible power cycle receives Q_H from a hot reservoir at temp T_H and rejects energy by heat transfer to the surroundings at temp T_O. The work developed by the power cycle is used to drive a refrigeration cycle that removes Q_C from a cold reservoir at temp T_C and discharges energy by heat transfer to the same surroundings at T_O.

(a) Develop an expression for the ratio (Q_C/Q_H) in terms of the temp ratios (T_H/T_O) and (T_C/T_O)

(b) Plot Q_C/Q_H versus T_H/T_O for T_C/T_O = 0.85, 0.9 and 0.95, and versus T_C/T_O for T_H/T_O = 2, 3 and 4.
[Ref: 3]”

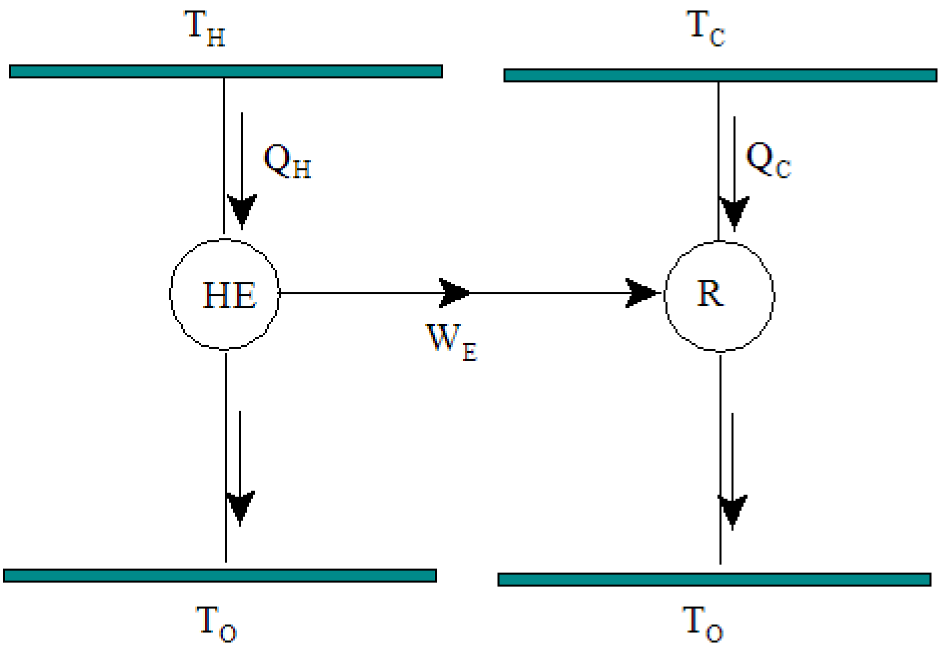


Fig.Prob.6.12

EES Solution:

```
"Solution:"

"COP_R = 1 / [(TO/TC) - 1] = QC / W_E = QC / [QH * (1- (TO/TH))]

Therefore: QC / QH = [1 -  (TO/TH)] / [(TO/TC) - 1] "

"Therefore:"

QCbyQH = A / B

A= 1-1/ THbyTO

B = (1/ TCbyTO) - 1

TCbyTO = 0.95

THbyTO = 4
```

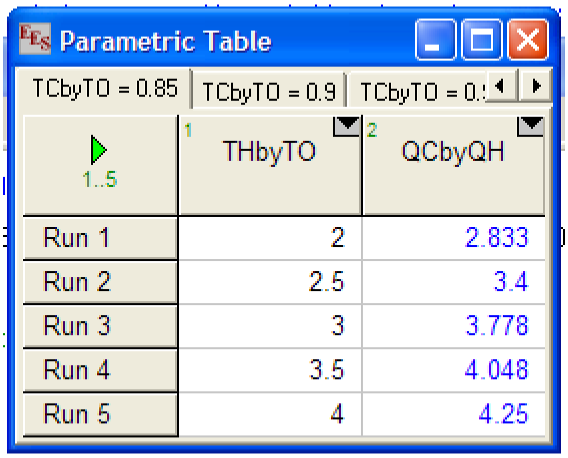
Results:

```
Unit Settings: SI C kPa kJ mass deg
A  = 0.75          B  = 0.05263        QCbyQH = 14.25     TCbyTO  = 0.95      THbyTO  = 4
```

To plot the results:

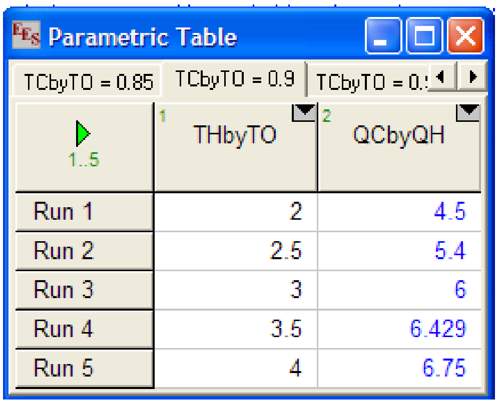
First produce the Parametric Table:

1. **TCbyTO = 0.85:**



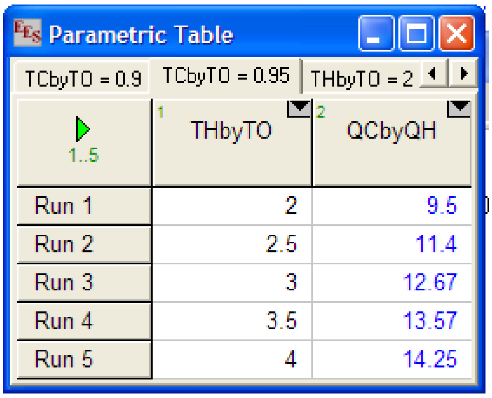
1..5	THbyTO	QCbyQH
Run 1	2	2.833
Run 2	2.5	3.4
Run 3	3	3.778
Run 4	3.5	4.048
Run 5	4	4.25

2. **TCbyTO = 0.9:**



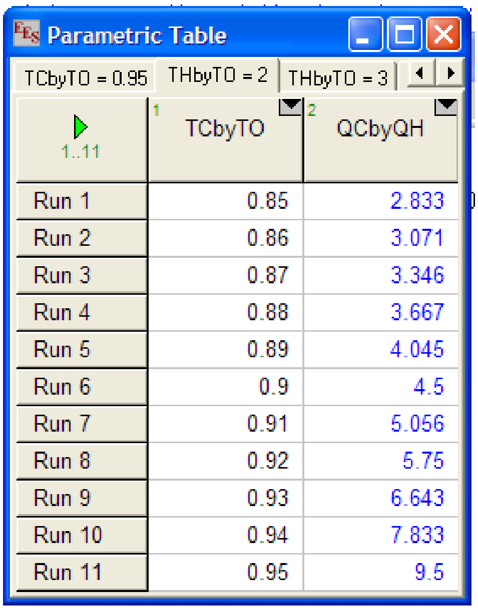
1..5	THbyTO	QCbyQH
Run 1	2	4.5
Run 2	2.5	5.4
Run 3	3	6
Run 4	3.5	6.429
Run 5	4	6.75

3. **TCbyTO = 0.95:**



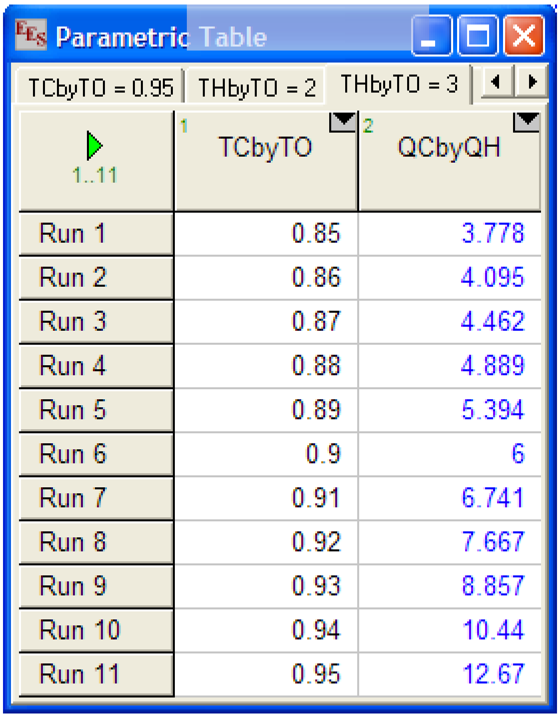
1..5	THbyTO	QCbyQH
Run 1	2	9.5
Run 2	2.5	11.4
Run 3	3	12.67
Run 4	3.5	13.57
Run 5	4	14.25

4. **THbyTO = 2:**



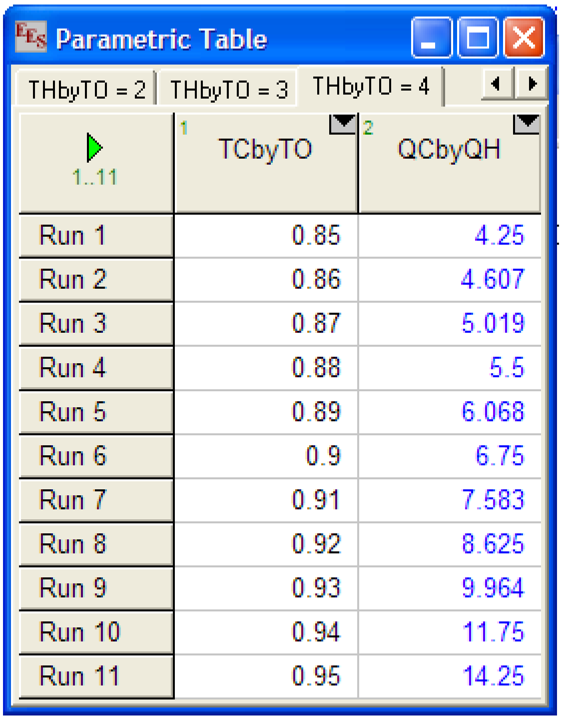
1..11	TCbyTO	QCbyQH
Run 1	0.85	2.833
Run 2	0.86	3.071
Run 3	0.87	3.346
Run 4	0.88	3.667
Run 5	0.89	4.045
Run 6	0.9	4.5
Run 7	0.91	5.056
Run 8	0.92	5.75
Run 9	0.93	6.643
Run 10	0.94	7.833
Run 11	0.95	9.5

5. **THbyTO = 3:**



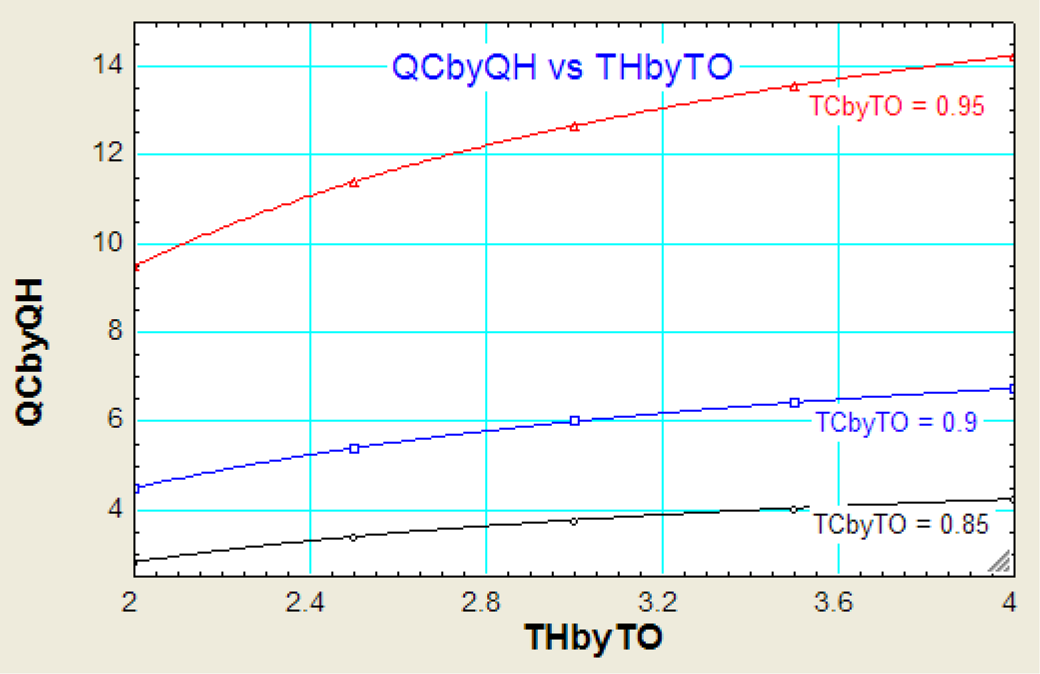
1..11	TCbyTO	QCbyQH
Run 1	0.85	3.778
Run 2	0.86	4.095
Run 3	0.87	4.462
Run 4	0.88	4.889
Run 5	0.89	5.394
Run 6	0.9	6
Run 7	0.91	6.741
Run 8	0.92	7.667
Run 9	0.93	8.857
Run 10	0.94	10.44
Run 11	0.95	12.67

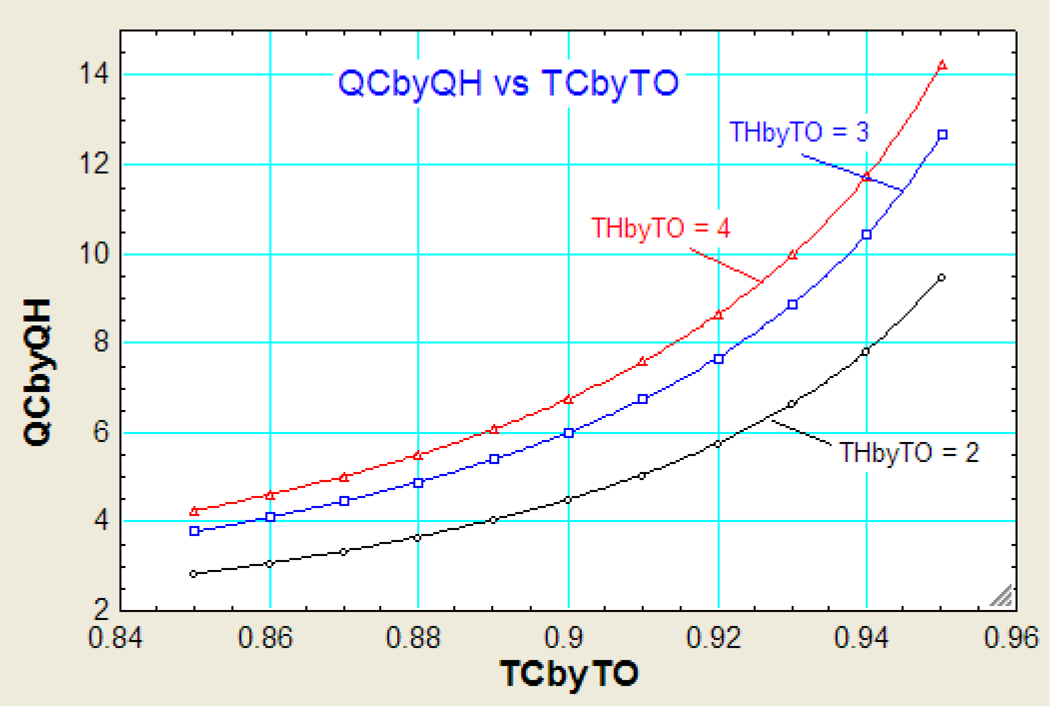
6. **THbyTO = 4:**



	1 TCbyTO	2 QCbyQH
Run 1	0.85	4.25
Run 2	0.86	4.607
Run 3	0.87	5.019
Run 4	0.88	5.5
Run 5	0.89	6.068
Run 6	0.9	6.75
Run 7	0.91	7.583
Run 8	0.92	8.625
Run 9	0.93	9.964
Run 10	0.94	11.75
Run 11	0.95	14.25

Now, plot the results:





==

“**Prob.6.13.** A reversible power cycle receives energy Q_H from a hot reservoir at temp T_H and rejects Q_C to a reservoir at temp T_C. The work developed by the power cycle is used to drive a rev. heat pump that removes energy Q_C_prime from a reservoir at temp T_C_prime and rejects energy Q_H_prime to a reservoir at temp T_H_prime.

(a) Develop an expression for the ratio (Q_H_prime/Q_H) in terms of the temperatures of four reservoirs
(b) What must be the relationship of temperatures T_H, T_C, T_C_prime and T_H_prime for (Q_H_prime / Q_H) to exceed a value of unity?
(c) Letting T_H_prime = T_C = T_O, plot (Q_H_prime / Q_H) versus (T_H/T_O) for (T_C_prime/T_O) = 0.85, 0.9 and 0.95, and versus
(T_C_prime/T_O) for (T_H/T_O) = 2, 3 and 4.
[Ref: 3]”

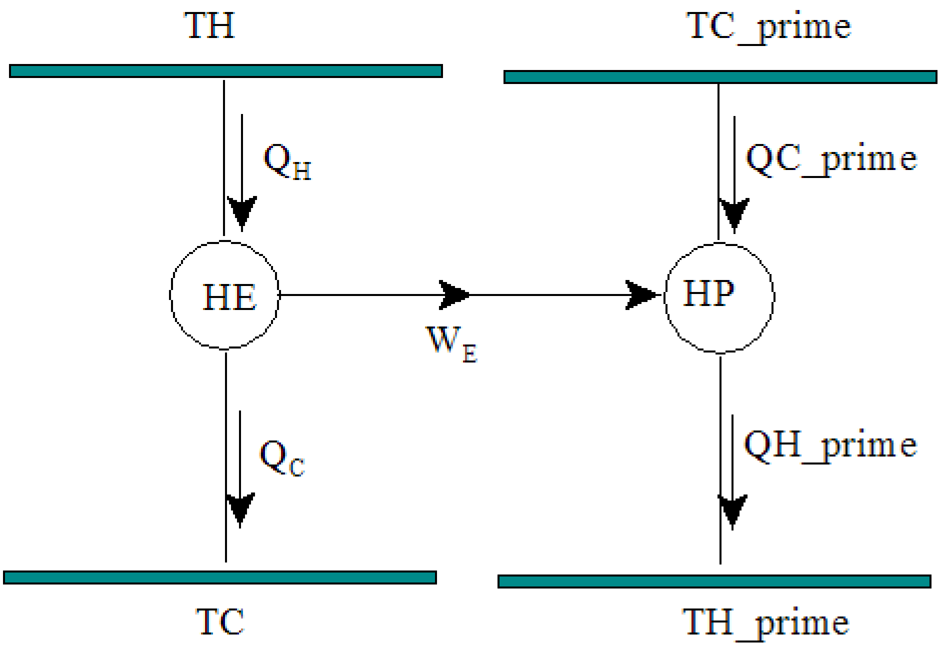


Fig.Prob.6.13

EES Solution:

Part-(a):

```
"COP_HP = Q_H_prime / W_E = T_H_prime / (T_H_prime- T_C_prime) =

Q_H_prime / [Q_H * (1- (T_C/T_H))]

i.e.     1/ (1 - T_C_prime/T_H_prime) =  Q_H_prime / [Q_H * (1- (T_C/T_H))]


Therefore: (Q_H_prime / Q_H) = [1 -  (T_C/T_H)] / [1 - (T_C_prime/T_H_prime)] … Ans.
```

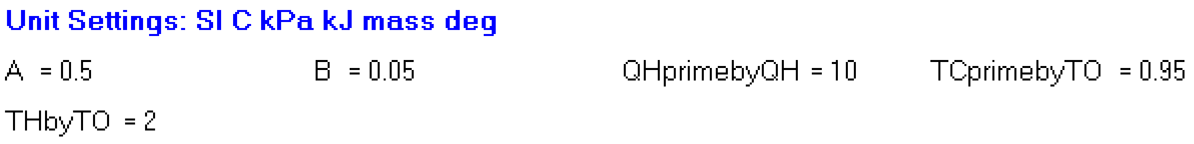
Part-(b):

```
Therefore:  (Q_H_prime / Q_H) > 1 if (T_C/T_H) < (T_C_prime /T_H_prime) …. Ans.
```

Part-(c):

```
Now: Let T_H_prime = T_C = T_O.

Then:  (Q_H_prime / Q_H) = [1 -  (T_O/T_H)] / [1 - (T_C_prime/T_O)]"


"Therefore:"

QHprimebyQH = A / B

A= 1-1/ THbyTO

B = (1- TCprimebyTO)

TCprimebyTO = 0.95

{THbyTO = 2}
```

Results:

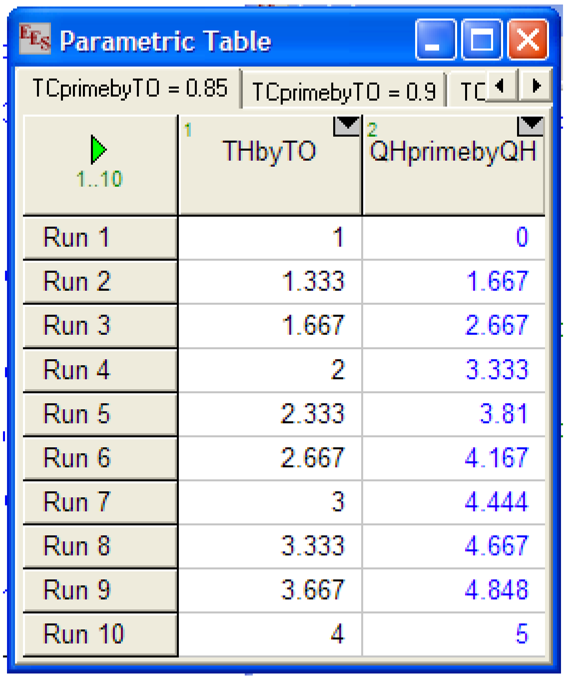


```
Unit Settings: SI C kPa kJ mass deg
A  = 0.5                    B  = 0.05                    QHprimebyQH = 10        TCprimebyTO  = 0.95
THbyTO  = 2
```

To plot the results:

First produce the Parametric Table for different TCprimebyTO values:

1. **TCprimebyTO = 0.85:**



1..10	THbyTO	QHprimebyQH
Run 1	1	0
Run 2	1.333	1.667
Run 3	1.667	2.667
Run 4	2	3.333
Run 5	2.333	3.81
Run 6	2.667	4.167
Run 7	3	4.444
Run 8	3.333	4.667
Run 9	3.667	4.848
Run 10	4	5

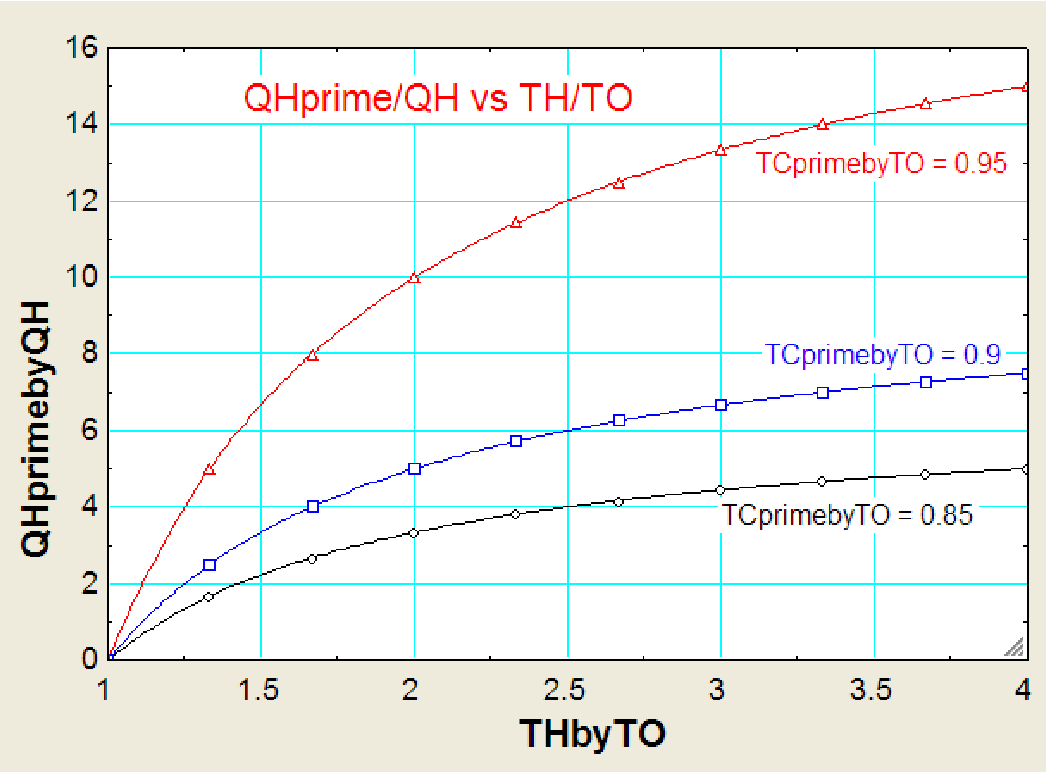
2. **TCprimebyTO = 0.9:**

1..10	THbyTO	QHprimebyQH
Run 1	1	-1.505E-36
Run 2	1.333	2.5
Run 3	1.667	4
Run 4	2	5
Run 5	2.333	5.714
Run 6	2.667	6.25
Run 7	3	6.667
Run 8	3.333	7
Run 9	3.667	7.273
Run 10	4	7.5

3. **TCprimebyTO = 0.95:**

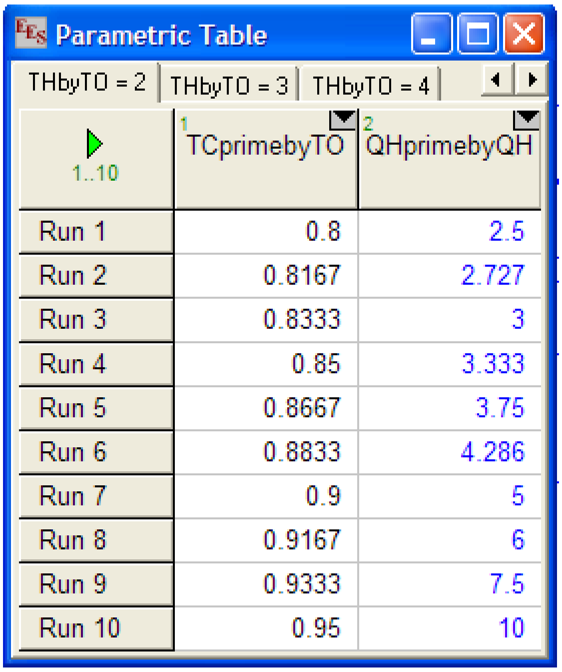
1..10	THbyTO	QHprimebyQH
Run 1	1	-1.505E-36
Run 2	1.333	5
Run 3	1.667	8
Run 4	2	10
Run 5	2.333	11.43
Run 6	2.667	12.5
Run 7	3	13.33
Run 8	3.333	14
Run 9	3.667	14.55
Run 10	4	15

And, plot:



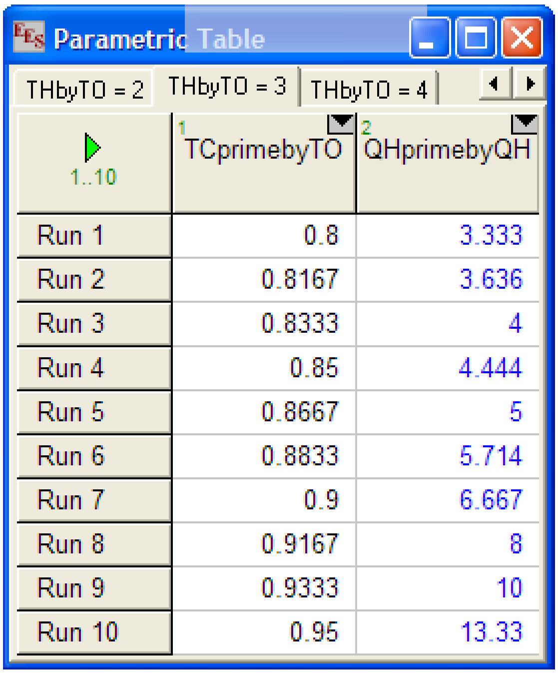
Now, produce the Parametric Table for different THbyTO values:

4. **THbyTO = 2:**



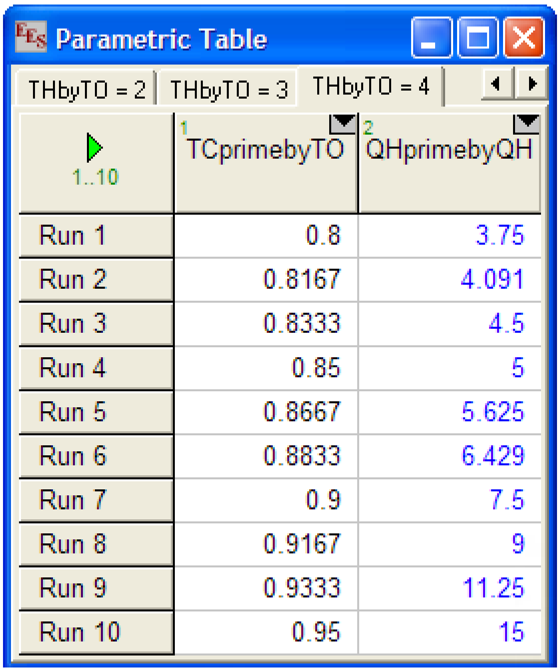
1..10	TCprimebyTO	QHprimebyQH
Run 1	0.8	2.5
Run 2	0.8167	2.727
Run 3	0.8333	3
Run 4	0.85	3.333
Run 5	0.8667	3.75
Run 6	0.8833	4.286
Run 7	0.9	5
Run 8	0.9167	6
Run 9	0.9333	7.5
Run 10	0.95	10

5. **THbyTO = 3:**



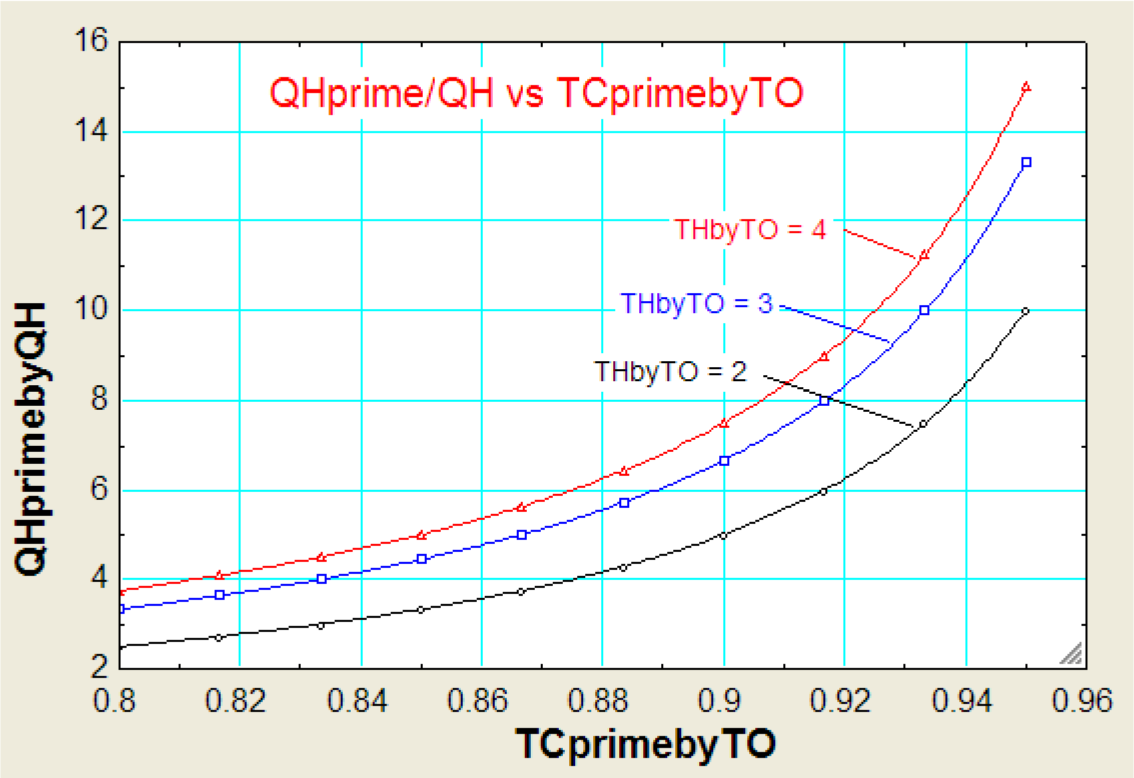
1..10	1 TCprimebyTO	2 QHprimebyQH
Run 1	0.8	3.333
Run 2	0.8167	3.636
Run 3	0.8333	4
Run 4	0.85	4.444
Run 5	0.8667	5
Run 6	0.8833	5.714
Run 7	0.9	6.667
Run 8	0.9167	8
Run 9	0.9333	10
Run 10	0.95	13.33

6. **THbyTO = 4:**



1..10	1 TCprimebyTO	2 QHprimebyQH
Run 1	0.8	3.75
Run 2	0.8167	4.091
Run 3	0.8333	4.5
Run 4	0.85	5
Run 5	0.8667	5.625
Run 6	0.8833	6.429
Run 7	0.9	7.5
Run 8	0.9167	9
Run 9	0.9333	11.25
Run 10	0.95	15

Now, plot the results:



==

6.3 Problems solved with TEST:

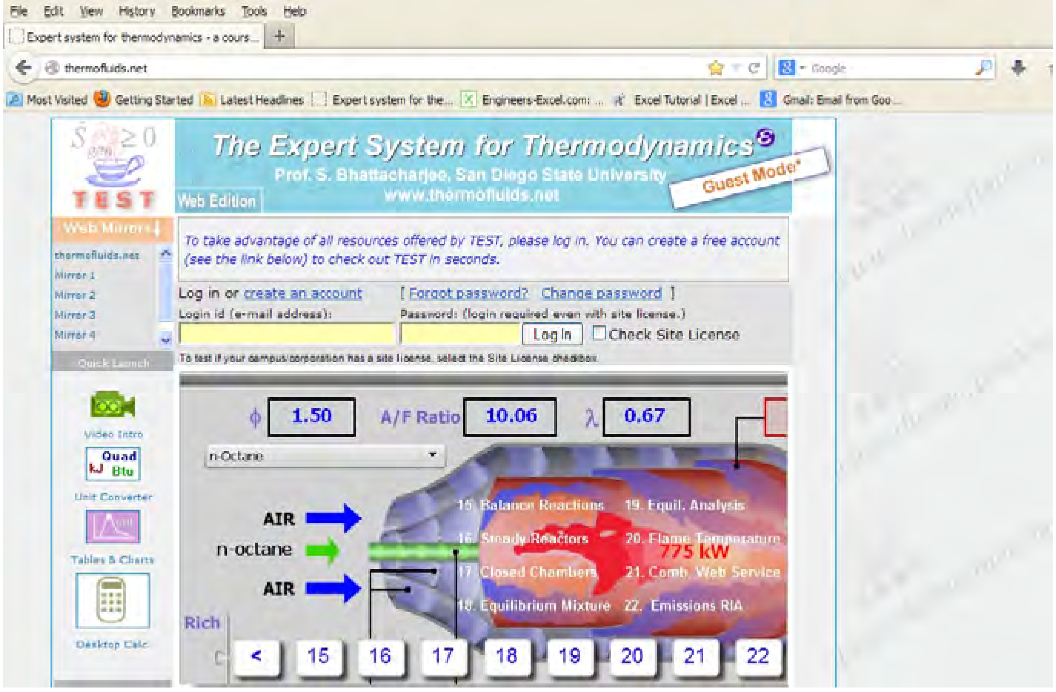
Prob.6.14. A heat pump working on a reversed Carnot cycle takes in energy from a reservoir maintained at 5 C and delivers it to another reservoir where the temp is 77 C. The heat pump derives power for its operation from a reversible heat engine operating with higher and lower temps of 1077 C and 77 C. For every 100 kW of energy supplied to reservoir at 77 C, estimate the energy taken from the reservoir at 1077 C. [VTU-BTD-June–July 2013]:

TEST Solution:

It is assumed that one has already visited www.thermofluids.net and completed the 'free registration'.

Following are the steps:

1. Go to www.thermofluids.net:



To take advantage of all resources offered by TEST, please log in. You can create a free account (see the link below) to check out TEST in seconds.

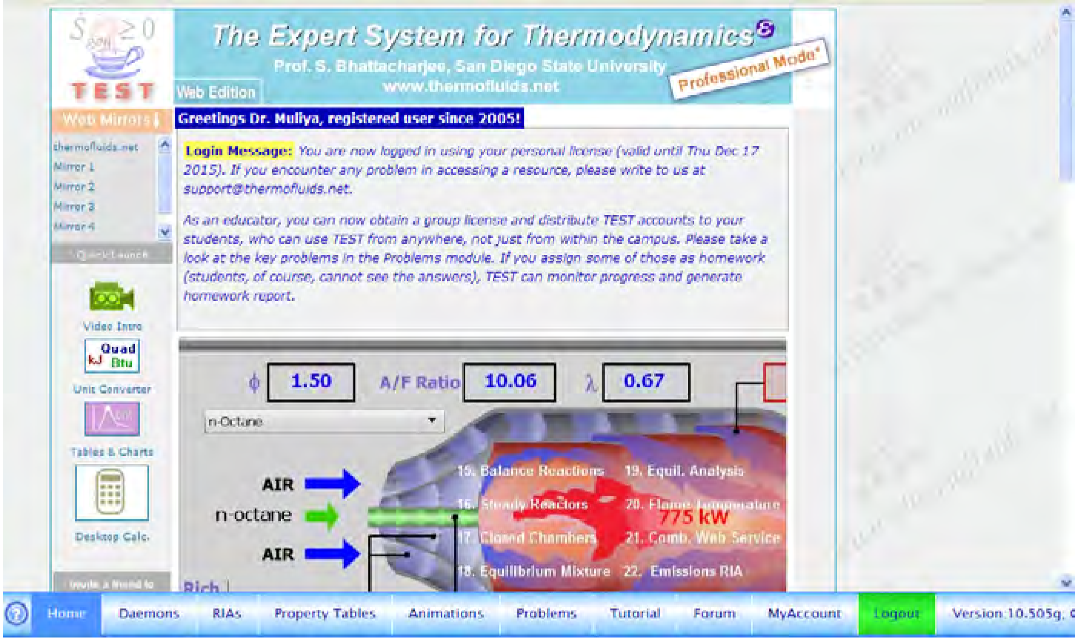
Log in or create an account [Forgot password? Change password]

Login id (e-mail address):

Password: (login required even with site license.)

To test if your campus/corporation has a site license, select the Site License checkbox.

2. Fill in the e-mail address and password; you get the personalized greeting screen:

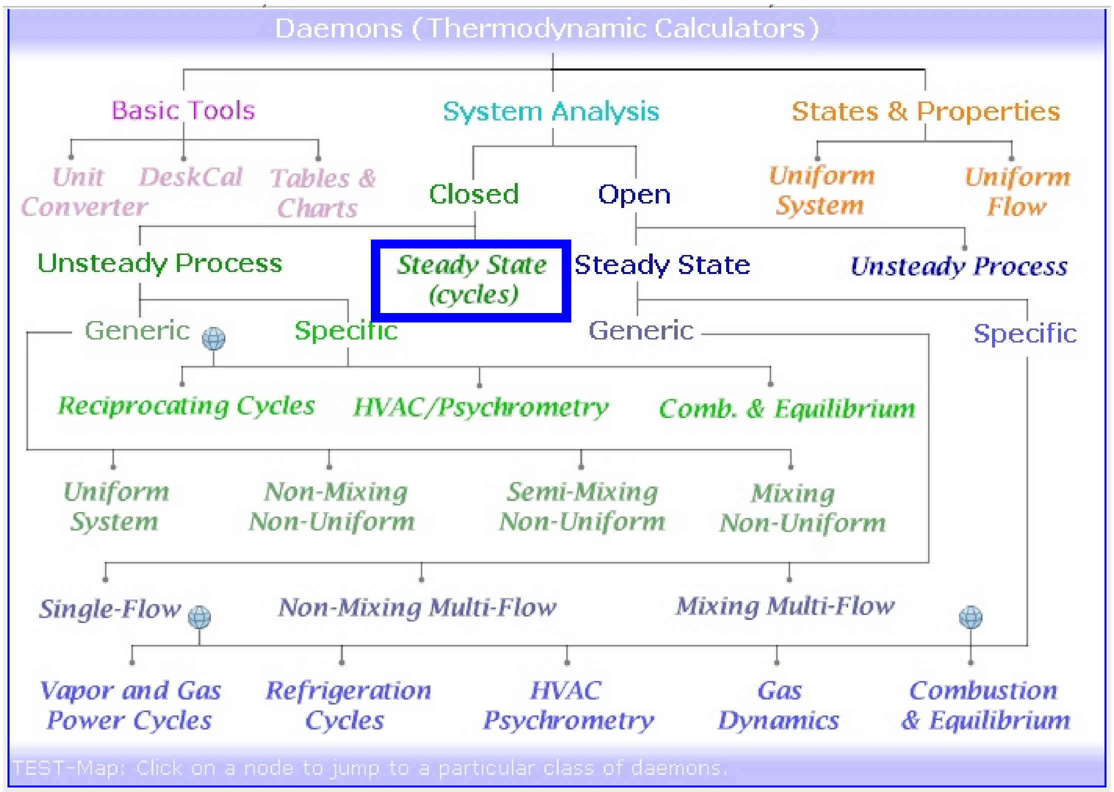


Greetings Dr. Muliya, registered user since 2005!

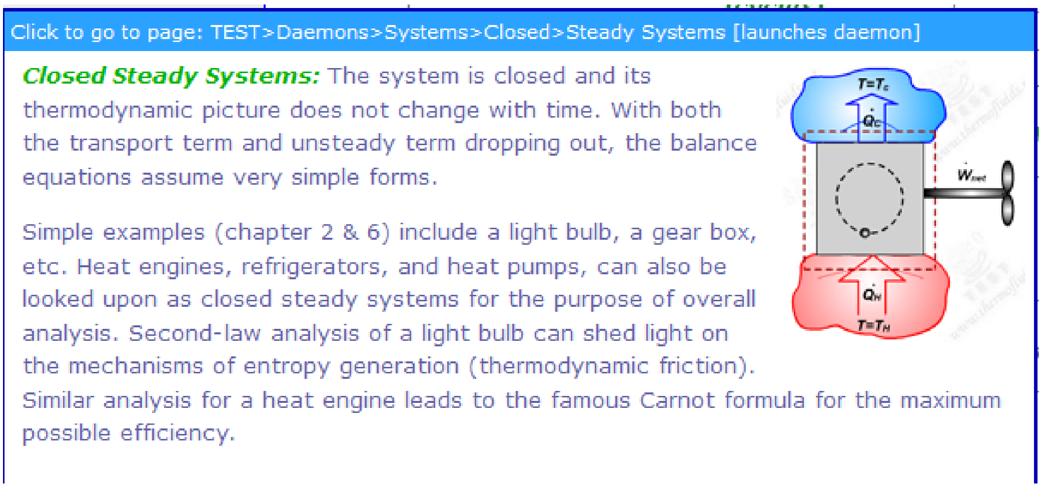
Login Message: *You are now logged in using your personal license (valid until Thu Dec 17 2015). If you encounter any problem in accessing a resource, please write to us at support@thermofluids.net.*

As an educator, you can now obtain a group license and distribute TEST accounts to your students, who can use TEST from anywhere, not just from within the campus. Please take a look at the key problems in the Problems module. If you assign some of those as homework (students, of course, cannot see the answers), TEST can monitor progress and generate homework report.

3. Click on Daemons at the bottom of screen above. We get:



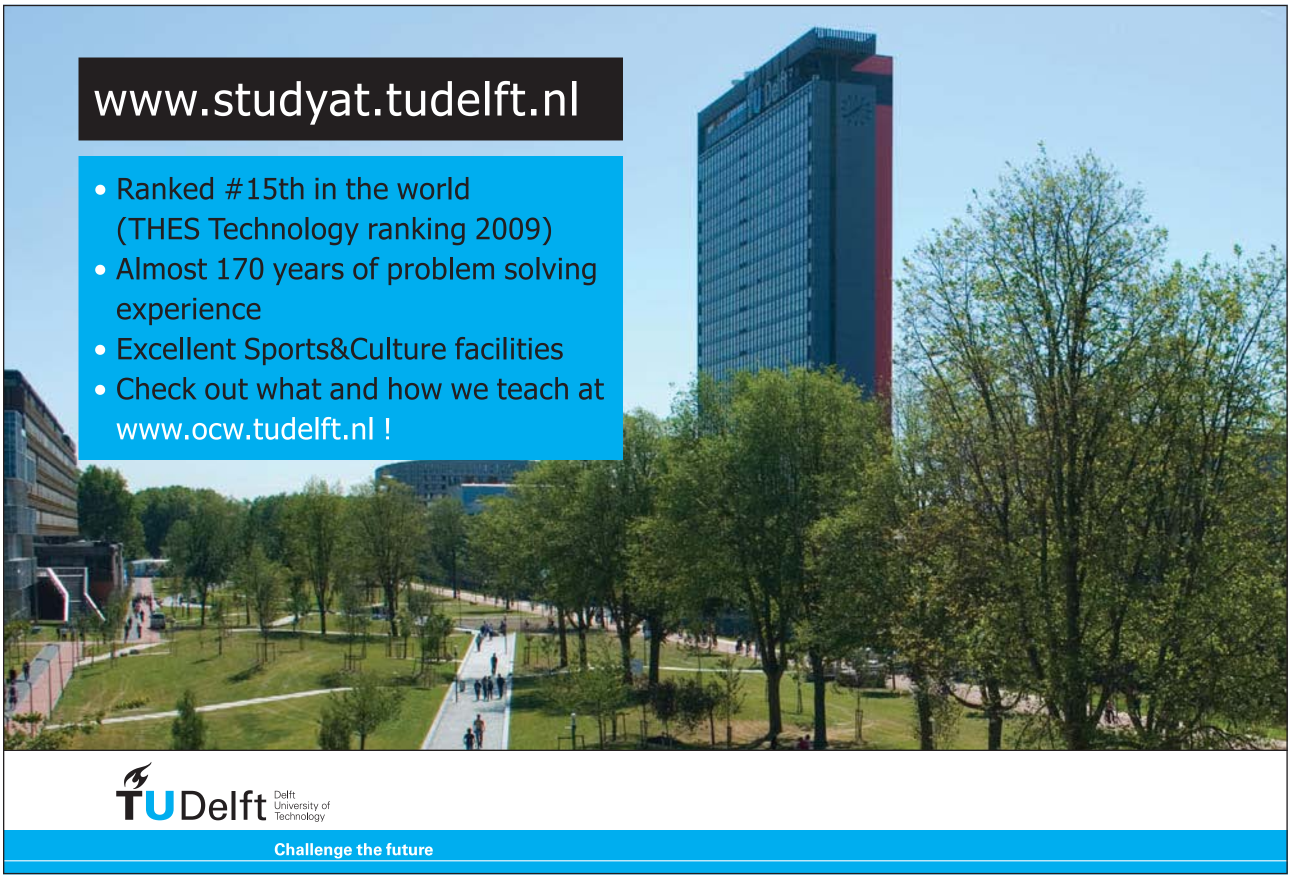
If you hover the mouse pointer over Steady State (cycles) shown above, we get:



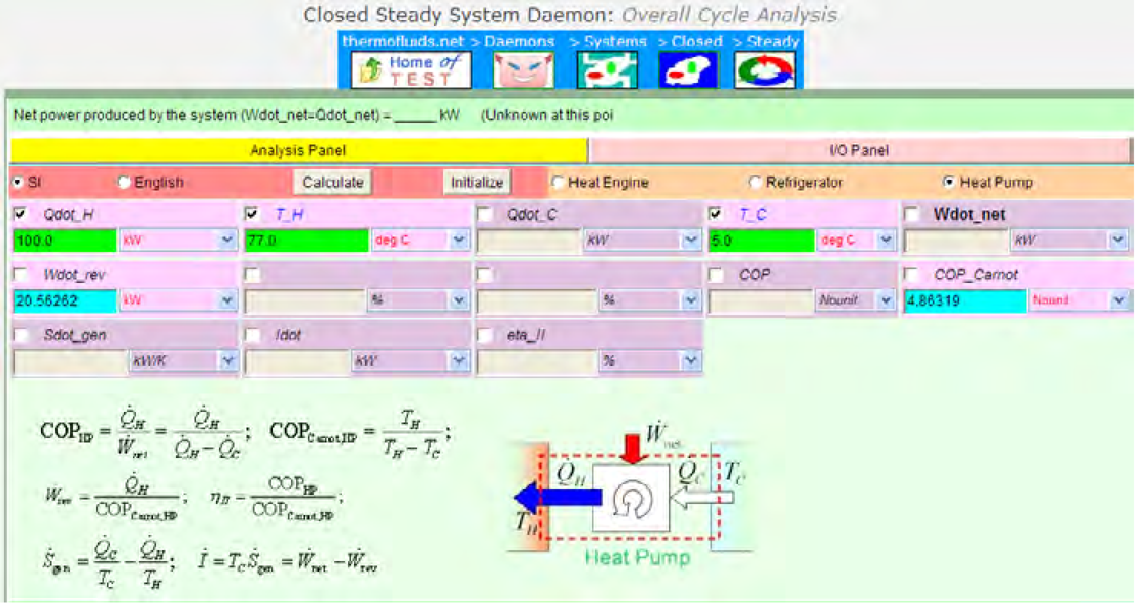
Click to go to page: TEST>Daemons>Systems>Closed>Steady Systems [launches daemon]

Closed Steady Systems: The system is closed and its thermodynamic picture does not change with time. With both the transport term and unsteady term dropping out, the balance equations assume very simple forms.

Simple examples (chapter 2 & 6) include a light bulb, a gear box, etc. Heat engines, refrigerators, and heat pumps, can also be looked upon as closed steady systems for the purpose of overall analysis. Second-law analysis of a light bulb can shed light on the mechanisms of entropy generation (thermodynamic friction). Similar analysis for a heat engine leads to the famous Carnot formula for the maximum possible efficiency.



4. Since we need to make only an **overall analysis of cycles**, we choose Steady State (cycles) in the Daemons screen. Click on 'Steady State (cycles)'. We choose the Heat Pump radio button in the screen that shows up and fill in values of T_H = 77 C, T_C = 5 C and Q_H = 100 kW. Hit Enter and we get:



Net power produced by the system (Wdot_net=Qdot_net) = ______ kW (Unknown at this poi

● SI ○ English ○ Heat Engine ○ Refrigerator ● Heat Pump

☑ Qdot_H: 100.0 kW
☑ T_H: 77.0 deg C
☐ Qdot_C: kW
☑ T_C: 5.0 deg C
☐ Wdot_net: kW
☐ Wdot_rev: 20.56262 kW
☐ %
☐ %
☐ COP: Nounit
☐ COP_Carnot: 4.86319 Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net}} = \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_C}; \quad COP_{Carnot,HP} = \frac{T_H}{T_H - T_C};$$

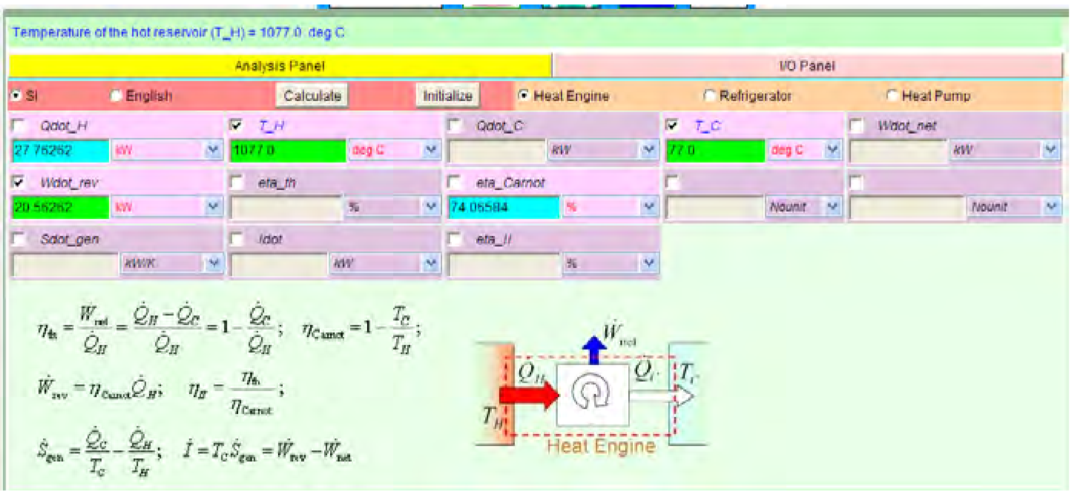
$$\dot{W}_{rev} = \frac{\dot{Q}_H}{COP_{Carnot,HP}}; \quad \eta_{II} = \frac{COP_{HP}}{COP_{Carnot,HP}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C \dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

i.e. Wdot_rev required for Heat Pump is 20.56262 kW.

5. Now, this Work is supplied by the rev. heat engine.

Now, click on Heat Engine Radio button, Fill in T_H = 1077 C, T_C = 77 C and Wdot_rev = 20.56262 kW and hit Enter. We get:



Temperature of the hot reservoir (T_H) = 1077.0 deg C

● SI ○ English ● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: 27.76262 kW
☑ T_H: 1077.0 deg C
☐ Qdot_C: kW
☑ T_C: 77.0 deg C
☐ Wdot_net: kW
☑ Wdot_rev: 20.56262 kW
☐ eta_th: %
☐ eta_Carnot: 74.05584 %
☐ Nounit
☐ Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot} \dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C \dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

Thus: we see that energy taken from reservoir at 1077 C by the rev. Heat engine for every 100 kW supplied by Heat Pump to reservoir at 77 C = Qdot_H = 27.76262 kW … Ans.

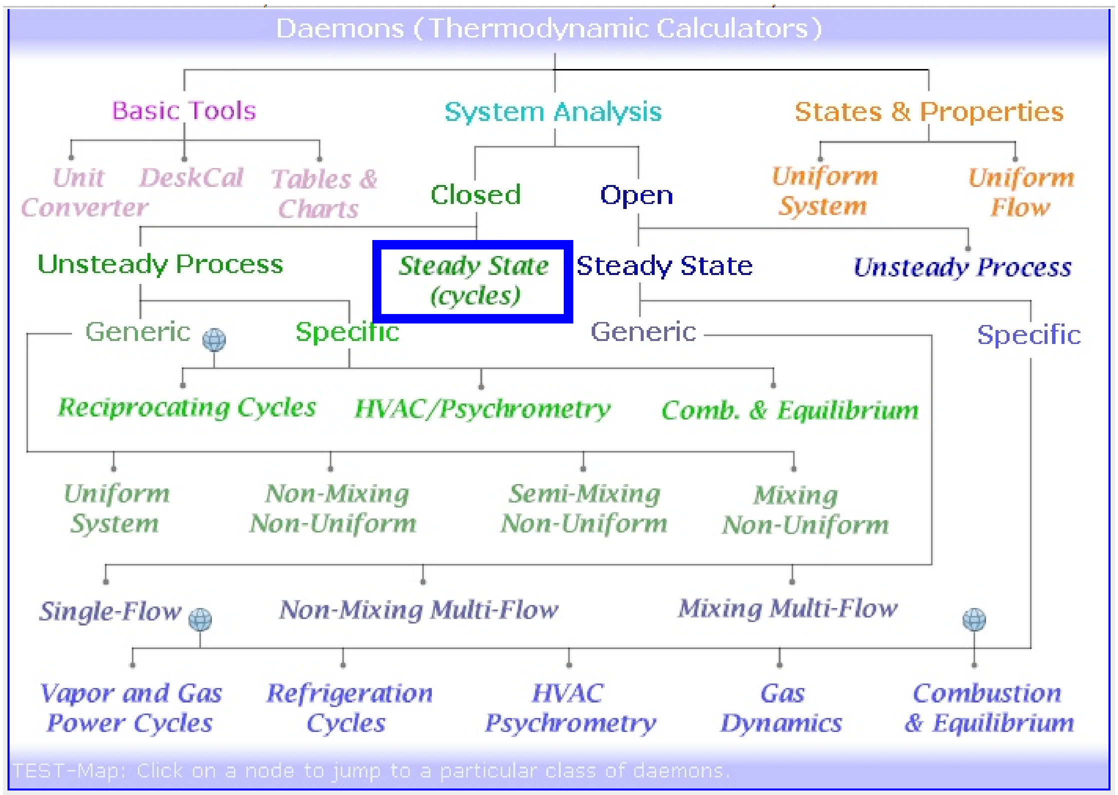
===

Prob. 6.15. The minimum power required to drive a heat pump which maintains a house at 20 C is 3 kW. If the outside temp is 3 C, estimate the amount of heat which the house loses per minute. [VTU-BTD-Dec. 06–Jan. 07:]"

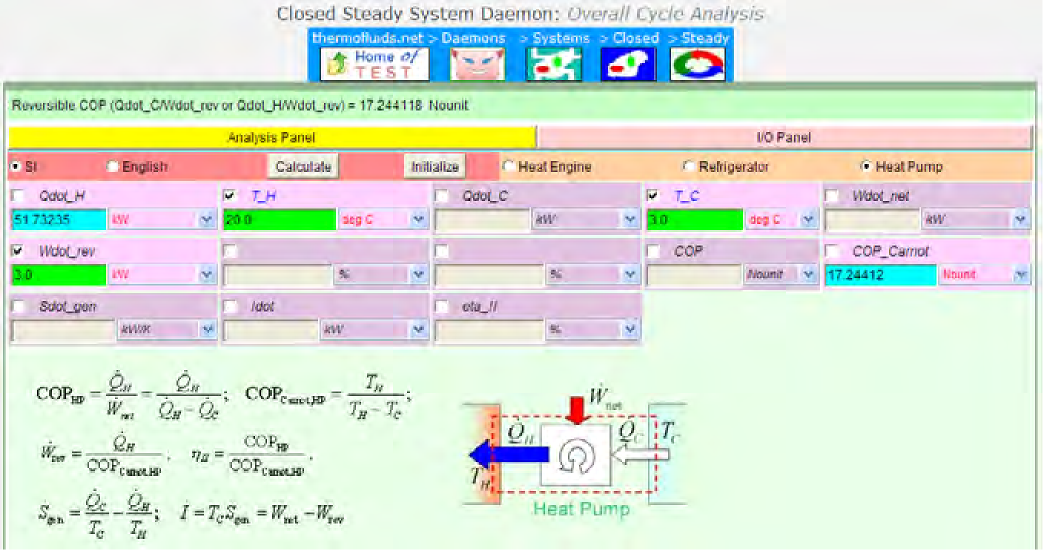
Note that this is the same as Prob.6.1, which was solved with EES:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree:



2. Click on Steady State (Cycles); following screen appears. Choose Heat Pump Radio button, fill in T_H = 20 C, T_C = 3 C, Wdot_rev = 3 kW, and hit Return. We get:



Reversible COP (Qdot_C/Wdot_rev or Qdot_H/Wdot_rev) = 17.244118 Nounit

● SI ○ English ○ Heat Engine ○ Refrigerator ● Heat Pump

☐ Qdot_H: 51.73235 kW
☑ T_H: 20.0 deg C
☐ Qdot_C: kW
☑ T_C: 3.0 deg C
☐ Wdot_net: kW
☑ Wdot_rev: 3.0 kW
☐ COP: Nounit
☐ COP_Carnot: 17.24412 Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net}} = \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_C}; \quad COP_{Carnot,HP} = \frac{T_H}{T_H - T_C};$$

$$\dot{W}_{rev} = \frac{\dot{Q}_H}{COP_{Carnot,HP}}; \quad \eta_{II} = \frac{COP_{HP}}{COP_{Carnot,HP}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C \dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

Thus: QH = 51.73 kW = 3103.941 kJ/min … Ans.

Note: Compare the value obtained for QH with EES, which was QH = 3102 kW.

Slight difference is due to the fact that with EES, to convert temperatures we used:

K = C + 273, whereas with TEST, it automatically takes K = C + 273.15

==

Prob. 6.16. It is proposed to produce 1000 kg of ice per hour from liquid water at 0 C in summer when the ambient atmospheric temp is 37 C. It is planned to use a heat engine to operate the refrigeration plant. Hot water at 70 C, produced by solar heating acts as a source to the heat engine which uses the atmosphere as the sink. Calculate: (i) the power required by the refrigeration plant (ii) the ratio of energy extracted from freezing water to that absorbed by the heat engine, and (iii) the rate of rejection of heat by both the devices. Take enthalpy of fusion of water at 0 C as 333.43 kJ/kg. [VTU-BTD-Dec. 08–Jan. 09]"

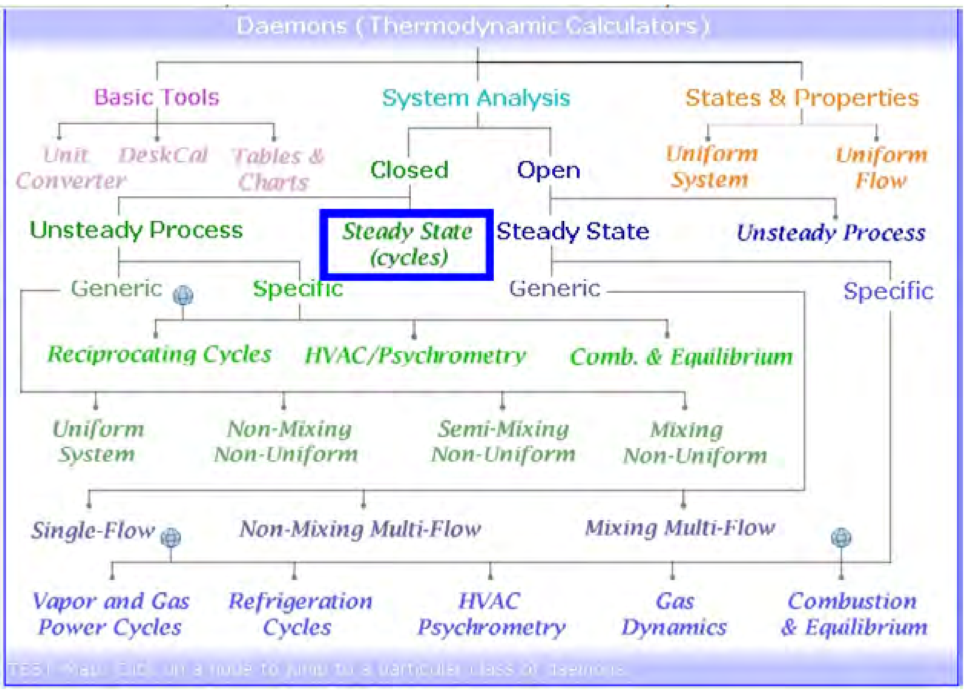
Note: This is the same as Prob.6.2, which was solved with EES.

For the refrigerator, Qdot_C = 333.43 * 1000 / 3600 kW = 92.619446 kW.

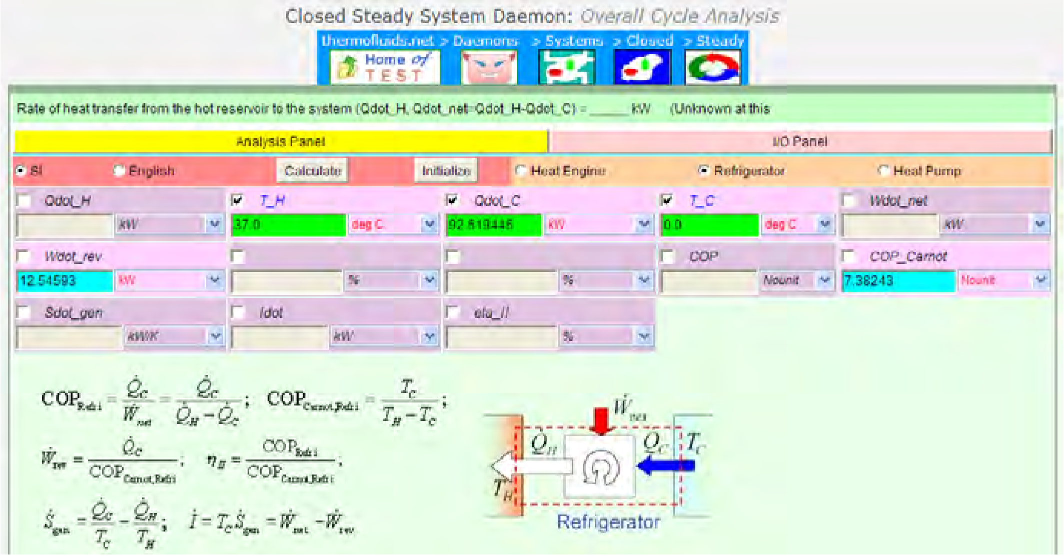
TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree:



2. Click on Steady State (Cycles); following screen appears. Choose Refrigerator Radio button, fill in T_H = 37 C, T_C = 0 C, Qdot_C = 92.619446 kW, and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Rate of heat transfer from the hot reservoir to the system (Qdot_H, Qdot_net=Qdot_H-Qdot_C) = _____ kW (Unknown at this

● SI ○ English ○ Heat Engine ● Refrigerator ○ Heat Pump

☐ Qdot_H: kW
☑ T_H: 37.0 deg C
☑ Qdot_C: 92.619446 kW
☑ T_C: 0.0 deg C
☐ Wdot_net: kW
☐ Wdot_rev: 12.54593 kW
☐ COP: Nounit
☐ COP_Carnot: 7.38243 Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\mathrm{COP}_{\mathrm{Refri}} = \frac{\dot{Q}_C}{\dot{W}_{net}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C}; \quad \mathrm{COP}_{\mathrm{Carnot,Refri}} = \frac{T_C}{T_H - T_C};$$

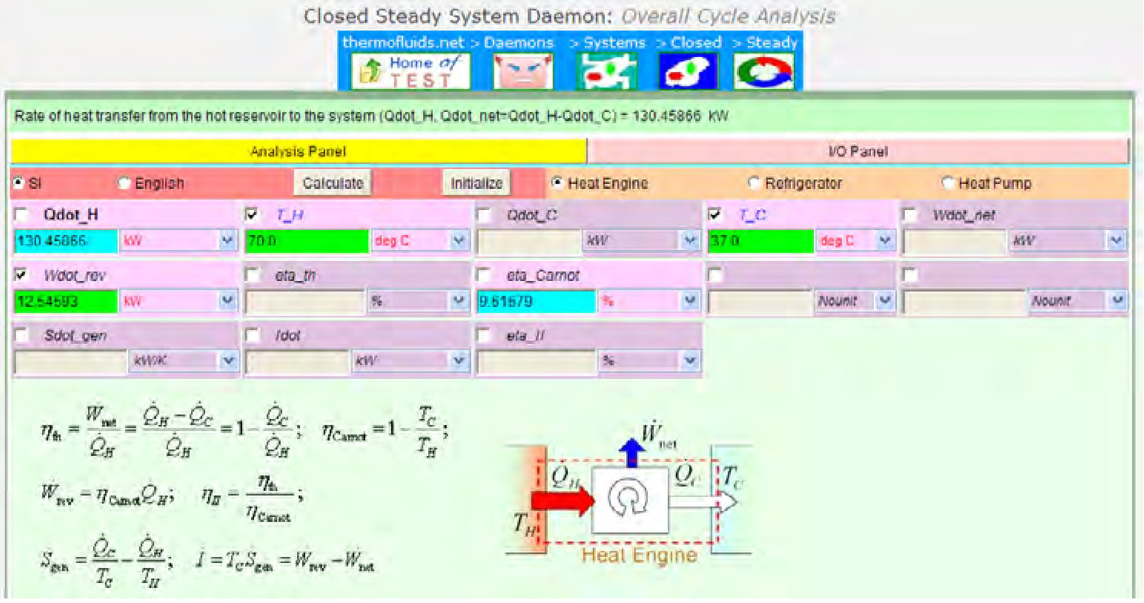
$$\dot{W}_{rev} = \frac{\dot{Q}_C}{\mathrm{COP}_{\mathrm{Carnot,Refri}}}; \quad \eta_{II} = \frac{\mathrm{COP}_{\mathrm{Refri}}}{\mathrm{COP}_{\mathrm{Carnot,Refri}}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C \dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

Note that Wdot_rev = 12.54593 kW….. Ans.

This work is produced by the rev. heat engine.

3. Click on the Heat Engine Radio button, fill in T_H = 70 C, T_C = 37 C and Wdot_rev = 12.54593 kW, and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Rate of heat transfer from the hot reservoir to the system (Qdot_H, Qdot_net=Qdot_H-Qdot_C) = 130.45866 kW

● SI ○ English ● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: 130.45866 kW
☑ T_H: 70.0 deg C
☐ Qdot_C: kW
☑ T_C: 37.0 deg C
☐ Wdot_net: kW
☑ Wdot_rev: 12.54593 kW
☐ eta_th: %
☐ eta_Carnot: 9.61679 %
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C \dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

Thus QH = 130.46 kW…Ans.

(b) Ratio of energy extracted from freezing water to that absorbed by the heat engine = 92.619 / 130.459 = 0.71 …. Ans.

(c) Rate of rejection of heat by both the devices:

For the Refrigerator:

Qdot_H = Qdot_C + Wdot_rev =

$92.619 + 12.54593 = 105.165$ kW ... Ans.

For the Heat Engine:

Qdot_C = Qdot_H – Wnet =

$130.45866 - 12.54593 = 117.913$ kW ... Ans.

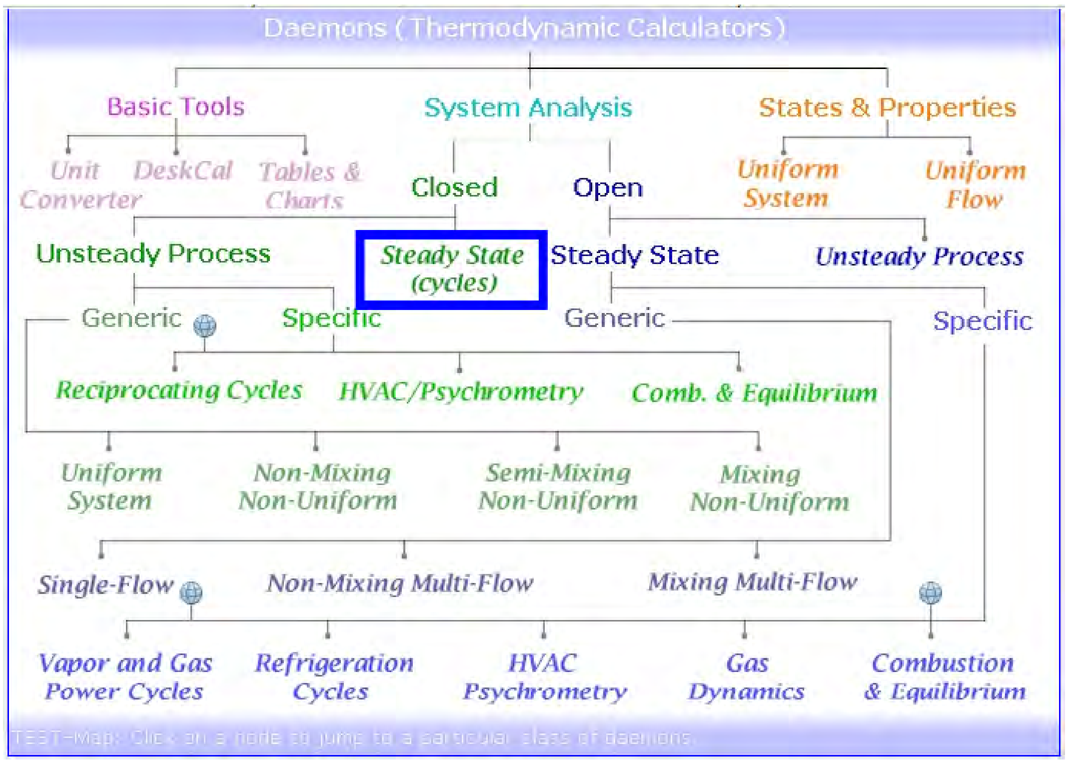
===

Prob.6.17. A Carnot engine receives heat at 750 K and rejects the waste heat to the environment at 300 K. The entire output of the heat engine is used to drive a Carnot refrigerator that removes heat from the cooled space at -15 C at a rate of 400 kJ/min and rejects to the same environment at 300 K. Determine: (i) the rate of heat supplied to the heat engine, and (ii) total rate of heat rejection to the environment. [VTU-BTD-Dec. 2012]

TEST Solution:

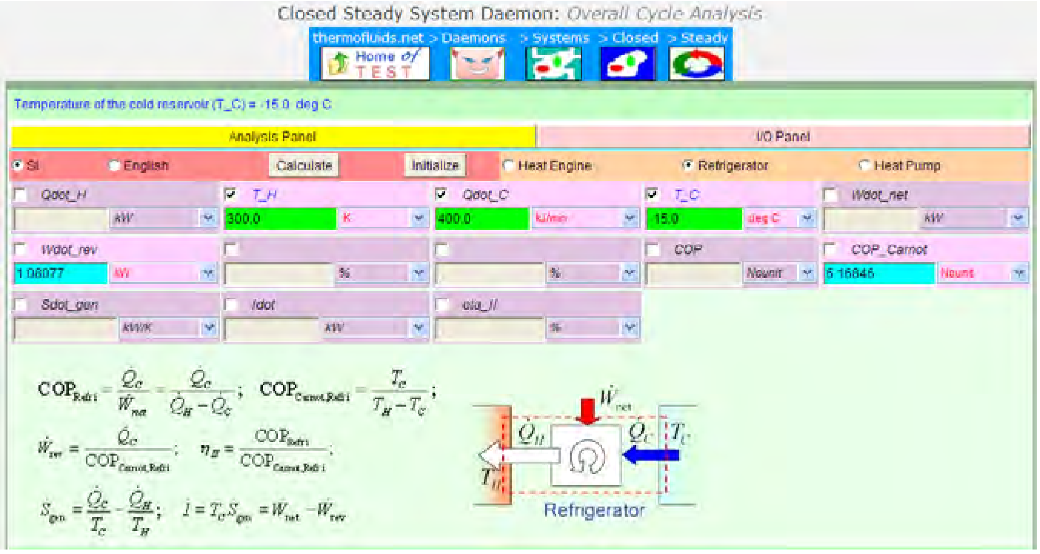
Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree:



TEST-Map: Click on a node to jump to a particular class of daemons.

2. Click on Steady State (Cycles); following screen appears. Choose Refrigerator Radio button, fill in T_H = 300K, T_C = -15 C, Qdot_C = 400 kJ/min, and hit Return. We get:



Temperature of the cold reservoir (T_C) = -15.0 deg C

● SI ○ English ○ Heat Engine ● Refrigerator ○ Heat Pump

☐ Qdot_H: kW
☑ T_H: 300.0 K
☑ Qdot_C: 400.0 kJ/min
☑ T_C: 15.0 deg C
☐ Wdot_net: kW
☐ Wdot_rev: 1.08077 kW
☐ COP: Nounit
☐ COP_Carnot: 6.16846 Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

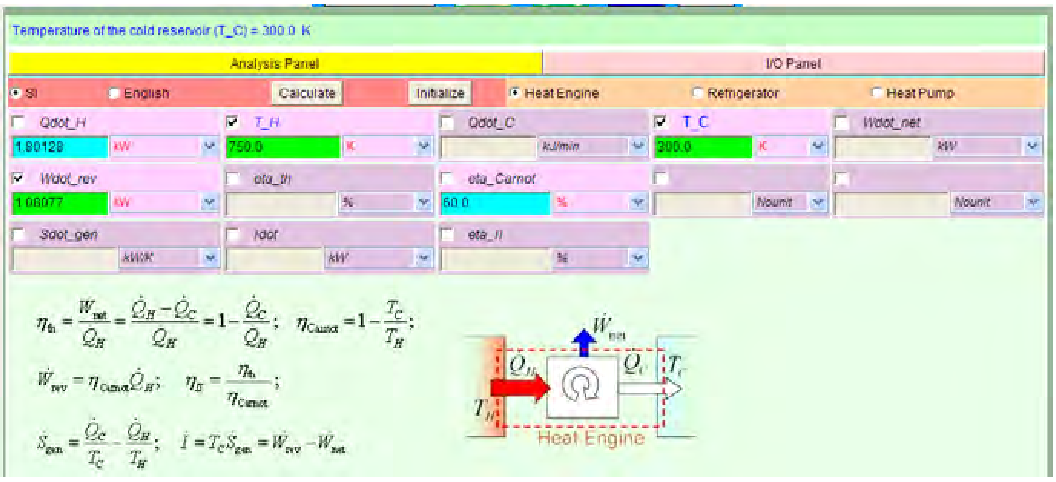
$$\mathrm{COP}_{\mathrm{Refri}} = \frac{\dot{Q}_C}{\dot{W}_{net}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C}; \quad \mathrm{COP}_{\mathrm{Carnot,Refri}} = \frac{T_C}{T_H - T_C};$$

$$\dot{W}_{rev} = \frac{\dot{Q}_C}{\mathrm{COP}_{\mathrm{Carnot,Refri}}}; \quad \eta_{II} = \frac{\mathrm{COP}_{\mathrm{Refri}}}{\mathrm{COP}_{\mathrm{Carnot,Refri}}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_0\dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

We see that Wdot_rev = 1.08077 kW. This is the work required by the Refrigerator, and it is the work output of the rev. heat engine.

3. Now, choose the Heat Engine Radio button, fill in the data, i.e. T_H = 750 K, T_C = 300 K, Wdot_rev = 1.08077 kW, and hit Return (or, click Calculate). We get:



Temperature of the cold reservoir (T_C) = 300.0 K

● SI ○ English ● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: 1.80128 kW
☑ T_H: 750.0 K
☐ Qdot_C: kJ/min
☑ T_C: 300.0 K
☐ Wdot_net: kW
☑ Wdot_rev: 1.08077 kW
☐ eta_th: %
☐ eta_Carnot: 60.0 %
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{\mathrm{Carnot}} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{\mathrm{Carnot}}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{\mathrm{Carnot}}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_0\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

Thus:

Rate of Heat supplied to the Heat Engine = Qdot_H = 1.80128 kW … Ans.

Total rate of heat rejection to environment = Heat rejected by Refrig + Heat rejected by Heat Engine= [(400/60) + 1.08077] + [1.80128 – 1.08077] = 8.468 kW … Ans.

==

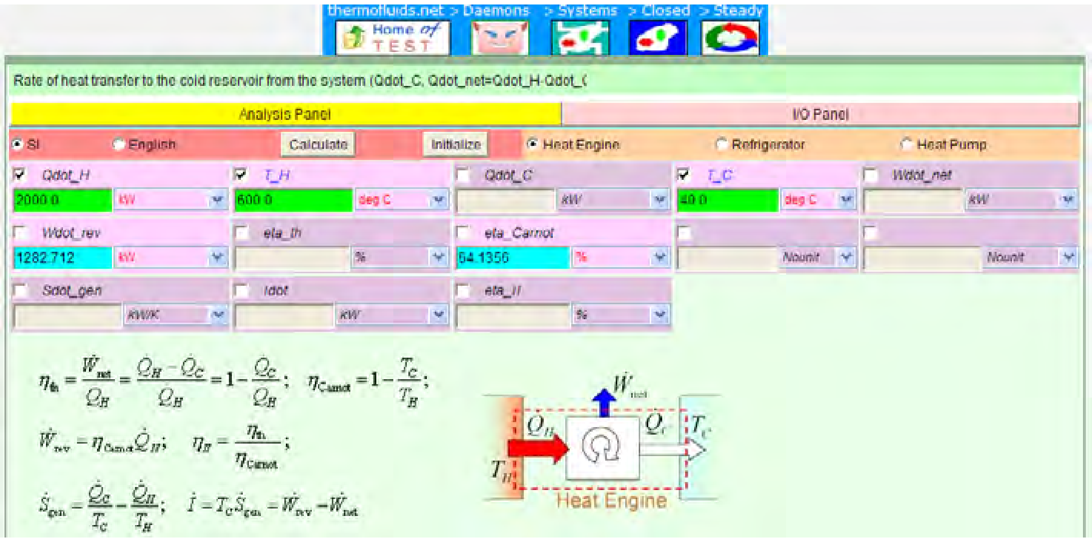
Prob.6.18 A reversible heat engine operates between two reservoirs at temperatures of 600 C and 40 C. The engine drives a reversible refrigerator, which operates between 40 C and -20 C. The heat transfer to the engine is 2000 kW and net work output from combined engine and refrigerator system is 360 kW. Calculate the heat transfer to the refrigerator and the net heat transfer to the reservoir at 40 C. [VTU-BTD-June–July, 2009 and Dec. 07–Jan. 08]

This problem is the same as Prob.6.4 which was solved with EES.

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in T_H = 600 C, T_C = 40 C, Qdot_H = 2000 kW, and hit Return. We get:



Rate of heat transfer to the cold reservoir from the system (Qdot_C, Qdot_net=Qdot_H-Qdot_(

● SI ○ English Calculate Initialize ● Heat Engine ○ Refrigerator ○ Heat Pump

☑ Qdot_H: 2000.0 kW
☑ T_H: 600.0 deg C
☐ Qdot_C: kW
☑ T_C: 40.0 deg C
☐ Wdot_net: kW
☐ Wdot_rev: 1282.712 kW
☐ eta_th: %
☐ eta_Carnot: 64.1356 %
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

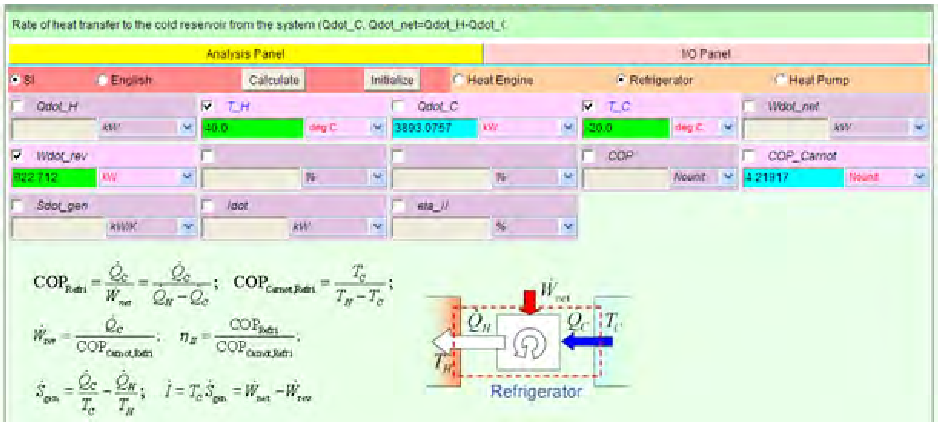
Note that Rev. work output is: 1282.712 kW.

3. Now, by data, Net work output is: 360 kW;

Therefore, **Work input to rev. refrigerator is = (1282.712 – 360) = 922.712 kW.**

Enter it for Refrigerator:

See below:



Rate of heat transfer to the cold reservoir from the system (Qdot_C, Qdot_net=Qdot_H-Qdot_(

● SI ○ English ○ Heat Engine ● Refrigerator ○ Heat Pump

☐ Qdot_H: kW
☑ T_H: 40.0 deg C
☐ Qdot_C: 3893.0757 kW
☑ T_C: -20.0 deg C
☐ Wdot_net: kW
☑ Wdot_rev: 922.712 kW
☐ COP: Nounit
☐ COP_Carnot: 4.21917 Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\mathrm{COP}_{\mathrm{Refri}}=\frac{\dot{Q}_C}{\dot{W}_{net}}=\frac{\dot{Q}_C}{\dot{Q}_H-\dot{Q}_C};\quad \mathrm{COP}_{\mathrm{Carnot,Refri}}=\frac{T_C}{T_H-T_C};$$

$$\dot{W}_{rev}=\frac{\dot{Q}_C}{\mathrm{COP}_{\mathrm{Carnot,Refri}}};\quad \eta_{II}=\frac{\mathrm{COP}_{\mathrm{Refri}}}{\mathrm{COP}_{\mathrm{Carnot,Refri}}};$$

$$\dot{S}_{gen}=\frac{\dot{Q}_C}{T_C}-\frac{\dot{Q}_H}{T_H};\quad \dot{I}=T_C\dot{S}_{gen}=\dot{W}_{net}-\dot{W}_{rev}$$

Thus: COP_Carnot = 4.2197.

And, Qdot_C = 3893.08 kW…. Heat transfer to the Refrigerator …Ans.
And Net heat transfer to reservoir at 40 C = Q_H of Refrig + Q_C of Heat Engine = (3893.08 + 922.71) + (2000 – 1282.71) = 5538.08 kW … Ans.
(Note: Compare the results obtained with EES. They match very well.)

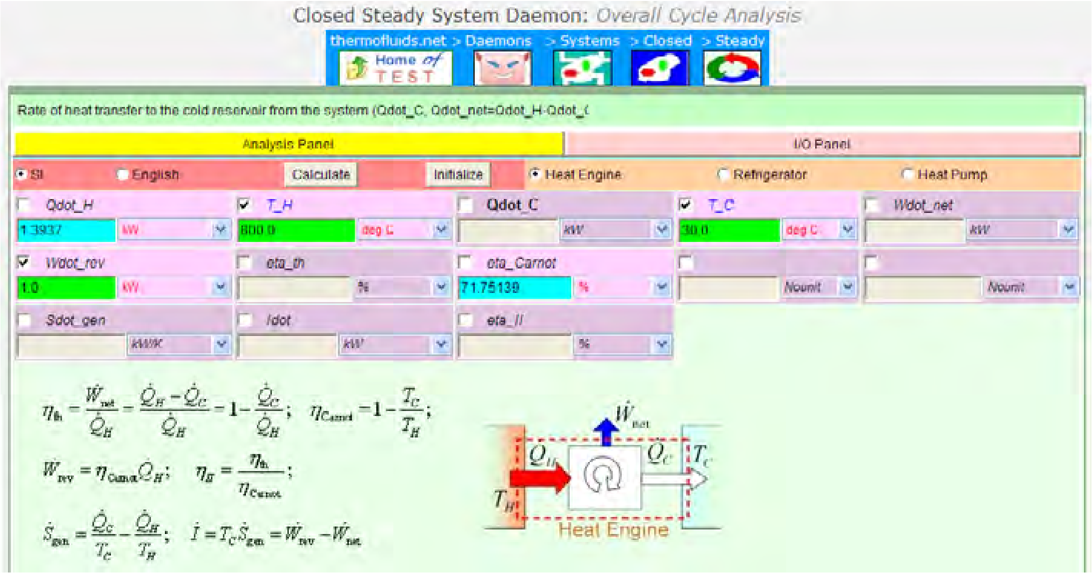
===

Prob. 6.19. A reversible heat engine operates between a source temp of 800 C and a sink temp of 30 C. What is the least rate of heat rejection per kW net output of the engine? [VTU-BTD-Dec. 2011]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in T_H = 800 C, T_C = 30 C, Wdot_rev = 1 kW, and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Rate of heat transfer to the cold reservoir from the system (Qdot_C, Qdot_net=Qdot_H-Qdot_(

● SI ○ English

● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: 1.3937 kW

☑ T_H: 800.0 deg C

☐ Qdot_C: kW

☑ T_C: 30.0 deg C

☐ Wdot_net: kW

☑ Wdot_rev: 1.0 kW

☐ eta_th: %

☐ eta_Carnot: 71.75139 %

☐ Sdot_gen: kW/K

☐ Idot: kW

☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

Thus, we see that Qdot_H, i.e. heat supplied to HE is 1.3937 kW.

Then, Qdot_C = (Qdot_H – Wnet_rev) = least rate of heat rejection per kW of net work out-put.

i.e. Qdot_C = (Qdot_H – Wdot_rev) = 0.3937 kW …. Ans.

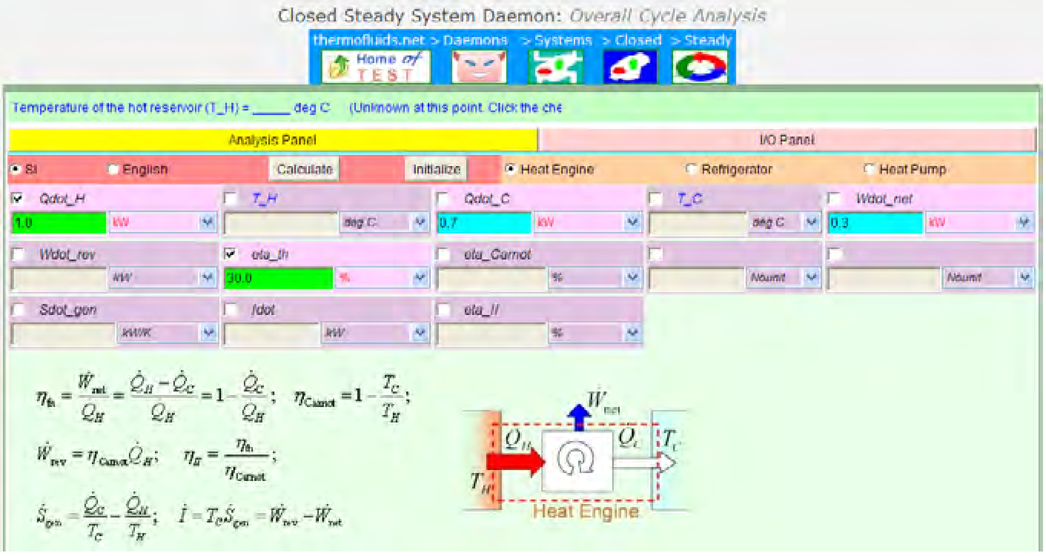
==

Prob.6.20. A heat engine is used to drive a heat pump. The heat transfers from the heat engine and the heat pump are used to heat the water circulating through a radiator of a building. If the COP of the heat pump is 4 and the efficiency of the heat engine is 0.3, how much heat is transferred to the radiator water for every kJ heat transferred to the heat engine? [VTU-BTD-Dec. 09–Jan. 10]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in Qdot_H = 1 kW, eta_th = 30%, and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

thermofluids.net > Daemons > Systems > Closed > Steady

Temperature of the hot reservoir (T_H) = _____ deg C (Unknown at this point. Click the che

● SI ○ English | Heat Engine ● | ○ Refrigerator | ○ Heat Pump

☑ Qdot_H: 1.0 kW

☐ T_H: deg C

☐ Qdot_C: 0.7 kW

☐ T_C: deg C

☐ Wdot_net: 0.3 kW

☐ Wdot_rev: kW

☑ eta_th: 30.0 %

☐ eta_Carnot: %

☐ Sdot_gen: kW/K

☐ Idot: kW

☐ eta_II: %

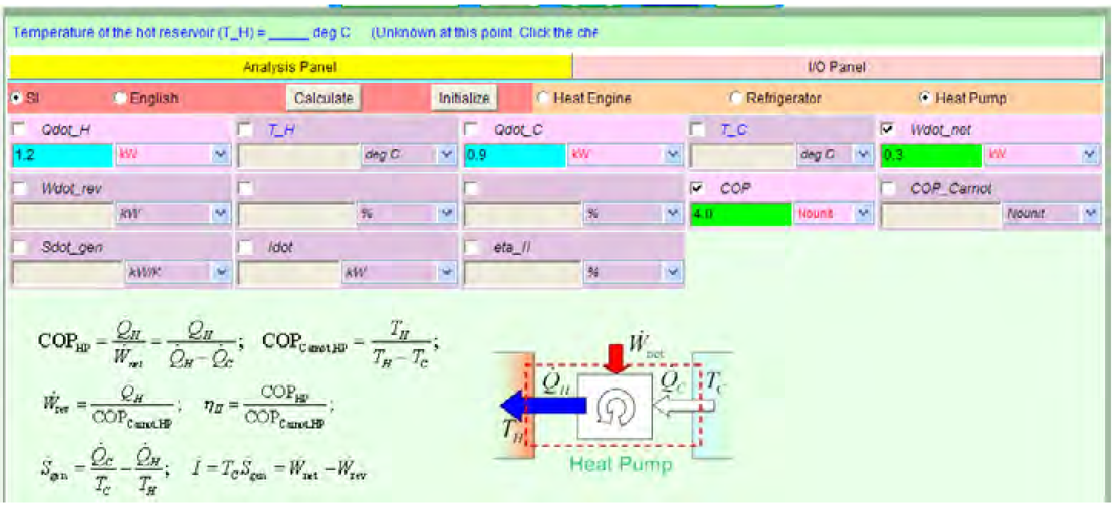
$$\eta_{th} = \frac{\dot W_{net}}{\dot Q_H} = \frac{\dot Q_H - \dot Q_C}{\dot Q_H} = 1 - \frac{\dot Q_C}{\dot Q_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot W_{rev} = \eta_{Carnot}\dot Q_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot S_{gen} = \frac{\dot Q_C}{T_C} - \frac{\dot Q_H}{T_H}; \quad \dot I = T_0\dot S_{gen} = \dot W_{rev} - \dot W_{net}$$

i.e. we get: Wdot_net = 0.3 kW, Qdot_C = 0.7 kW.

3. Now, select the Heat Pump Radio button. Enter Wdot_net = 0.3 kW, COP = 4. Click on Calculate (or, hit Enter). We get:



Temperature of the hot reservoir (T_H) = _____ deg C (Unknown at this point. Click the che

● SI ○ English ○ Heat Engine ○ Refrigerator ● Heat Pump

☐ Qdot_H: 1.2 kW
☐ T_H: deg C
☐ Qdot_C: 0.9 kW
☐ T_C: deg C
☑ Wdot_net: 0.3 kW
☐ Wdot_rev: kW
☐ %
☐ %
☑ COP: 4.0 Nounit
☐ COP_Carnot: Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\mathrm{COP}_{HP}=\frac{\dot{Q}_H}{\dot{W}_{net}}=\frac{\dot{Q}_H}{\dot{Q}_H-\dot{Q}_C};\quad \mathrm{COP}_{Carnot,HP}=\frac{T_H}{T_H-T_C};$$

$$\dot{W}_{rev}=\frac{\dot{Q}_H}{\mathrm{COP}_{Carnot,HP}};\quad \eta_{II}=\frac{\mathrm{COP}_{HP}}{\mathrm{COP}_{Carnot,HP}};$$

$$\dot{S}_{gen}=\frac{\dot{Q}_C}{T_C}-\frac{\dot{Q}_H}{T_H};\quad \dot{I}=T_C\dot{S}_{gen}=\dot{W}_{net}-\dot{W}_{rev}$$

Thus: Qdot_H = 1.2 kW.

Total heat to Radiator of building per kW of heat supplied to heat engine = Qdot_C of engine + Qdot_H of Heat Pump = 1.9 kW … Ans.

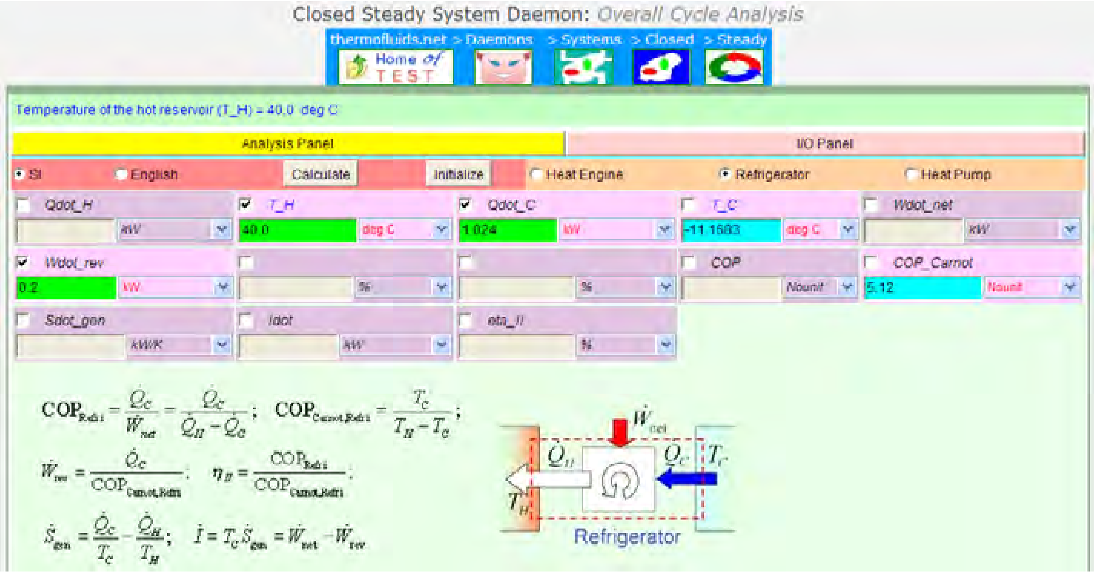
==

Prob.6.21. A Carnot refrigerator consume s 200 W of power when the ambient atmosphere is 40 C. The rate of energy leak in to the refrigerator is estimated at 20 W per degree Celsius temp difference between the ambient atmosphere and the cold space of the refrigerator. If the refrigerator is continuously operated, determine the temp at which the cold space is maintained.[VTU-BTD-Jan./Feb. 2005 – New Scheme]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Refrigerator Radio button, fill in T_H = 40 C, Wdot_rev = 0.2 kW, and for Qdot_C, assume a trial value and hit Return. Observe the value of T_C obtained. Now, vary the value of Qdot_C ***by trial and error*** such that the equation Qdot_C = 20 * (T_H – T_C) is satisfied.
3. Finally, we get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Temperature of the hot reservoir (T_H) = 40.0 deg C

● SI ○ English ○ Heat Engine ● Refrigerator ○ Heat Pump

☐ Qdot_H: kW
☑ T_H: 40.0 deg C
☑ Qdot_C: 1.024 kW
☐ T_C: -11.1683 deg C
☐ Wdot_net: kW
☑ Wdot_rev: 0.2 kW
☐ COP: Nounit
☐ COP_Carnot: 5.12 Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$COP_{Refri}=\frac{\dot{Q}_C}{\dot{W}_{net}}=\frac{\dot{Q}_C}{\dot{Q}_H-\dot{Q}_C};\quad COP_{Carnot,Refri}=\frac{T_C}{T_H-T_C};$$

$$\dot{W}_{rev}=\frac{\dot{Q}_C}{COP_{Carnot,Refri}};\quad \eta_{II}=\frac{COP_{Refri}}{COP_{Carnot,Refri}};$$

$$\dot{S}_{gen}=\frac{\dot{Q}_C}{T_C}-\frac{\dot{Q}_H}{T_H};\quad \dot{I}=T_0\dot{S}_{gen}=\dot{W}_{net}-\dot{W}_{rev}$$

Thus:

Temp of refrigerated space = T_C = -11.1683 C … Ans.
And, Qdot_C = 1.024 kW …. Ans.

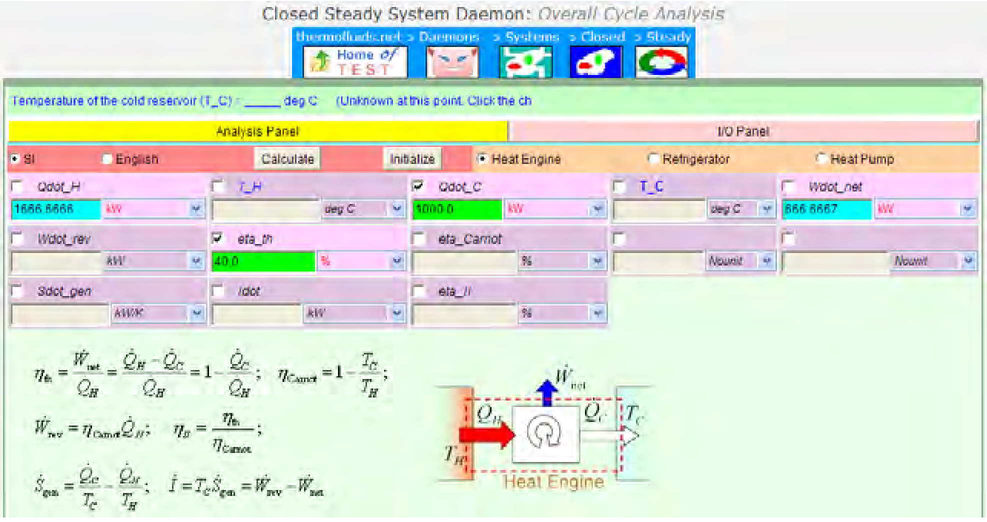
===

Prob.6.22. A heat engine with a thermal efficiency of 40% rejects 1000 kW of heat. How much heat does it receive? [Ref. 1]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in Qdot_C = 1000 kW, eta_th = 40%, and hit Return. We get:



Temperature of the cold reservoir (T_C) = ______ deg C (Unknown at this point. Click the ch

● SI ○ English ● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: 1666.6666 kW

☐ T_H: deg C

☑ Qdot_C: 1000.0 kW

☐ T_C: deg C

☐ Wdot_net: 666.6667 kW

☐ Wdot_rev: kW

☑ eta_th: 40.0 %

☐ eta_Carnot: %

☐ Sdot_gen: kW/K

☐ Idot: kW

☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

Thus: Heat received by the heat engine, Qdot_H = 1666.67 kW…. Ans.

===

Prob. 6.23. An automobile engine consumes fuel at a rate of 22 L/h and delivers 55 kW of power to the wheels. If the fuel has a heating value of 44000 kJ/kg and a density of 0.8 g/cm^3, determine the efficiency of the engine.[Ref: 1]

TEST Solution:

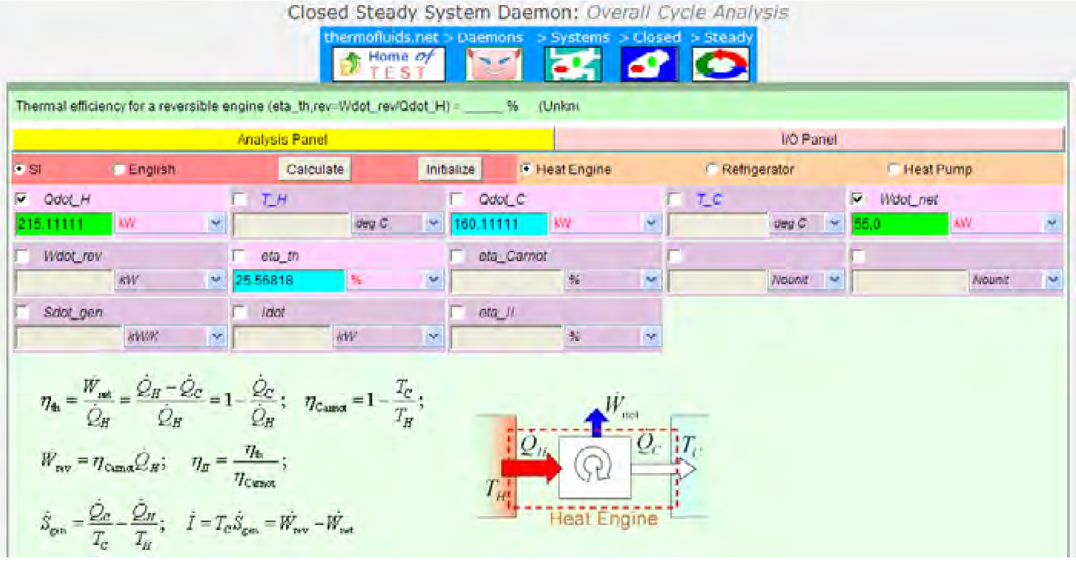
Note that 22 L/h is equivalent to:

Qdot_H =

$$\frac{22 \cdot 0.8 \cdot 44000}{3600} = 215.111 \qquad \text{kW}$$

Then following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in Qdot_H = 215.111 kW, Wdot_net = 55 kW, and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Thermal efficiency for a reversible engine (eta_th,rev=Wdot_rev/Qdot_H) = ______ % (Unkn

● SI ○ English

● Heat Engine ○ Refrigerator ○ Heat Pump

☑ Qdot_H 215.11111 kW

☐ T_H deg C

☐ Qdot_C 160.11111 kW

☐ T_C deg C

☑ Wdot_net 55.0 kW

☐ Wdot_rev kW

☐ eta_th 25.56818 %

☐ eta_Carnot %

☐ Sdot_gen kW/K

☐ Idot kW

☐ eta_II %

$$\eta_{th} = \frac{\dot W_{net}}{\dot Q_H} = \frac{\dot Q_H - \dot Q_C}{\dot Q_H} = 1 - \frac{\dot Q_C}{\dot Q_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot W_{rev} = \eta_{Carnot}\dot Q_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot S_{gen} = \frac{\dot Q_C}{T_C} - \frac{\dot Q_H}{T_H}; \quad \dot I = T_C \dot S_{gen} = \dot W_{rev} - \dot W_{net}$$

Thus: eta_th = 25.568% …. Ans.

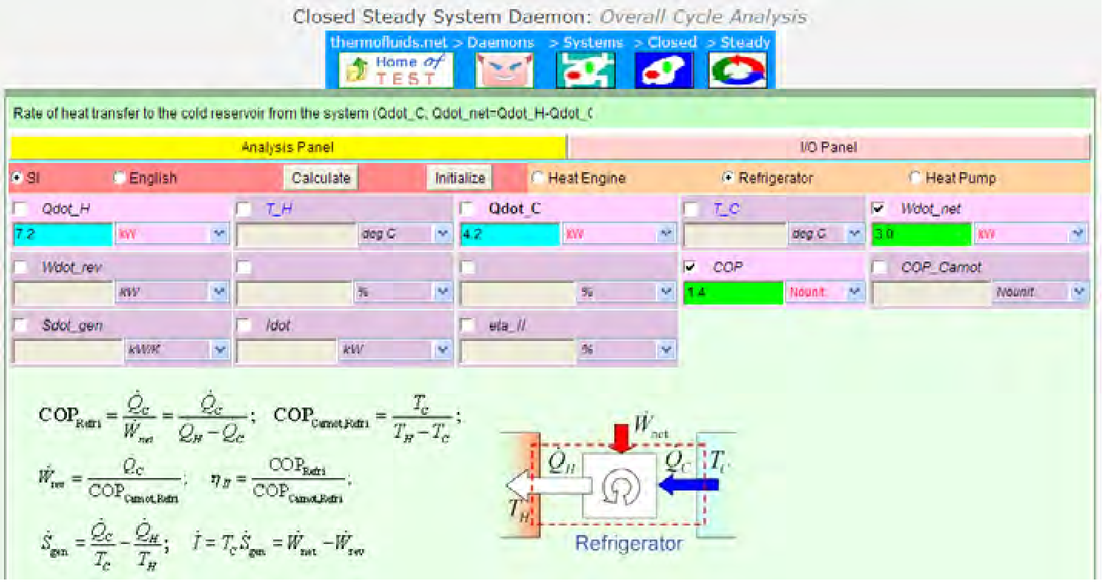
==

Prob. 6.24. A refrigerator used to cool a computer requires 3 kW of electrical power and has a COP of 1.4. Calculate the cooling effect of this refrigerator, in kW. [Ref: 1]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Refrigerator Radio button, fill in Wdot_net = 3 kW, COP = 1.4, and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Rate of heat transfer to the cold reservoir from the system (Qdot_C, Qdot_net=Qdot_H-Qdot_(

● SI ○ English ○ Heat Engine ● Refrigerator ○ Heat Pump

☐ Qdot_H: 7.2 kW
☐ T_H: deg C
☐ Qdot_C: 4.2 kW
☐ T_C: deg C
☑ Wdot_net: 3.0 kW
☐ Wdot_rev: kW
☑ COP: 1.4 NoUnit
☐ COP_Carnot: NoUnit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

Thus, cooling effect = Qdot_C = 4.2 kW … Ans.

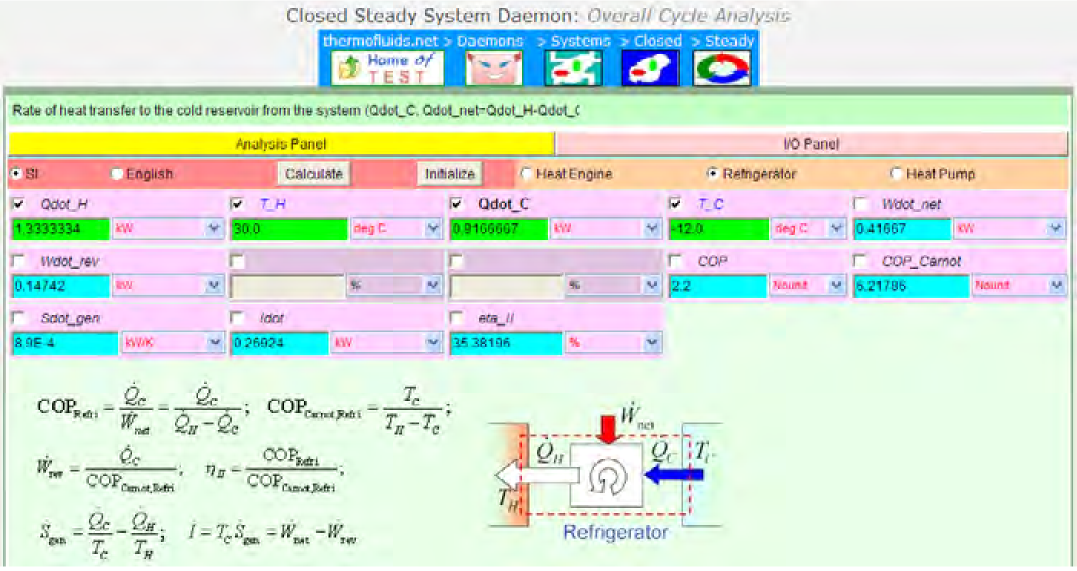
==

Prob.6.25. A food dept. is kept at -12 C by a refrigerator in an environment at 30 C. The total heat gain to the food dept. is estimated to be 3300 kJ/h and the heat rejection to the condenser is 4800 kJ/h. Determine the power input to the compressor in kW and the COP of the refrigerator. [Ref:1]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Refrigerator Radio button, fill in T_H = 30 C, T_C = -12 C, Qdot_H = 4800/3600 = 1.3333 kW, Qdot_C = 3300/3600 = 0.91667 kW, and hit Return. We get:



Rate of heat transfer to the cold reservoir from the system (Qdot_C. Qdot_net=Qdot_H-Qdot_(

● SI ○ English ○ Heat Engine ● Refrigerator ○ Heat Pump

☑ Qdot_H: 1.3333334 kW
☑ T_H: 30.0 deg C
☑ Qdot_C: 0.9166667 kW
☑ T_C: -12.0 deg C
☐ Wdot_net: 0.41667 kW
☐ Wdot_rev: 0.14742 kW
☐ COP: 2.2 %unit
☐ COP_Carnot: 6.21786 %unit
☐ Sdot_gen: 8.9E-4 kW/K
☐ Idot: 0.26924 kW
☐ eta_II: 35.38196 %

$$\mathrm{COP}_{\mathrm{Refri}} = \frac{\dot{Q}_C}{\dot{W}_{\mathrm{net}}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C}; \quad \mathrm{COP}_{\mathrm{Carnot,Refri}} = \frac{T_C}{T_H - T_C};$$

$$\dot{W}_{\mathrm{rev}} = \frac{\dot{Q}_C}{\mathrm{COP}_{\mathrm{Carnot,Refri}}}; \quad \eta_{II} = \frac{\mathrm{COP}_{\mathrm{Refri}}}{\mathrm{COP}_{\mathrm{Carnot,Refri}}};$$

$$\dot{S}_{\mathrm{gen}} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C \dot{S}_{\mathrm{gen}} = \dot{W}_{\mathrm{net}} - \dot{W}_{\mathrm{rev}}$$

Thus:

Wdot_net = 0.41667 kW, COP = 2.2 …. Ans.

===

Prob. 6.26. Bananas are to be cooled from 24 to 13 C at a rate of 215 kg/h by a refrigeration system. The power input to the refrigerator is 1.4 kW. Determine the rate of cooling, in kJ/min and the COP of the refrigerator. Sp. heat of banana above freezing is 3.35 kJ/kg.C. [Ref:1]

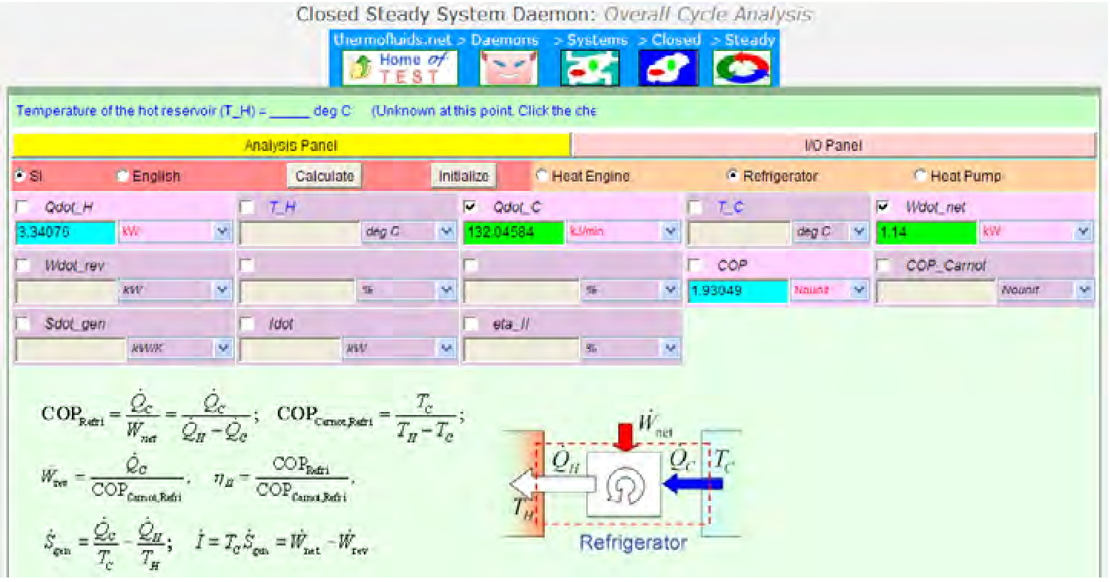
TEST Solution:

Heat to be removed = Qdot_C =

$$\frac{215\cdot 3.35\cdot(24-13)}{60} = 132.046 \quad \text{kJ/min}$$

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Refrigerator Radio button, fill in Wdot_net = 1.4 kW, Qdot_C = 132.04584 kJ/min, and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Temperature of the hot reservoir (T_H) = _____ deg C (Unknown at this point. Click the che

● SI ○ English ○ Heat Engine ● Refrigerator ○ Heat Pump

☐ Qdot_H: 3.34076 kW
☐ T_H: deg C
☑ Qdot_C: 132.04584 kJ/min
☐ T_C: deg C
☑ Wdot_net: 1.14 kW
☐ Wdot_rev: kW
☐ COP: 1.93049 Nounit
☐ COP_Carnot: Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\mathrm{COP}_{\mathrm{Refri}} = \frac{\dot{Q}_C}{\dot{W}_{net}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C}; \quad \mathrm{COP}_{\mathrm{Carnot,Refri}} = \frac{T_C}{T_H - T_C};$$

$$\dot{W}_{rev} = \frac{\dot{Q}_C}{\mathrm{COP}_{\mathrm{Carnot,Refri}}}; \quad \eta_{II} = \frac{\mathrm{COP}_{\mathrm{Refri}}}{\mathrm{COP}_{\mathrm{Carnot,Refri}}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

Thus:

COP = 1.93 … Ans.

Rate of cooling = Qdot_C = 132.05 kJ/min … Ans.

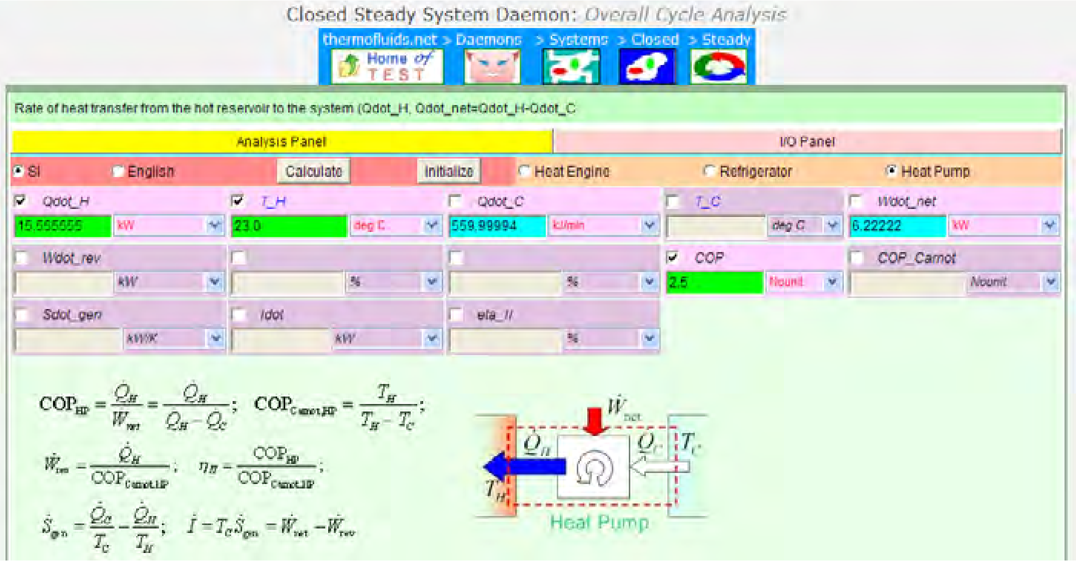
==

Prob.6.27. A heat pump is used to maintain a house at a constant temp of 23 C. The house is losing heat to the outside air through the walls and the windows at a rate of 60000 kJ/h while the energy generated within the house from people, lights and appliances amounts to 4000 kJ/h. For a COP of 2.5, determine the required power input to the heat pump. [Ref:1]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Pump Radio button, fill in Qdot_net = ([60000 – 4000] / 3600) =15.5556 kW, T_H = 23 C, COP = 2.5 and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Rate of heat transfer from the hot reservoir to the system (Qdot_H, Qdot_net=Qdot_H-Qdot_C

● SI ○ English | Calculate | Initialize | ○ Heat Engine ○ Refrigerator ● Heat Pump

☑ Qdot_H: 15.555555 kW
☑ T_H: 23.0 deg C
☐ Qdot_C: 559.99994 kJ/min
☐ T_C: deg C
☐ Wdot_net: 6.22222 kW
☐ Wdot_rev: kW
☑ COP: 2.5 Nounit
☐ COP_Carnot: Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\mathrm{COP}_{HP}=\frac{\dot{Q}_H}{\dot{W}_{net}}=\frac{\dot{Q}_H}{\dot{Q}_H-\dot{Q}_C};\quad \mathrm{COP}_{Carnot,HP}=\frac{T_H}{T_H-T_C};$$

$$\dot{W}_{rev}=\frac{\dot{Q}_H}{\mathrm{COP}_{Carnot,HP}};\quad \eta_{II}=\frac{\mathrm{COP}_{HP}}{\mathrm{COP}_{Carnot,HP}};$$

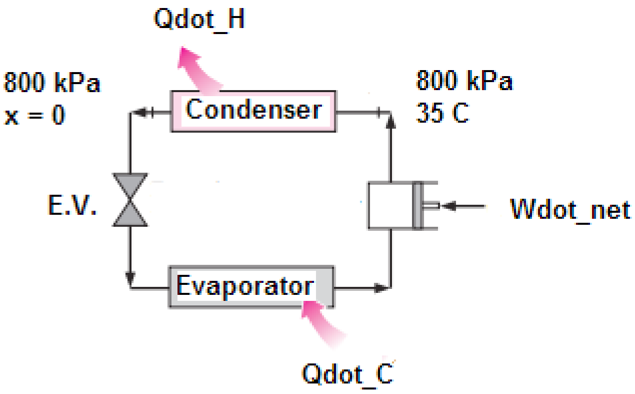
$$\dot{S}_{gen}=\frac{\dot{Q}_C}{T_C}-\frac{\dot{Q}_H}{T_H};\quad \dot{I}=T_C\dot{S}_{gen}=\dot{W}_{net}-\dot{W}_{rev}$$

Thus: Required power input = Wdot_net = 6.22 kW … Ans.

==

Prob.6.28. Refrigerant R-134a enters the condenser of a residential heat pump at 800 kPa and 35 C at a rate of 0.018 kg/s and leaves at 800 kPa as a saturated liquid. If the compressor consumes 1.2 kW of power, determine: (a) the COP of the heat pump, and (b) rate of heat absorption from the outside air.

[Ref: 1]

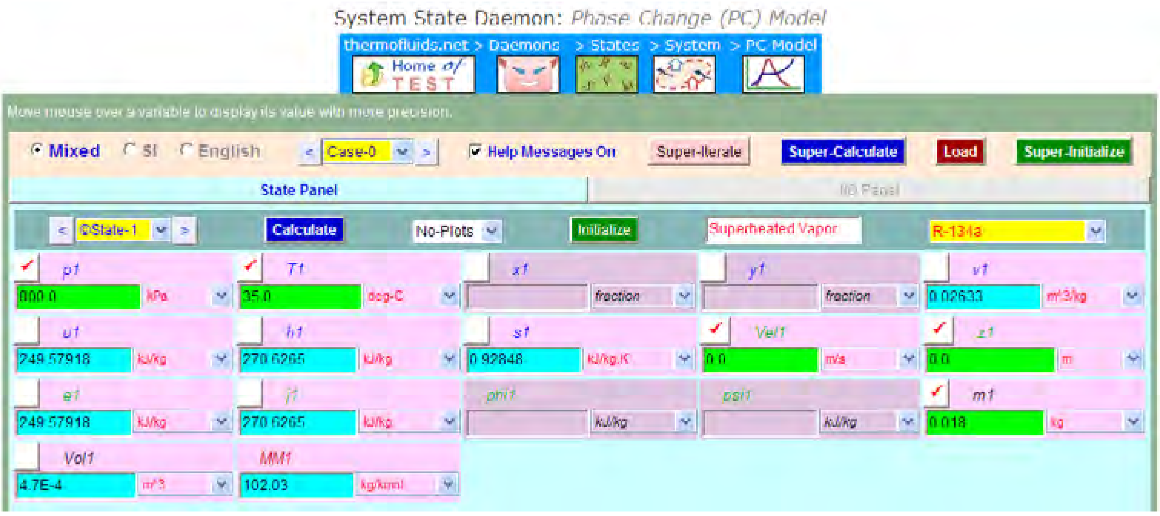


TEST Solution:

Following are the steps:

First, find out the heat rejected by the Refrigerant R134a in the condenser:

1. Go to State Daemon-Phase Change (PC) model. Choose R134a as the substance, Fill in the values of P1, T1 and m1, and click Calculate We get:



System State Daemon: *Phase Change (PC) Model*

thermofluids.net > Daemons > States > System > PC Model

Move mouse over a variable to display its value with more precision.

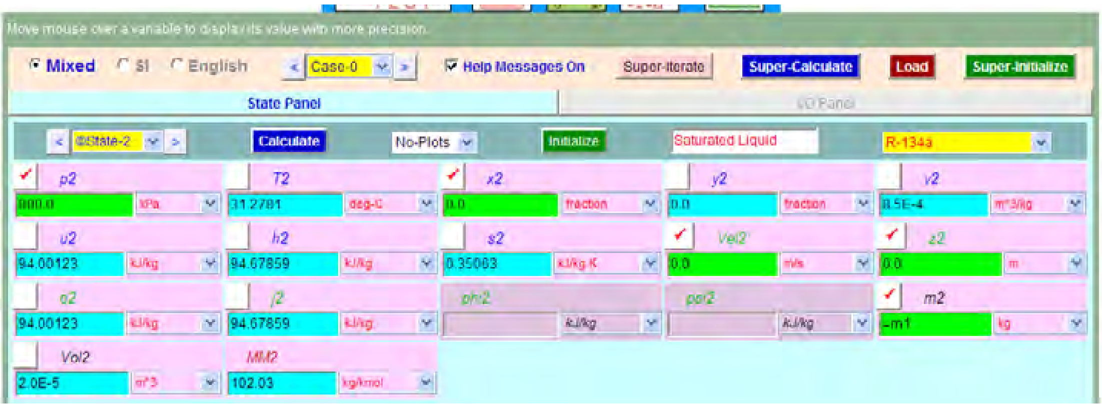
● Mixed ○ SI ○ English Case-0 ☑ Help Messages On

State Panel

@State-1 Superheated Vapor R-134a

☑ p1: 800.0 kPa
☑ T1: 35.0 deg-C
☐ x1: fraction
☐ y1: fraction
☐ v1: 0.02633 m^3/kg
☐ u1: 249.57918 kJ/kg
☐ h1: 270.6265 kJ/kg
☐ s1: 0.92848 kJ/kg.K
☑ Vel1: 0.0 m/s
☑ z1: 0.0 m
☐ e1: 249.57918 kJ/kg
☐ j1: 270.6265 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☑ m1: 0.018 kg
☐ Vol1: 4.7E-4 m^3
MM1: 102.03 kg/kmol

2. Next enter values of p2, x2 and m2 (= m1) for State 2, and click Calculate. We get:



Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On | Super-Iterate | Super-Calculate | Load | Super-Initialize

State Panel | I/O Panel

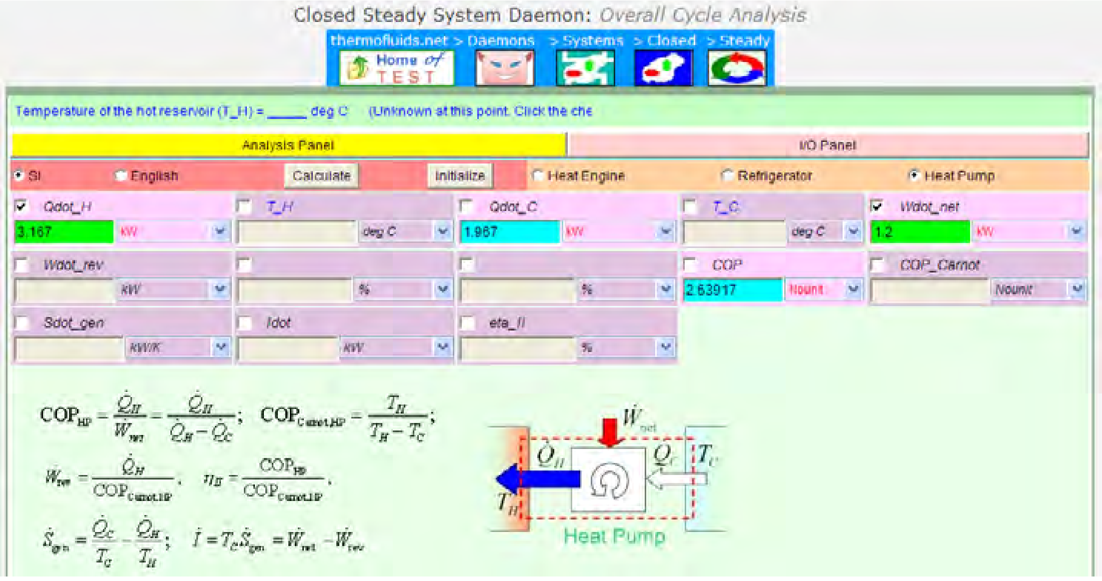
@State-2 | Calculate | No-Plots | Initialize | Saturated Liquid | R-134a

☑ p2	☐ T2	☑ x2	☐ y2	☐ v2
800.0 kPa	31.2781 deg-C	0.0 fraction	0.0 fraction	8.5E-4 m^3/kg
☐ u2	☐ h2	☐ s2	☑ Vel2	☑ z2
94.00123 kJ/kg	94.67859 kJ/kg	0.35063 kJ/kg.K	0.0 m/s	0.0 m
☐ e2	☐ j2	ph2	psi2	☑ m2
94.00123 kJ/kg	94.67859 kJ/kg	kJ/kg	kJ/kg	=m1 kg
☐ Vol2	MM2			
2.0E-5 m^3	102.03 kg/kmol			

Therefore, heat rejected = m1 * (h1 – h2) = 0.018 * (270.627 – 94.679) = 3.167062316894531 kJ/s (=kW).

Now, go to heat pump: i.e.

3. Select Steady State (Cycles) Daemon from the Daemon tree.
4. Click on Steady State (Cycles); following screen appears. Click Heat Pump Radio button, fill in Qdot_H = 3.167 kW, Wdot_net = 1.2 kW and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

thermofluids.net > Daemons > Systems > Closed > Steady

Temperature of the hot reservoir (T_H) = _____ deg C (Unknown at this point. Click the che

Analysis Panel | I/O Panel

● SI ○ English | Calculate | Initialize | ○ Heat Engine ○ Refrigerator ● Heat Pump

☑ Qdot_H	☐ T_H	☐ Qdot_C	☐ T_C	☑ Wdot_net
3.167 kW	deg C	1.967 kW	deg C	1.2 kW
☐ Wdot_rev	☐	☐	☐ COP	☐ COP_Carnot
kW	%	%	2.63917 Nounit	Nounit
☐ Sdot_gen	☐ Idot	☐ eta_II		
kW/K	kW	%		

$$\mathrm{COP_{HP}} = \frac{\dot{Q}_H}{\dot{W}_{net}} = \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_C}; \quad \mathrm{COP_{Carnot,HP}} = \frac{T_H}{T_H - T_C};$$

$$\dot{W}_{rev} = \frac{\dot{Q}_H}{\mathrm{COP_{Carnot,HP}}}; \quad \eta_{II} = \frac{\mathrm{COP_{HP}}}{\mathrm{COP_{Carnot,HP}}};$$

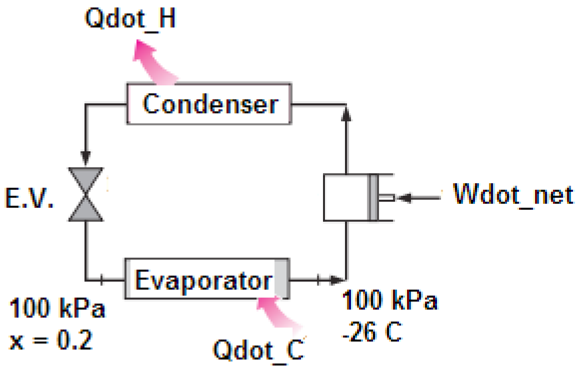
$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

Thus:

COP = 2.639
Rate of heat absorption from outside air = Qdot_C = 1.967 kW…. Ans.

==

Prob.6.29. Refrigerant R-134a enters the evaporator coils placed at the back of the freezer section of a household refrigerator at 100 kPa with a quality of 20% and leaves at 100 kPa and -26 C. If the compressor consumes 600 W and the COP of the refrigerator is 1.2, determine: (a) the mass flow rate of the refrigerant, and (b) the rate of heat rejected to the kitchen air. [Ref:1]

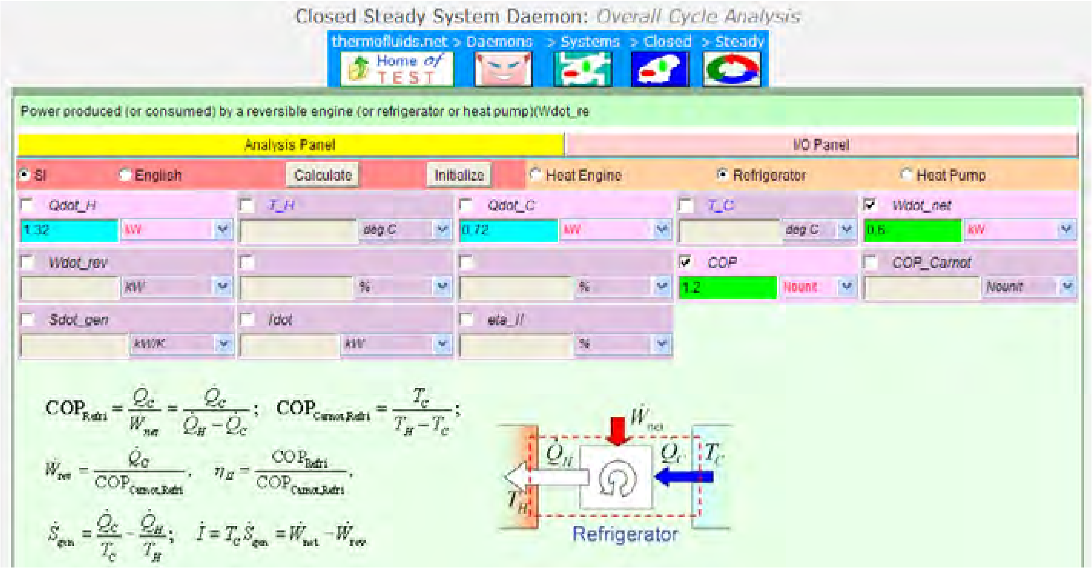


TEST Solution:

Following are the steps:

First, find out the heat absorbed by the Refrigerant R134a in the evaporator:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Refrigerator Radio button, fill in Wdot_net = 0.6 kW, COP = 1.2, and hit Return. We get:


Closed Steady System Daemon: *Overall Cycle Analysis*

Power produced (or consumed) by a reversible engine (or refrigerator or heat pump)(Wdot_re

● SI ○ English ○ Heat Engine ● Refrigorator ○ Heat Pump

☐ Qdot_H: 1.32 kW

☐ T_H: deg C

☐ Qdot_C: 0.72 kW

☐ T_C: deg C

☑ Wdot_net: 0.6 kW

☐ Wdot_rev: kW

☑ COP: 1.2 Nounit

☐ COP_Carnot: Nounit

☐ Sdot_gen: kW/K

☐ Idot: kW

☐ eta_II: %

$$\mathrm{COP}_{\mathrm{Refri}} = \frac{\dot{Q}_C}{\dot{W}_{net}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C}; \quad \mathrm{COP}_{\mathrm{Carnot,Refri}} = \frac{T_C}{T_H - T_C};$$

$$\dot{W}_{rev} = \frac{\dot{Q}_C}{\mathrm{COP}_{\mathrm{Carnot,Refri}}}; \quad \eta_{II} = \frac{\mathrm{COP}_{\mathrm{Refri}}}{\mathrm{COP}_{\mathrm{Carnot,Refri}}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_0\dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

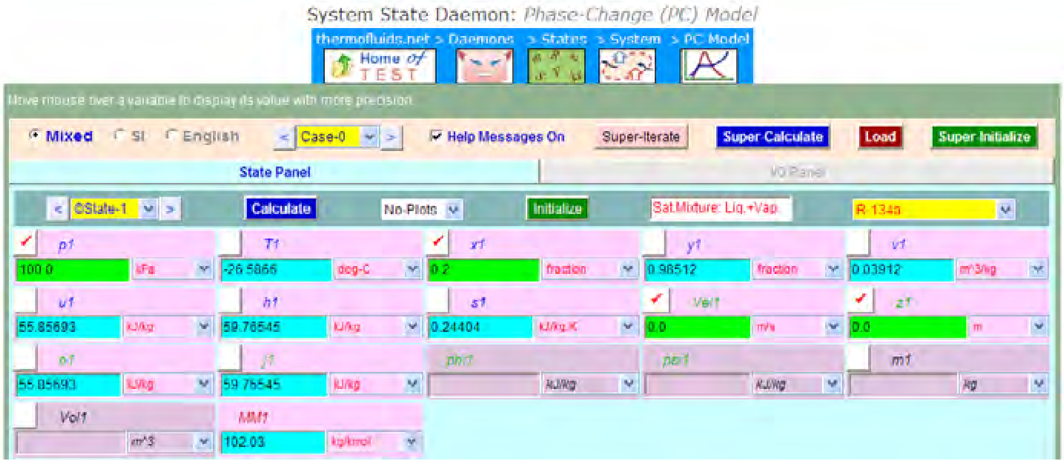
Therefore, heat removed in the evaporator = Qdot_C = 0.72 kW

And, heat rejected to room air from condenser = Qdot_H = 1.32 kW … Ans.

3. **Now, evaporator coil data are given with R134a. Qdot_C = 0.72 kW. To find the mass flow rate of R 134a:**

Go to R134a properties:

Go to **State Daemon-Phase Change (PC) model**. Choose R134a as the substance, Fill in the values of P1, x1 for State 1 and click Calculate We get:


System State Daemon: *Phase-Change (PC) Model*

thermofluids.net > Daemons > States > System > PC Model

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

State Panel | I/O Panel

State-1 | Calculate | No-Plots | Initialize | Sat.Mixture: Liq.+Vap. | R 134a

- ☑ p1: 100.0 kPa
- ☐ T1: -26.5866 deg-C
- ☑ x1: 0.2 fraction
- ☐ y1: 0.98512 fraction
- ☐ v1: 0.03912 m^3/kg
- ☐ u1: 55.85693 kJ/kg
- ☐ h1: 59.76545 kJ/kg
- ☐ s1: 0.24404 kJ/kg.K
- ☑ Vel1: 0.0 m/s
- ☑ z1: 0.0 m
- ☐ e1: 55.85693 kJ/kg
- ☐ j1: 59.76545 kJ/kg
- phi1: kJ/kg
- psi1: kJ/kg
- ☐ m1: kg
- ☐ Vol1: m^3
- MM1: 102.03 kg/kmol

Thus, h1 = 59.76545 kJ/kg.

Now, go to State 2 and fill in values of p2, T2 and click on Calculate. We get:


Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

State Panel | I/O Panel

State-2 | Calculate | No-Plots | Initialize | Superheated Vapor | R-134a

- ☑ p2: 100.0 kPa
- ☑ T2: -26.0 deg-C
- ☐ x2: fraction
- ☐ y2: fraction
- ☐ v2: 0.19322 m^3/kg
- ☐ u2: 214.16196 kJ/kg
- ☐ h2: 233.46706 kJ/kg
- ☐ s2: 0.94835 kJ/kg.K
- ☑ Vel2: 0.0 m/s
- ☑ z2: 0.0 m
- ☐ e2: 214.16196 kJ/kg
- ☐ j2: 233.46706 kJ/kg
- phi2: kJ/kg
- psi2: kJ/kg
- ☐ m2: kg
- ☐ Vol2: m^3
- MM2: 102.03 kg/kmol

Thus, h2 = 233.467 kJ/kg.

Therefore:

Qdot_H = 1.32 kW … Ans.

And, mass flow rate of R134a is determined from:

Qdot_C = 0.72 = m1 * (h2 – h1)

i.e. m1 = 0.72/(h2 – h1) = 0.004145 kg/s …. Ans.

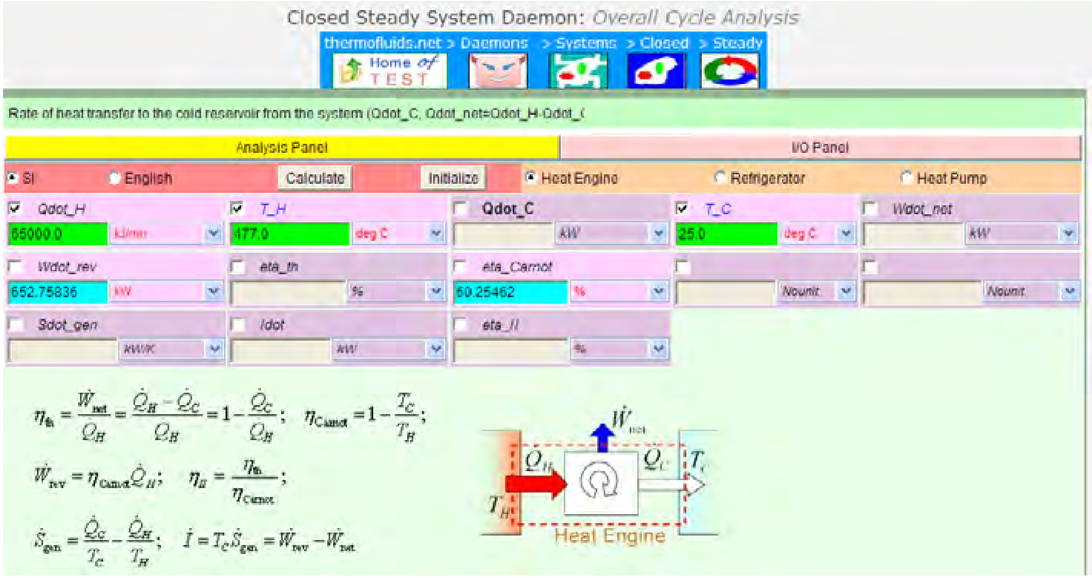
==

Prob.6.30. A heat engine (HE) operates between a source at 477 C and a sink at 25 C. If heat is supplied to the HE at a steady rate of 65000 kJ/min, determine the max. power output of this HE. [Ref: 1]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in Qdot_H = 65000 kJ/min, T_H = 477 C, T_C = 25 C and hit Return. We get:



Closed Steady System Daemon: Overall Cycle Analysis

Rate of heat transfer to the cold reservoir from the system (Qdot_C, Qdot_net=Qdot_H-Qdot_(

● SI ○ English ● Heat Engine ○ Refrigerator ○ Heat Pump

☑ Qdot_H: 65000.0 kJ/min

☑ T_H: 477.0 deg C

☐ Qdot_C: kW

☑ T_C: 25.0 deg C

☐ Wdot_net: kW

☐ Wdot_rev: 652.75836 kW

☐ eta_th: %

☐ eta_Carnot: 60.25462 %

☐ Sdot_gen: kW/K

☐ Idot: kW

☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

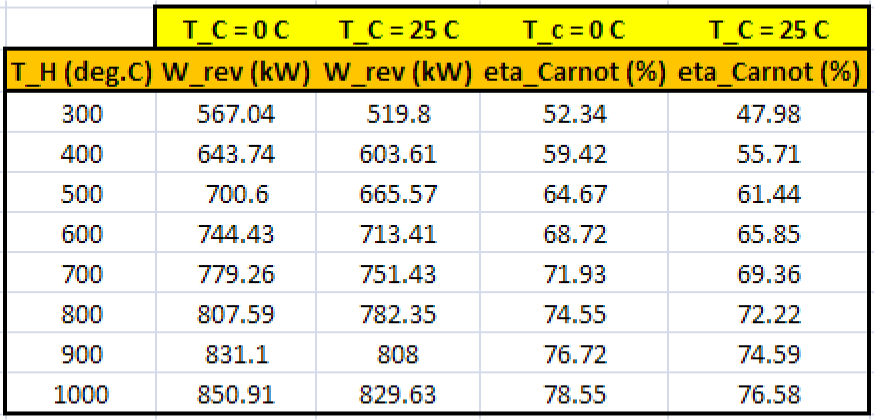
$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

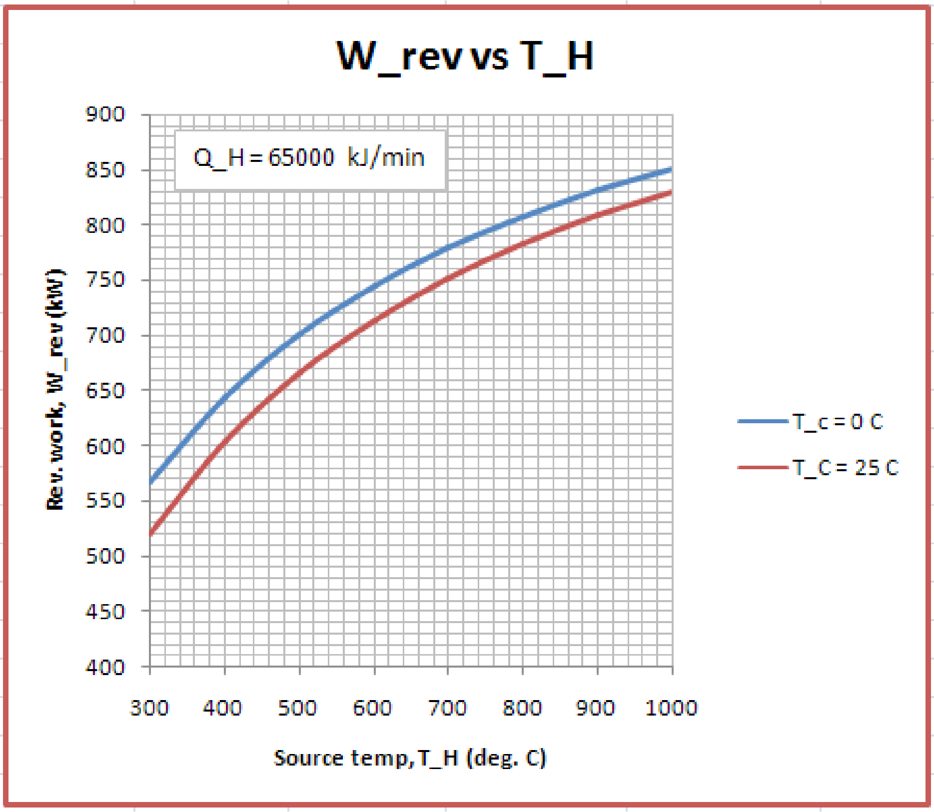
Thus: Max. power output = Wdot_rev = 652.76 kW …. Ans.

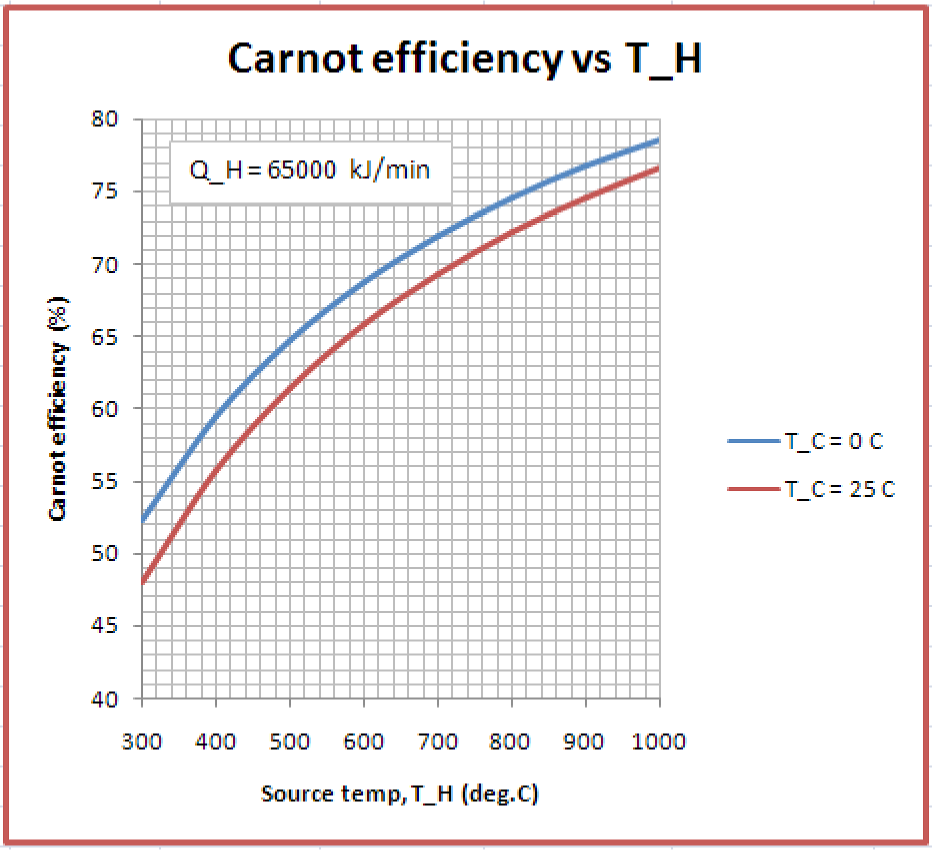
(b) To plot Power produced and eta_th as T_H varies from 300 to 1000 C, for sink temp T_C = 0, and 25 C:

Repeat the above procedure for different values of T_H, keeping T_C = 0 C and 25 C respectively, and tabulate the results as shown below, in EXCEL. And then, plot the results also in EXCEL:



	T_C = 0 C	T_C = 25 C	T_c = 0 C	T_C = 25 C
T_H (deg.C)	W_rev (kW)	W_rev (kW)	eta_Carnot (%)	eta_Carnot (%)
300	567.04	519.8	52.34	47.98
400	643.74	603.61	59.42	55.71
500	700.6	665.57	64.67	61.44
600	744.43	713.41	68.72	65.85
700	779.26	751.43	71.93	69.36
800	807.59	782.35	74.55	72.22
900	831.1	808	76.72	74.59
1000	850.91	829.63	78.55	76.58


W_rev vs T_H
Q_H = 65000 kJ/min
900
850
800
750
700
650
600
550
500
450
400
Rev. work, W_rev (kW)
300
400
500
600
700
800
900
1000
Source temp, T_H (deg. C)
T_c = 0 C
T_C = 25 C


Carnot efficiency vs T_H
Q_H = 65000 kJ/min
80
75
70
65
60
55
50
45
40
Carnot efficiency (%)
300
400
500
600
700
800
900
1000
Source temp, T_H (deg.C)
T_C = 0 C
T_C = 25 C

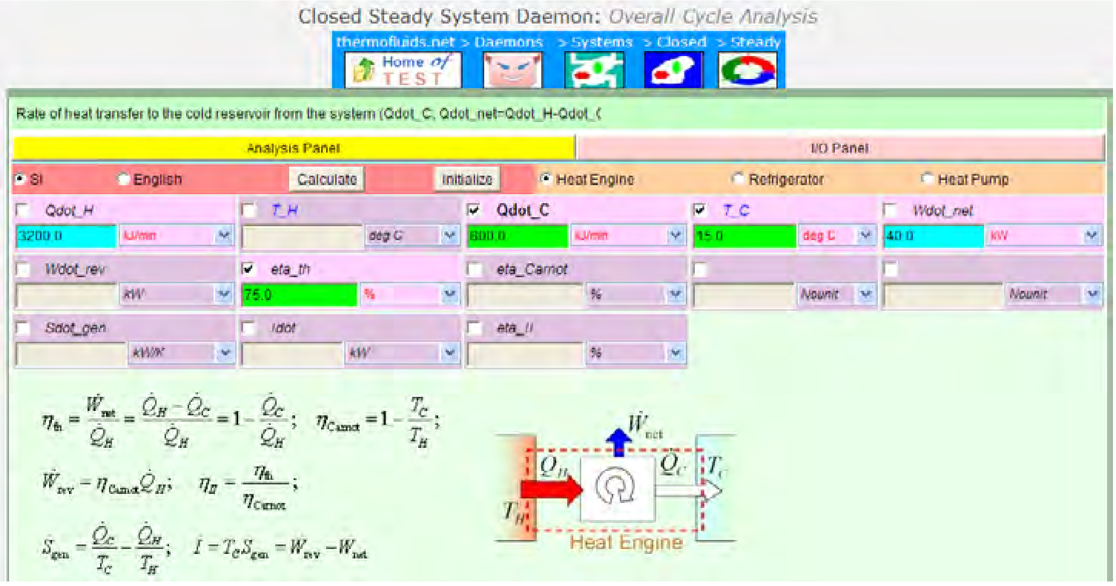
==

Prob.6.31. A heat engine (HE) is operating on a Carnot cycle and has a thermal efficiency of 75%. The waste heat from this engine is rejected to a nearby lake at 15 C at a rate of 800 kJ/min. Determine: (a) the power output of the engine, and (b) the temp of the source. [Ref: 1]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in Qdot_C = 800 kJ/min, T_C = 15 C, eta_th = 75% and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Rate of heat transfer to the cold reservoir from the system (Qdot_C, Qdot_net=Qdot_H-Qdot_(

● SI ○ English ● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: 3200.0 kJ/min
☐ T_H: deg C
☑ Qdot_C: 800.0 kJ/min
☑ T_C: 15.0 deg C
☐ Wdot_net: 40.0 kW
☐ Wdot_rev: kW
☑ eta_th: 75.0 %
☐ eta_Carnot: %
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_0\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

Thus: Power output = Wdot_net = 40 kW … Ans.

And, to find Temp. of Source, T_H:

We have:

Q_H/Q_C = T_H/T_C ….. for Carnot Engine, with temperatures in Kelvin

i.e. 3200/800 = T_H/(273+15)

i.e. T_H = 4 * 288

i.e. T_H =4 * 288 = 1152.0 K…Ans.

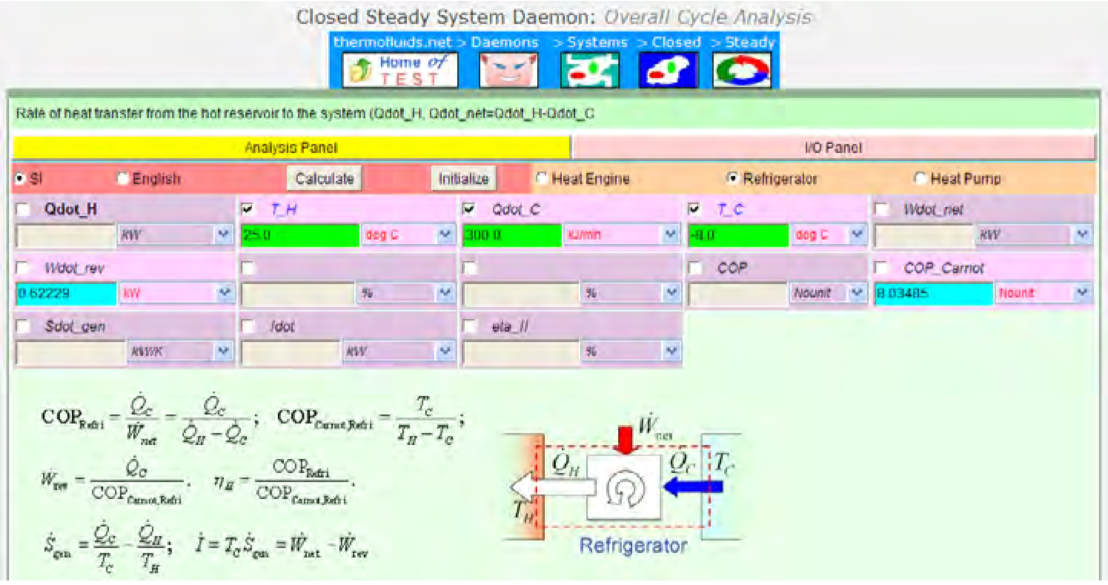
==

Prob.6.32. A refrigerator is to remove heat from the cooled space at a rate of 300 kJ/min to maintain the temp at -8 C. If the air surrounding the refrigerator is at 25 C, determine the minimum power input required for the refrigerator. [Ref: 1]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Refrigerator Radio button, fill in Qdot_C = 300 kJ/min, T_H = 25 C, T_C = -8 C and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Rate of heat transfer from the hot reservoir to the system (Qdot_H, Qdot_net=Qdot_H-Qdot_C

● SI ○ English Calculate Initialize ○ Heat Engine ● Refrigerator ○ Heat Pump

☐ Qdot_H: kW
☑ T_H: 25.0 deg C
☑ Qdot_C: 300.0 kJ/min
☑ T_C: -8.0 deg C
☐ Wdot_net: kW
☐ Wdot_rev: 0.62229 kW
☐ COP: Nounit
☐ COP_Carnot: 8.03485 Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\mathrm{COP}_{\mathrm{Refri}} = \frac{\dot{Q}_C}{\dot{W}_{net}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C}; \quad \mathrm{COP}_{\mathrm{Carnot,Refri}} = \frac{T_C}{T_H - T_C};$$

$$\dot{W}_{rev} = \frac{\dot{Q}_C}{\mathrm{COP}_{\mathrm{Carnot,Refri}}}, \quad \eta_{II} = \frac{\mathrm{COP}_{\mathrm{Refri}}}{\mathrm{COP}_{\mathrm{Carnot,Refri}}},$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_0 \dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

Thus: W_rev for refrigerator = 0.622 kW … Ans. (since the reversible, or the Carnot refrig. requires minimum work)

===

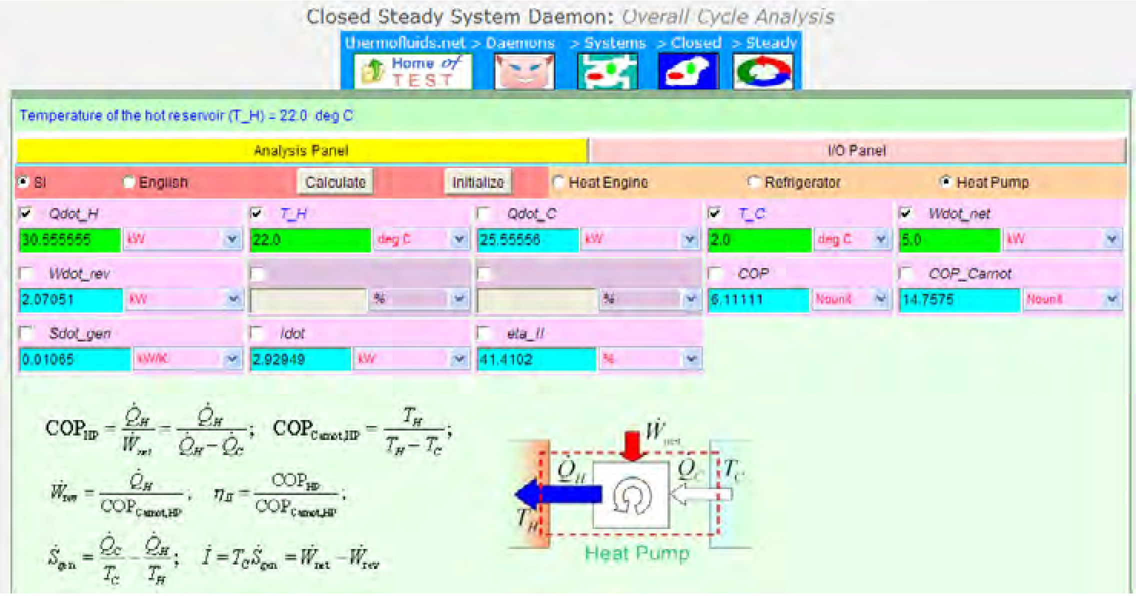
Prob.6.33. A heat pump is used to maintain a house at 22 C by extracting heat from the outside air on a day when the outside air temp is 2 C. The house is estimated to lose heat at a rate of 110000 kJ/h and the heat pump consumes 5 kW of electric power when running. Is this heat pump powerful enough to do the job? [Ref: 1]

TEST Solution:

Note that COP of a Rev. refrigerator or Heat pump is the max. possible value within the specified temp limits.

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Pump Radio button, fill in Qdot_H = 30.5555 kJ/s, T_H = 22 C, T_C = 2 C and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Temperature of the hot reservoir (T_H) = 22.0 deg C

● SI ○ English ○ Heat Engine ○ Refrigerator ● Heat Pump

☑ Qdot_H: 30.555555 kW
☑ T_H: 22.0 deg C
☐ Qdot_C: 25.55556 kW
☑ T_C: 2.0 deg C
☑ Wdot_net: 5.0 kW
☐ Wdot_rev: 2.07051 kW
☐ COP: 6.11111 NoUnit
☐ COP_Carnot: 14.7575 NoUnit
☐ Sdot_gen: 0.01065 kW/K
☐ Idot: 2.92949 kW
☐ eta_II: 41.4102 %

$$\mathrm{COP_{HP}} = \frac{\dot{Q}_H}{\dot{W}_{net}} = \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_C}; \quad \mathrm{COP_{Carnot,HP}} = \frac{T_H}{T_H - T_C};$$

$$\dot{W}_{rev} = \frac{\dot{Q}_H}{\mathrm{COP_{Carnot,HP}}}; \quad \eta_{II} = \frac{\mathrm{COP_{HP}}}{\mathrm{COP_{Carnot,HP}}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

Thus:

The motor is powerful enough to do the job since Wdot_net > Wdot_rev. … Ans.

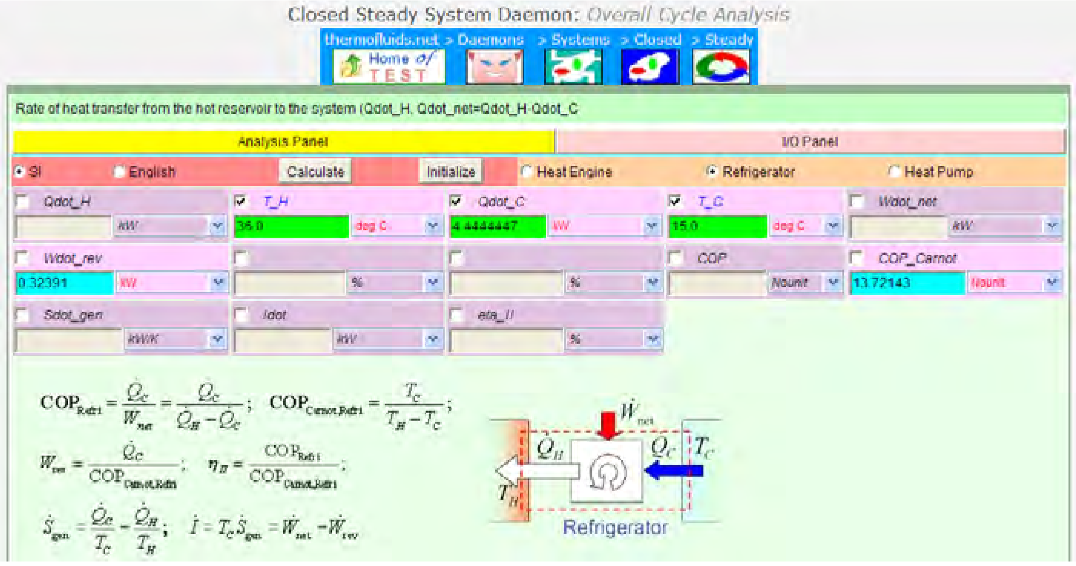
===

Prob.6.34. A Carnot refrigerator absorbs heat from a space at 15 C at a rate of 16000 kJ/h and rejects heat to a reservoir at 36 C. Determine the COP of the refrigerator, the power input in kW, and the rate of heat rejected to high temp reservoir in kJ/h. [Ref: 1]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Refrigerator Radio button, fill in Qdot_C = 16000/3600 = 4.4444 kJ/s, T_H = 36 C, T_C = 15 C and hit Return. We get:



Rate of heat transfer from the hot reservoir to the system (Qdot_H. Qdot_net=Qdot_H-Qdot_C

● SI ○ English ○ Heat Engine ● Refrigerator ○ Heat Pump

☐ Qdot_H: kW
☑ T_H: 36.0 deg C
☑ Qdot_C: 4.4444447 kW
☑ T_C: 15.0 deg C
☐ Wdot_net: kW
☐ Wdot_rev: 0.32391 kW
☐ COP: Nounit
☐ COP_Carnot: 13.72143 Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\mathrm{COP}_{\mathrm{Refri}} = \frac{\dot{Q}_C}{\dot{W}_{net}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C}; \quad \mathrm{COP}_{\mathrm{Carnot,Refri}} = \frac{T_C}{T_H - T_C};$$

$$\dot{W}_{rev} = \frac{\dot{Q}_C}{\mathrm{COP}_{\mathrm{Carnot,Refri}}}; \quad \eta_{II} = \frac{\mathrm{COP}_{\mathrm{Refri}}}{\mathrm{COP}_{\mathrm{Carnot,Refri}}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{net} - \dot{W}_{rev}$$

Thus:

COP_carnot = 13.72, Wdot_rev = 0.32391 kW….Ans.

Q_H = Q_C + Wdot_rev = 4.44444 + 0.32391 = 4.76835 kW = 4.76835 * 3600 kJ/h

= 17166.06 kJ/h …. Ans.

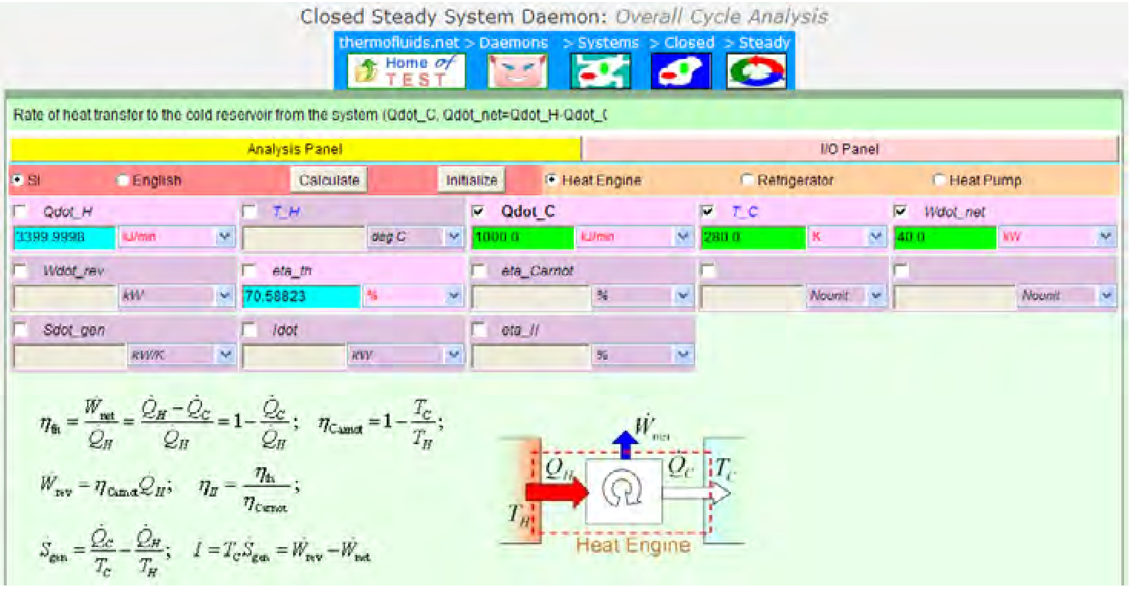
===

Prob.6.35. A power cycle operates between a reservoir at temp T and a lower temp reservoir at 280 K. At steady state, the cycle develops 40 kW of power while rejecting 1000 kJ/min of energy by heat transfer to the cold reservoir. Determine the minimum theoretical value for T, in Kelvin. [Ref: 3]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in Qdot_C = 1000 kJ/min, Wdot_net = 40 kW, T_C = 280 K and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

Rate of heat transfer to the cold reservoir from the system (Qdot_C, Qdot_net=Qdot_H-Qdot_(

● SI ○ English ● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: 3399.9998 kJ/min
☐ T_H: deg C
☑ Qdot_C: 1000.0 kJ/min
☑ T_C: 280.0 K
☑ Wdot_net: 40.0 kW
☐ Wdot_rev: kW
☐ eta_th: 70.58823 %
☐ eta_Carnot: %
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_0\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

Now, Q_H/Q_C = T_H/T_C for Carnot heat engine.

Therefore:

T_H = T_C * (Q_H/Q_C) = 280*(3400/1000) = 1120 K … Ans.

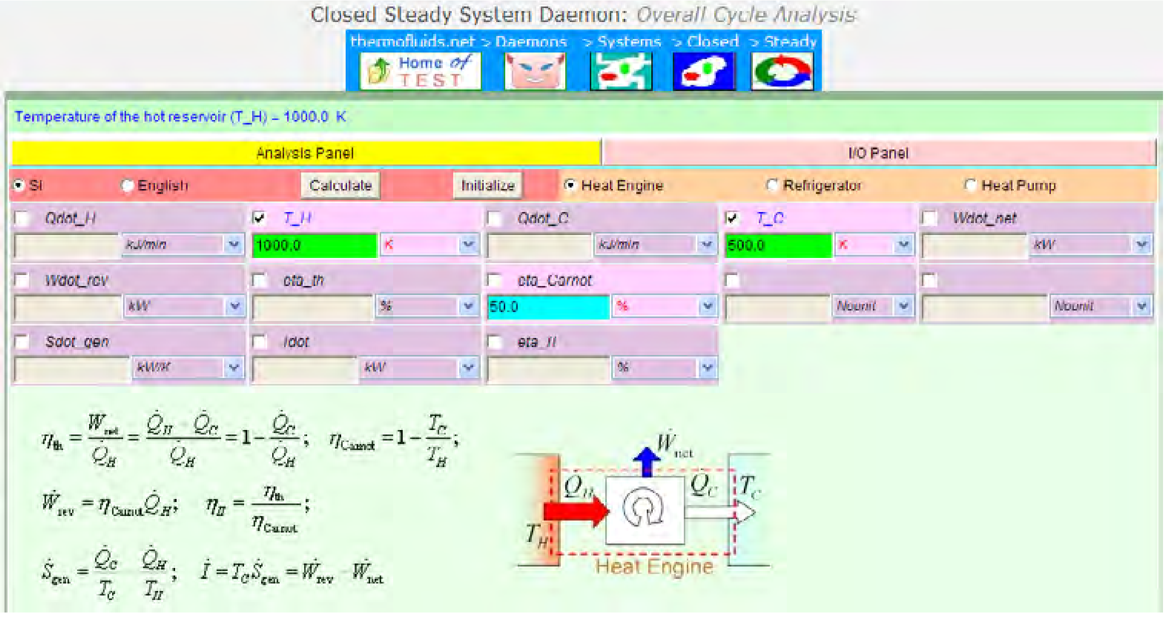
===

Prob.6.36. A certain reversible power cycle has the same thermal efficiency for hot and cold reservoirs at 1000 and 500 K, respectively, as for hot and cold reservoirs at temp T and 1000 K. Determine T, in Kelvin. [Ref: 3]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in T_H = 1000 K, T_C = 500 K and hit Return. We get:



Temperature of the hot reservoir (T_H) = 1000.0 K

● SI ○ English ● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: kJ/min
☑ T_H: 1000.0 K
☐ Qdot_C: kJ/min
☑ T_C: 500.0 K
☐ Wdot_net: kW
☐ Wdot_rev: kW
☐ eta_th: %
☐ eta_Carnot: 50.0 %
☐ Nounit
☐ Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

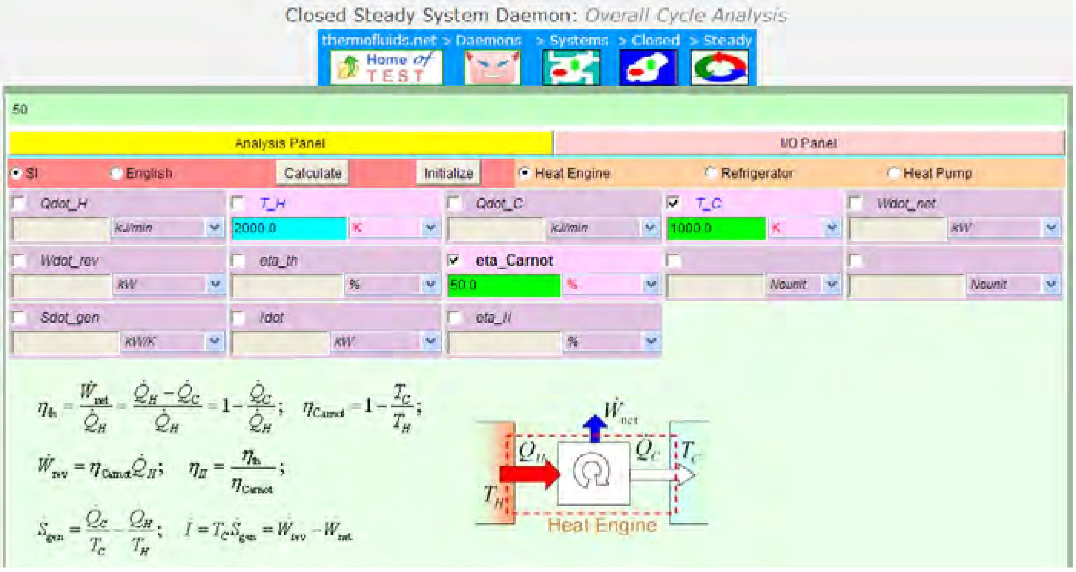
$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_0\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

Thus eta_Carnot = 50%.

3. **Enter this value of eta_Carnot, and T_C = 1000 K for the next case, and hit Return. We get:**



50

● SI ○ English

● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: kJ/min
☐ T_H: 2000.0 K
☐ Qdot_C: kJ/min
☑ T_C: 1000.0 K
☐ Wdot_net: kW
☐ Wdot_rev: kW
☐ eta_th: %
☑ eta_Carnot: 50.0 %
☐ Nounit
☐ Nounit
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$

Thus, T_H for eta = 50% is: 2000 K .. Ans.

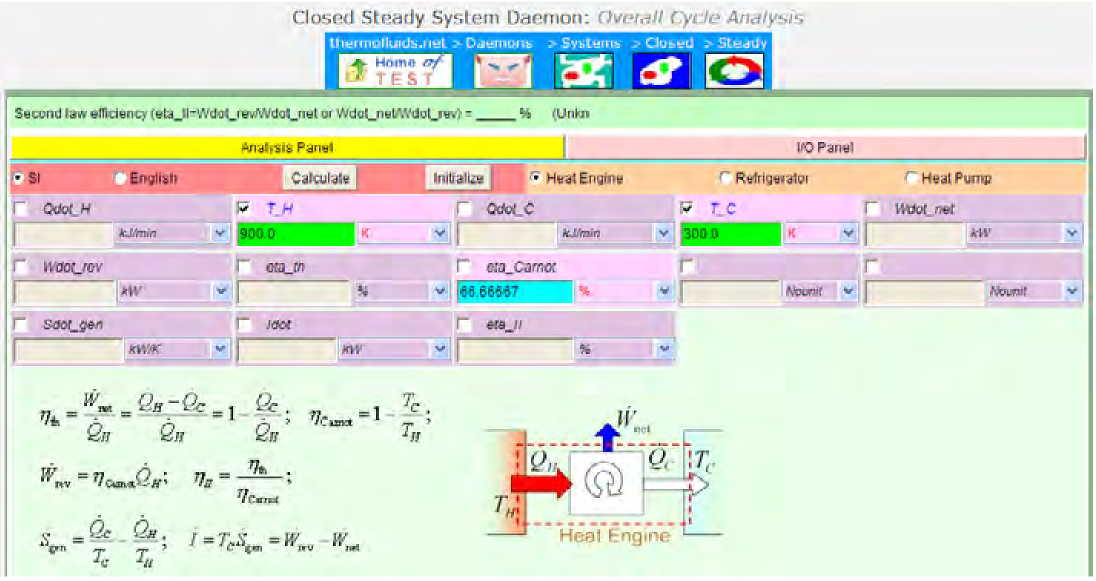
===

Prob.6.37. An inventor claims to have developed a device that executes a power cycle while operating between reservoirs at 900 and 300 that has a thermal efficiency of (a) 66%, (b) 50%. Evaluate the claim for each case. [Ref: 3]

TEST Solution:

Following are the steps:

1. Select Steady State (Cycles) Daemon from the Daemon tree.
2. Click on Steady State (Cycles); following screen appears. Click Heat Engine Radio button, fill in T_H = 900 K, T_C = 300 K and hit Return. We get:



Closed Steady System Daemon: *Overall Cycle Analysis*

thermofluids.net > Daemons > Systems > Closed > Steady

Second law efficiency (eta_II=Wdot_rev/Wdot_net or Wdot_net/Wdot_rev) = _____ % (Unkn

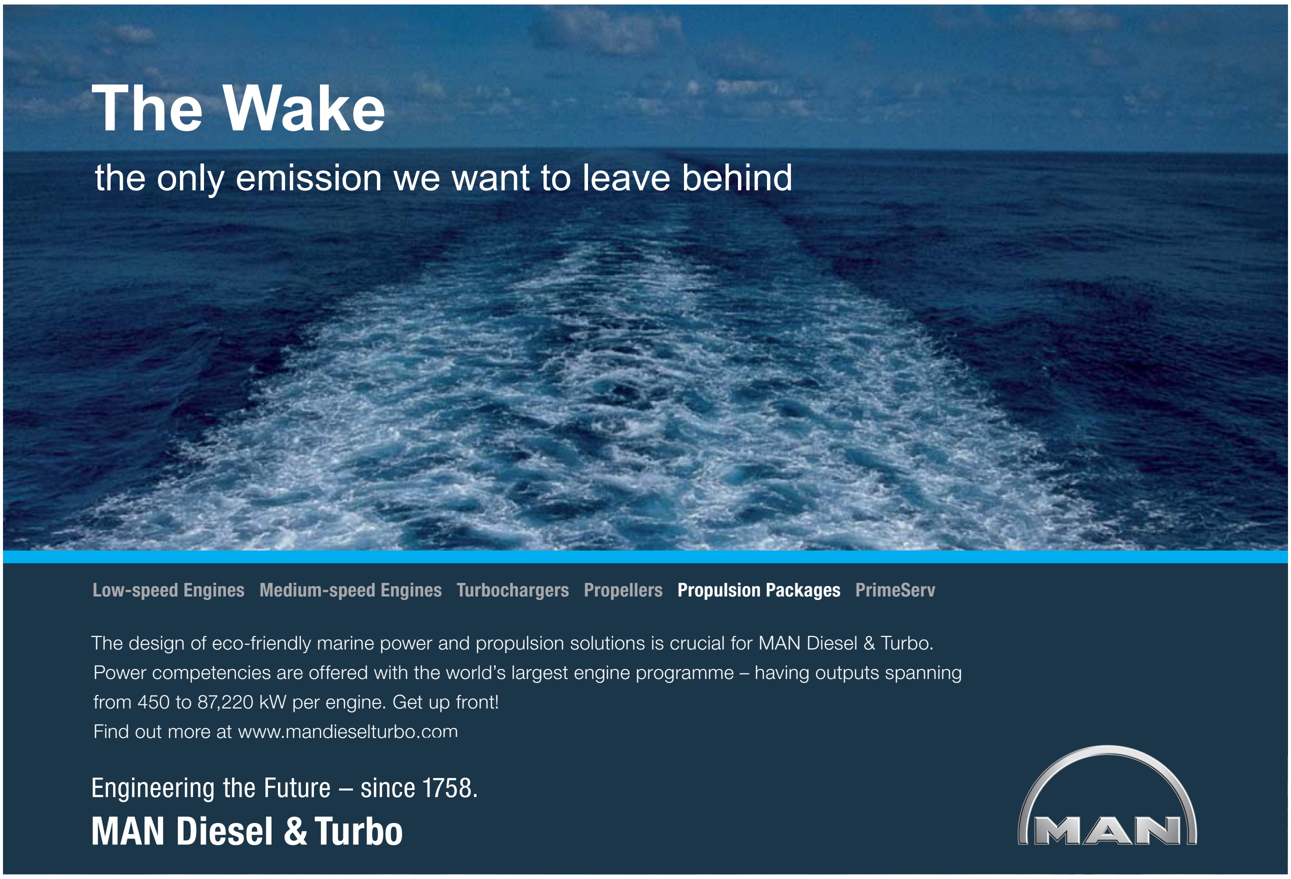
● SI ○ English Calculate Initialize ● Heat Engine ○ Refrigerator ○ Heat Pump

☐ Qdot_H: kJ/min
☑ T_H: 900.0 K
☐ Qdot_C: kJ/min
☑ T_C: 300.0 K
☐ Wdot_net: kW
☐ Wdot_rev: kW
☐ eta_th: %
☐ eta_Carnot: 66.66667 %
☐ Sdot_gen: kW/K
☐ Idot: kW
☐ eta_II: %

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{\dot{Q}_H - \dot{Q}_C}{\dot{Q}_H} = 1 - \frac{\dot{Q}_C}{\dot{Q}_H}; \quad \eta_{Carnot} = 1 - \frac{T_C}{T_H};$$

$$\dot{W}_{rev} = \eta_{Carnot}\dot{Q}_H; \quad \eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}};$$

$$\dot{S}_{gen} = \frac{\dot{Q}_C}{T_C} - \frac{\dot{Q}_H}{T_H}; \quad \dot{I} = T_C\dot{S}_{gen} = \dot{W}_{rev} - \dot{W}_{net}$$



Note that eta_Carnot is: 66.667%. This is the max. possible efficiency.
Therefore, eta_th = 66% and 50% are feasible, theoretically.

===

6.4 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.
4. *P.K. Nag*, Engineering Thermodynamics, 2nd Ed. Tata McGraw Hill Publishing Co., 1995.
5. *R.K. Rajput,* A Text Book of Engineering Thermodynamics, Laxmi Publications, New Delhi,1998.

7 Entropy

Learning objectives:

1. First Law leads to a property, **'energy'** and the Second Law leads to another property called **'entropy'**.
2. Entropy, being an 'abstract' concept, is better studied by seeing how it is applied in the analysis of commonly encountered processes.
3. Rather than absolute value of entropy, 'entropy change' is of practical use and we study entropy changes for various processes involving pure substances, incompressible substances and ideal gases.
4. Application of entropy principle in analyzing some practically important cases are studied.
5. 'Entropy balance' for various systems is studied.
6. Above topics are illustrated by solving several problems.

7.1 Definitions, Statements and Formulas used [1,2,4]:

1. Remember: we had the Clausius Inequality for a cycle:

Considering the usual sign conventions for Heat and Work, (i.e. Heat going In is +ve, Work going Out is +ve)

$\sum \frac{Q}{T} = 0$ ……for a Reversible engine (Carnot Engine) ……eqn. 6.7

$\sum \frac{Q}{T} < 0$ ……for an Irreversible engine ……eqn. 6.8

If $\sum \frac{Q}{T} > 0$ ……It is an Impossible engine ……eqn. 6.9

2. **Clausius defined entropy as:**

$dS = \left(\frac{dQ}{T}\right)$ ..kJ/K...for an internally rev. process....eqn. 7.1

Entropy is an *extensive property*. Entropy per unit mass, 's' is an *intensive property*.

3. 'Entropy change' for a process is defined by:

$\Delta S := S_2 - S_1 = \int_1^2 \left(\frac{dQ}{T}\right)$ kJ/K....eqn.7.2

4. For an Isothermal process:

$$\Delta S = \frac{Q}{T_0} \quad \text{kJ/K} \text{ .....eqn. 7.3}$$

5. **‘Increase of Entropy’ principle:**

$$dS \geq \frac{dQ}{T} \quad \text{....eqn. 7.4}$$

In the above, equality sign holds for an *internally reversible* process, and the inequality for an *irreversible* process.

i.e. entropy change for an irreversible process is greater than the integral of (dQ/T) evaluated for that process. Note that T is the absolute temp at the boundary where dQ is transferred between the system and the surroundings.

Integral of (dQ/T) represents ‘entropy transfer’ with heat.

Note that in an irreversible process, for a closed system, entropy change is greater than the entropy transfer.

i.e. there is some ‘entropy generation’, S_{gen} in an irreversible process.

We write this as:

$$\Delta S_{sys} = S_2 - S_1 = \int_1^2 \frac{dQ}{T} + S_{gen} \quad \text{....eqn. 7.5}$$

Also, for an 'isolated system', above equation reduces to:

$$\Delta S_{isolated} \geq 0 \quad \text{....eqn. 7.6}$$

i.e. Entropy of an isolated system during a process *always increases* or, in the limiting case of a reversible process, remains constant. It *never* decreases.

6. Viewing the System and its Surroundings as two sub-systems of an isolated system, we write:

$$S_{gen} = \Delta S_{total} = \Delta S_{sys} + \Delta S_{surr} \geq 0 \quad \text{....eqn. 7.7}$$

Thus,

$S_{gen} > 0$ ....for Irreversible process

$S_{gen} = 0$ .... for Reversible process

$S_{gen} < 0$ ... for Impossible process

'Entropy generation' is a measure of irreversibilities present in a process.

6. **Entropy change of 'pure substances':**

Ex: Steam/Water. Steam Tables give the values of properties. Also, see Chapter 2 of Part-I to see the use of different software to get all the properties, including entropy.

Note that in Steam Tables, entropy of sat. liquid, s_f at 0.01 C is taken as zero. For R-134a, sf of sat. liq. is taken as zero at -40 C. Entropy values are therefore, -ve below these reference values.

In the sat. mixture region, entropy is determined as:

$$s = s_f + x \cdot s_{fg} \quad \text{....eqn. 7.8}$$

where x is the quality.

In an Isentropic process:

$\Delta s = 0$ or: $s_2 = s_1$

7. **Tds relations:**

For a closed system containing simple, compressible substance:

For unit mass:

$T \cdot ds = du + p \cdot dv$ .kJ/kg....eqn. 7.9

Eqn. 7.9 is known as the first Tds eqn, or Gibbs eqn.

Also:

$h = u + P \cdot v$

$dh = du + P \cdot dv + v \cdot dP$

But, $T \cdot ds = du + P \cdot dv$

Therefore:

$T \cdot ds = dh - v \cdot dP$ ....eqn. 7.10

Eqn. 7.10 is known as second Tds eqn.

Now, entropy changes during a process for a simple compressible system can be obtained by integrating the following equations:

$$ds = \frac{du}{T} + \frac{P \cdot dv}{T} \quad \text{...eqn. 7.11}$$

$$ds = \frac{dh}{T} - \frac{v \cdot dP}{T} \quad \text{...eqn. 7.12}$$

8. **Entropy change of liquids and solids:**

Liquids and solids are taken as incompressible. i.e. dv = 0. Therefore, eqn. 7.11 reduces to:

$$ds = \frac{du}{T} = \frac{c \cdot dT}{T}$$ ...since cp = cv = c and du = c.dT for incompressible substances

Then, entropy change, for liquids/solids is:

$$s_2 - s_1 = \int_1^2 \frac{c(T).dT}{T} = c_{avg}\cdot\ln\left(\frac{T_2}{T_1}\right) \quad \text{kJ/kg.K ....eqn. 7.13}$$

For an *isentropic process* (for a liquid/solid), we have: $(s_2-s_1) = 0$, i.e. $T_2 = T_1$, i.e. for liquids/solids, an isentropic process is also an isothermal process.

9. **Entropy changes for ideal gases:**

For an Ideal gas: du = cv . dT and P = R.T/v. Substituting in eqn. 7.11, we get:

$$ds = c_v\cdot\frac{dT}{T} + R\cdot\frac{dv}{v} \quad \text{....eqn. 7.14}$$

Then, entropy change for a process between states 1 and 2:

$$s_2 - s_1 = \int_1^2 c_v(T)\,\frac{dT}{T} + R\cdot\ln\left(\frac{v_2}{v_1}\right) \quad \text{....eqn. 7.15}$$

$$\text{i.e.} \quad s_2 - s_1 = c_v\cdot\ln\left(\frac{T_2}{T_1}\right) + R\cdot\ln\left(\frac{v_2}{v_1}\right) \quad \text{....eqn. 7.15, a}$$

Similarly, using eqn. 7.12 for an ideal gas, we get:

$$s_2 - s_1 = \int_1^2 c_p(T)\,\frac{dT}{T} - R\cdot\ln\left(\frac{P_2}{P_1}\right) \quad \text{....eqn. 7.16}$$

i.e. $$s_2 - s_1 = c_p\cdot\ln\left(\frac{T_2}{T_1}\right) - R\cdot\ln\left(\frac{P_2}{P_1}\right) \quad \text{....eqn. 7.16, a}$$

Heating a gas at constant volume:

$$dQ = c_v\cdot dT$$

Then: $$\frac{dQ}{T} = c_v\cdot\frac{dT}{T}$$

i.e. $$ds = c_v\cdot\frac{dT}{T}$$

i.e. $$s_2 - s_1 = c_v\cdot\ln\left(\frac{T_2}{T_1}\right) \quad \text{...eqn. 7.17}$$

Heating a gas at constant pressure:

$$s_2 - s_1 = c_p\cdot\ln\left(\frac{T_2}{T_1}\right) \quad \text{...eqn. 7.18}$$

Isothermal process:

$$Q = \int T\,ds = T\cdot(s_2 - s_1)$$

and, $$W = P_1\cdot v_1\cdot\ln\left(\frac{v_2}{v_1}\right) = R\cdot T_1\cdot\ln\left(\frac{v_2}{v_1}\right)$$ per kg of gas, since P1.v1 = R.T1

Therefore:

$$T\cdot(s_2 - s_1) = R\cdot T_1\cdot\ln\left(\frac{v_2}{v_1}\right)$$

i.e. $$s_2 - s_1 = R\cdot\ln\left(\frac{v_2}{v_1}\right) \quad \text{eqn. 7.19....since T1 = T2 = T}$$

Adiabatic process:

We have: dQ = 0

Then, dQ/T = 0

i.e. ds = 0 ……eqn. 7.20

Polytropic process:

We start with:

$$s_2 - s_1 = c_v \cdot \ln\left(\frac{T_2}{T_1}\right) + R \cdot \ln\left(\frac{v_2}{v_1}\right) \quad \text{....eqn. 7.15, a}$$

Then, for Polytropic process (P.v^n = const.):

$$\frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^n$$

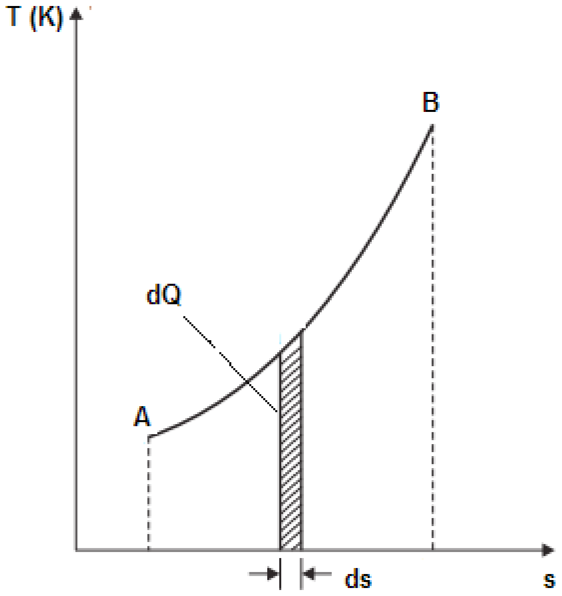
Also: $$\frac{P_1 \cdot v_1}{T_1} = \frac{P_2 \cdot v_2}{T_2}$$

Substituting in eqn. 7.15,a and simplifying, we get:

$$s_2 - s_1 = c_v \cdot \left(\frac{n - \gamma}{n - 1}\right) \cdot \ln\left(\frac{T_2}{T_1}\right) \quad \text{per kg of gas .... eqn. 7.21}$$

10. Property diagrams involving entropy:

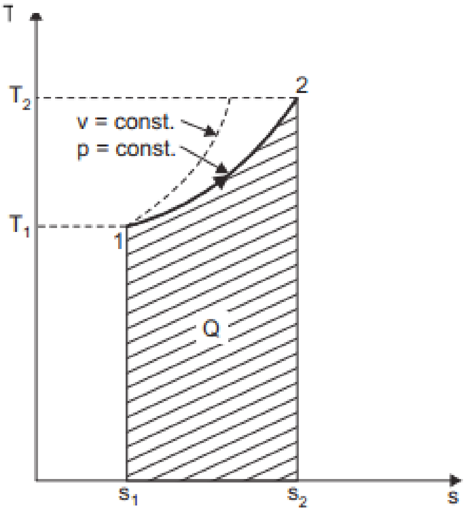
Area under a process curve in a T-s diagram gives the heat transfer in that process:



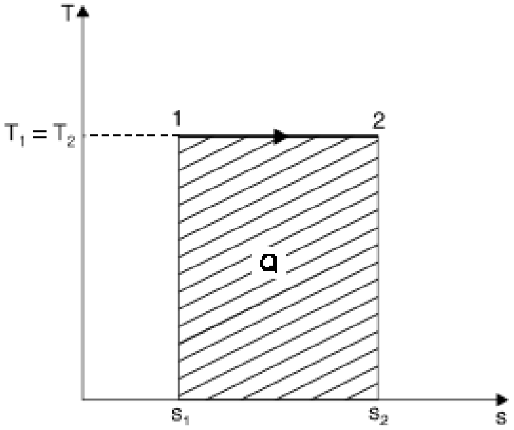
Temp-entropy (T-s) and Enthalpy-entropy (h-s) diagrams are used in the analysis of thermodynamic processes and cycles.

Some examples of processes in a T-s diagram:

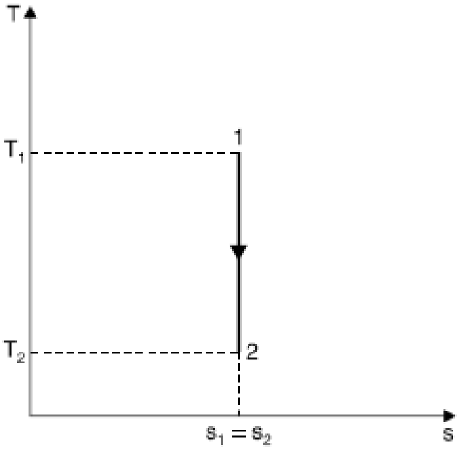
a) **For const. pressure and const. volume processes:**



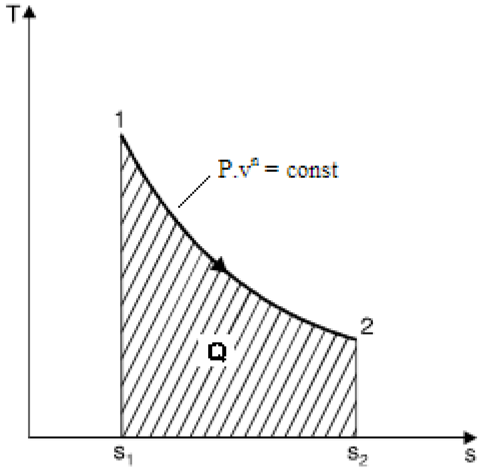
b) **For Isothermal process (i.e. T = const.):**



c) **For an Isentropic process:**



d) **For Polytropic process (i.e. $P.v^n$ = const.)**



11. **Applications of entropy principle to some practical cases:**

a) **Transfer of heat through a finite temp difference:**

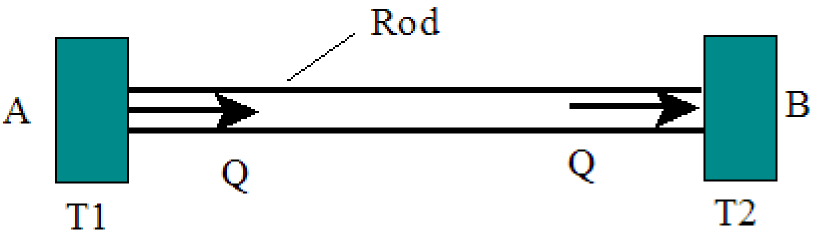


Fig.7.1

Let Q (W) be transferred from a reservoir A at a temp T1 to a reservoir B at a temp T2, through a rod connecting A and B. Let T1 > T2.

Then, considering the isolated system consisting of A, B and the rod:

$$\Delta S_{univ} = \Delta S_A + \Delta S_B \quad \text{where:}$$

$$\Delta S_A = \frac{-Q}{T1} \quad \text{...entropy change of reservoir A, -ve since heat is leaving the reservoir}$$

$$\Delta S_B = \frac{Q}{T2} \quad \text{...entropy change of reservoir A, -ve since heat is leaving the reservoir}$$

Note: the connecting rod suffers no entropy change in steady state, since its coordinates do not change.

Therefore:

$$\Delta S_{univ} = Q \cdot \frac{(T1 - T2)}{T1 \cdot T2} > 0 \quad \text{...since } T1>T2$$

And, the process is **irreversible, but possible.**

Also:

If T1 = T2, $\Delta S_{univ} = 0$, and the **process is reversible.**

If T1 < T2, $\Delta S_{univ} < o$, and the **process is impossible.**

b) **Mixing of two fluids:**

In the fig. below, there are two sub-systems, separated by a partition. Mass, sp. heat and temperatures in the two sub-systems are m1, c1, t1 and m2 , c2, t2 respectively. When the partition is removed, two fluids mix and let the final equilibrium temp be tf.

Let $t_2 < t_f < t_1$.

Problem is to find the entropy change for the universe, ΔS_{univ}:

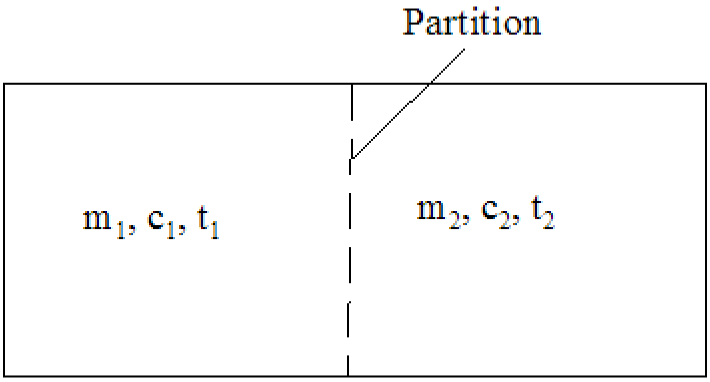


Fig.7.2

Then, tf is found out by making an energy balance:

$$m_1 \cdot c_1 \cdot (t_1 - t_f) = m_2 \cdot c_2 \cdot (t_f - t_2)$$

i.e. $$t_f = \frac{m_1 \cdot c_1 \cdot t_1 + m_2 \cdot c_2 \cdot t_2}{m_1 \cdot c_1 + m_2 \cdot c_2}$$

Entropy change for fluid in subsystem 1:

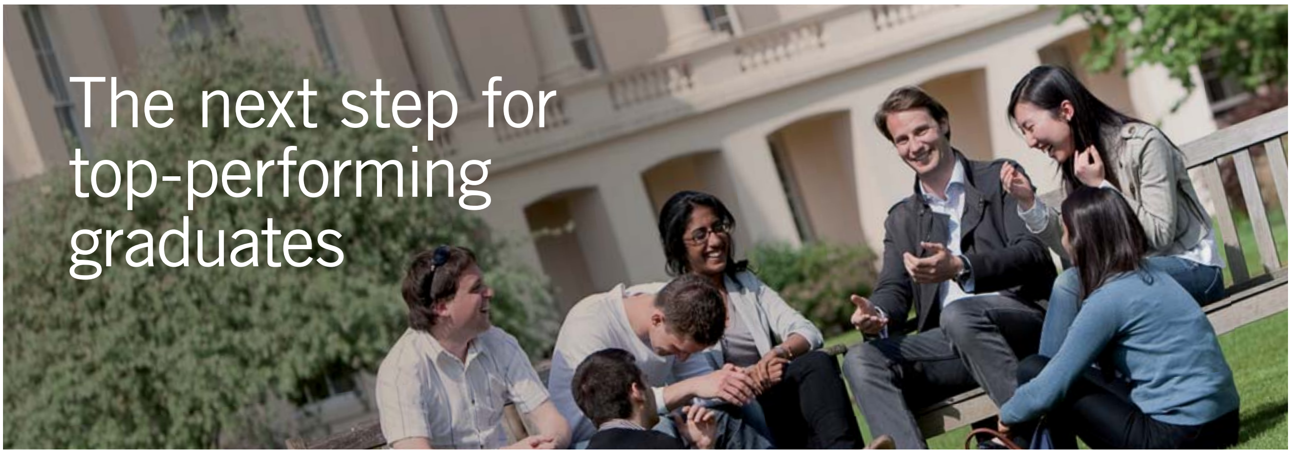
$$\Delta S_1 = \int_{T1}^{Tf} \frac{dQ_{rev}}{T} = \int_{T1}^{Tf} \frac{m_1 \cdot c_1 \cdot dT}{T} = m_1 \cdot c_1 \cdot \ln\left(\frac{T_f}{T_1}\right) = m_1 \cdot c_1 \cdot \frac{t_f + 273}{t_1 + 273}$$

This will be -ve since T1 > Tf.

Similarly, entropy change for fluid in subsystem 2:

$$\Delta S_2 = m_2 \cdot c_2 \cdot \ln\left(\frac{T_f}{T_2}\right) = m_2 \cdot c_2 \cdot \ln\left(\frac{t_f + 273}{t_2 + 273}\right)$$

This will be +ve since T2 < Tf.



Therefore:

$$\Delta S_{univ} = \Delta S_1 + \Delta S_2 = m_1 \cdot c_1 \cdot \ln\left(\frac{T_f}{T_1}\right) + m_2 \cdot c_2 \cdot \ln\left(\frac{T_f}{T_2}\right)$$

i.e. $\Delta S_{univ} > 0$ and, the mixing process is irreversible.

If $m_1 = m_2 = m$, *and* $c_1 = c_2 = c$, *we get:*

$$\Delta S_{univ} = m \cdot c \cdot \ln\left(\frac{{T_f}^2}{T_1 - T_2}\right) \qquad \text{and,} \qquad T_f = \frac{T_1 + T_2}{2}$$

And, we get: $$\Delta S_{univ} = 2 \cdot m \cdot c \cdot \ln\left[\frac{\frac{(T_1+T_2)}{2}}{\sqrt{T_1 \cdot T_2}}\right]$$

This is always +ve since arithmetic mean of two numbers is always greater than their geometric mean.

12. **Entropy balance:**

Entropy balance for any system undergoing any process can be expressed in the general form as:

$$S_{in} - S_{out} + S_{gen} = \Delta S_{system}$$

where $S_{in} - S_{out} =$ "Net entropy transfer by heat or mass"

$S_{gen} =$ "Entropy generation"

$\Delta S_{system} =$ "Change in entropy"

OR:

In the rate form, the entropy balance is:

$$Sdot_{in} - Sdot_{out} + Sdot_{gen} = \frac{\Delta S_{sysyem}}{dt}$$

where $$\text{Sdot}_{in} - \text{Sdot}_{out} = \text{"Rate of net entropy transfer by heat or mass"}$$

$$\text{Sdot}_{gen} = \text{"Rate of entropy generation"}$$

$$\frac{\Delta S_{system}}{dt} = \text{"Rate of change in entropy"}$$

For a general steady flow process, it simplifies to:

$$\text{Sdot}_{gen} = \sum \text{mdot}_e \cdot s_e - \sum \text{mdot}_i \cdot s_i - \sum \frac{\text{Qdot}_k}{T_k}$$

Note:

ΔSsystem = $S_{final} - S_{initial} = S_2 - S_1$, *since entropy is a property* and does not change unless the state of the system changes.

Entropy transfer:

1. **By heat transfer:** $S_{heat} = Q/T$

(No entropy transfer by Work. i.e. $S_{work} = 0$)

2. **Mass flow:** $S_{mass} = m.s$

Entropy generation:

$$S_{in} - S_{out} + S_{gen} = \Delta S_{system} \quad \text{.... kJ/K}$$

And, for a *reversible process*, entropy generation is zero.

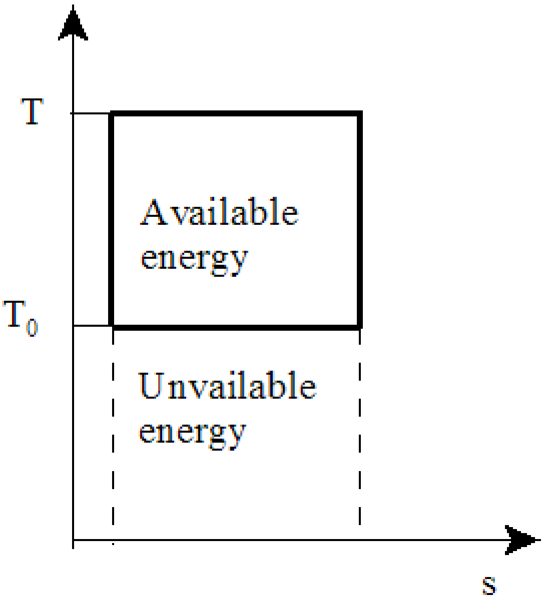
13. Available and Unavailable energy:

Note that according to the Second Law, all the energy supplied to a heat engine can not be converted in to work; part of the energy *must be rejected* to a sink.

Available energy is that portion of the energy supplied as heat which can be converted in to work by a reversible engine.

Unavailable energy is that portion of the energy supplied as heat which can not be converted in to work by a reversible engine.

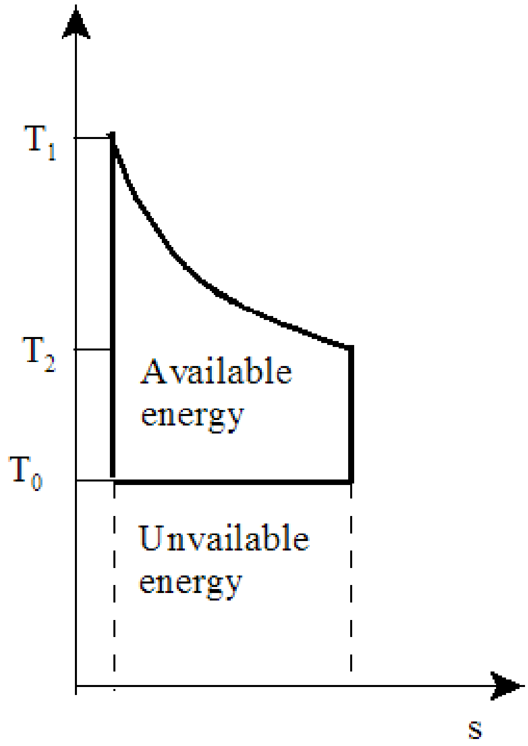
i) **For a Carnot engine (i.e. reversible engine)** Available and Unavilable energy are shown on a T-s diagram below:



Available energy = $W = (1 - T0/T).\ Q = Q - T0.\ (Q/T) = Q - T0.\Delta s$,

where T, T0 are the source and sink temperatures.

ii) **For a reversible engine *absorbing heat from a finite body* (not an infinite source), and rejecting heat to a sink at T0, we have:**



In this case, Available energy = Q – T0.Δs,

where T0 is the ambient temp and Δs is the entropy change of Source.

iii) When Q is transferred as heat from a body at temp T1 to a body at temp T2, the **loss in available energy is equal to** the difference in the available energy at T1 and the available energy at T2.

i.e. Loss in available energy = Q. (1 – T0/T1) – Q. (1 – T0/T2)

= T0. (Q/T2 – Q.T1)

= T0. ΔS_u

In the above, **ΔS_u** denotes entropy change of the universe.

If there is any irreversibility in heat transfer, $\Delta S_u > 0$ and there is a loss in available energy.

So, all spontaneous processes are associated with a loss in available energy.

===

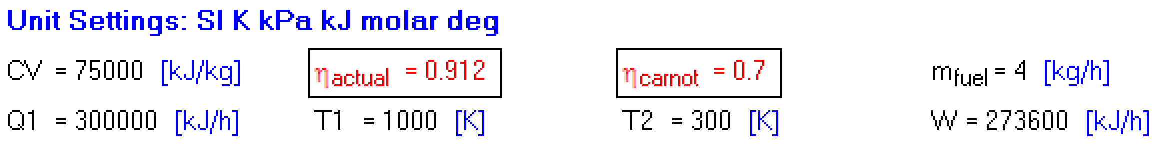
7.2 Problems solved with EES:

"**Prob.7.1.** An inventor claims that his engine has the following specifications: Power developed = 76 kW, Fuel burnt per hr = 4 kg, heating value of fuel = 75000 kJ/kg, Temp limits: 727 C and 27 C. Discuss the possibility of the claim. [VTU-Aug.-Sept. 2000]"

EES Solution:

```
"Data:"

T1=(727+273) "K"
T2=(27+273) "K"
W=76*3600 "kJ/h"
m_fuel=4 "kg/h"
CV=75000 "kJ/kg"

"Calculations:"

Q1=m_fuel*CV "kJ/h"
eta_carnot=1-T2/T1
eta_actual=W/Q1
```

Results:



```
Unit Settings: SI K kPa kJ molar deg
CV  = 75000  [kJ/kg]     ηactual = 0.912    ηcarnot = 0.7    mfuel = 4  [kg/h]
Q1  = 300000  [kJ/h]     T1  = 1000  [K]    T2  = 300  [K]   W = 273600  [kJ/h]
```

Thus:

eta_actual = 0.912, eta_carnot = 0.7
i.e. eta_actual > eta_carnot. This is not possible, as per II Law.
Therefore, the claim of the inventor is not feasible …. Ans.

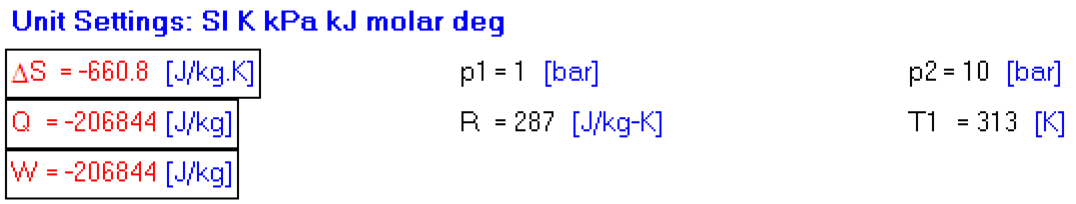
==

"**Prob.7.2.** Air is compressed in a reversible isothermal steady flow process from 1 bar, 40 C to 10 bar. Determine per kg of air: (i) work done (ii) heat transferred, and (iii) change in entropy. [VTU-Jan. 2004]"

EES Solution:

```
"Data:"

p1=1"bar"
T1=40+273 "K"
p2=10 "bar"
R=287 "J/kg.K"

"Calculations:"

"For steady flow, isothermal process:"

W = R * T1 * ln(p1/p2) "J/kg"

Q = W "J/kg"

DELTAS = Q / T1"J/kg.K"
```

Solution:



```
Unit Settings: SI K kPa kJ molar deg
ΔS = -660.8  [J/kg.K]        p1 = 1   [bar]            p2 = 10  [bar]
Q  = -206844 [J/kg]          R  = 287  [J/kg-K]        T1  = 313  [K]
W  = -206844 [J/kg]
```

Thus:

Work done = W = -206.844 kJ/kg … -ve sign means work done on the system … Ans.

Heat transferred = Q = -206.844 kJ/kg … -ve sign means heat leaves the system … Ans.

Change in entropy = Delta_S = -0.6608 kJ/kg.K …. Ans.

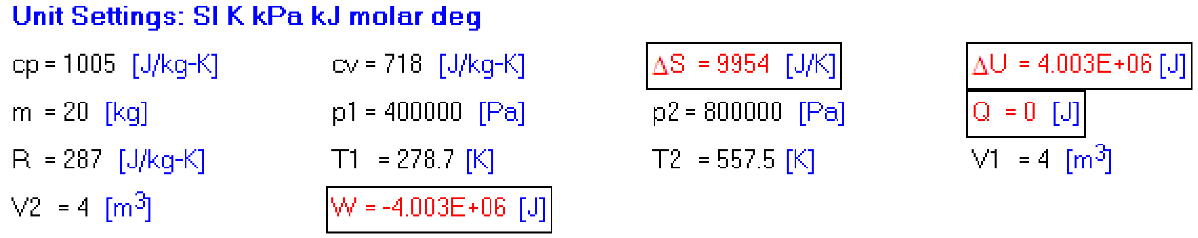
==

"**Prob.7.3.** An insulated cylinder of capacity 4 m^3 contains 20 kg of air (cv = 0.718 kJ/kg.K, cp = 1.005 kJ/kg.K). Paddle work is done on the air by stirring till its pressure increases from 4 bar to 8 bar. Determine: (i) change in internal energy (ii) work done (iii) heat transfer, and (iv) change in entropy. [VTU-Jan. 2003]"

EES Solution:

```
"Data:"

p1= 4E05"Pa"
p2 = 8E05"Pa"
V1= 4"m3"
V2 = 4"m3"
m = 20"kg of air"
cv = 718"J/kg.K"
cp =1005"J/kg.K"

"Calculations:"

R = cp - cv "...for an Ideal gas"

p1 * V1/ (R * T1)= m "...Ideal gas law .... finds T1"

p2 * V2 / (R * T2)= m "...Ideal gas law .... finds T2"

DELTAU = m * cv * (T2-T1) "J .... change in internal energy"

Q=0 "..heat transfer is zero, since cylinder is insulated"

Q = DELTAU + W "....by First Law to a closed system"

DELTAS = m * cv * ln(T2/T1) "J....change in entropy"
```

Results:



Unit Settings: SI K kPa kJ molar deg

cp = 1005 [J/kg-K]
cv = 718 [J/kg-K]
ΔS = 9954 [J/K]
ΔU = 4.003E+06 [J]
m = 20 [kg]
p1 = 400000 [Pa]
p2 = 800000 [Pa]
Q = 0 [J]
R = 287 [J/kg-K]
T1 = 278.7 [K]
T2 = 557.5 [K]
V1 = 4 [m^3]
V2 = 4 [m^3]
W = -4.003E+06 [J]

Thus:

Change in int. energy = Delta_U = 4.003E06 J …. Ans.
Work done = W = -4.003E06 J … -ve sign means work done on the system … Ans.
Heat transferred = Q = 0 J … -ve sign means heat leaves the system … Ans.
Change in entropy = Delta_S = 9954 J/K …. Ans.

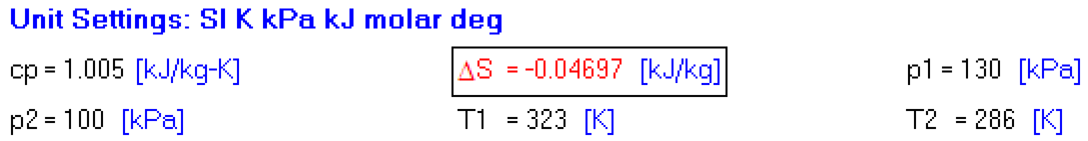
===

"**Prob.7.4.** Air is flowing steadily in an insulated duct. The pressure and temp of air at two stations A and B are given below. Assume for air cp = 1.005 kJ/kg.K, h = cp . T and P.v/T = 0.287 kJ/kg.K where P, v and T are usual notations. Establish the direction of flow.
Station A: Pressure = 130 kPa, Temp = 50 C
Station B: Pressure = 100 kPa, Temp = 13 C.
[VTU-Aug. 2002]»

EES Solution:

```
"Data:"

p1=130"kPa ... pressure at station A"
p2=100"kPa .... pressure at station B"
T1=50+273"K .... temp at station A"
T2=13+273"K.... temp at station B"
cp=1.005"kJ/kg.K ... sp. heat "

{p * V / T= R = 0.287 kJ/kg.K}

"Calculations:"

“Assume that the flow is from A to B.”

"We have, from combined First and Second Laws:"

"Tds = dh - v.dp"
"Therefore:   ds = (dh/T) - (v.dp/T)"

DELTAS = cp * ln(T2/T1) - 0.287 * ln(p2/p1)" kJ/kg..change in entropy of the fluid while going from A to B"
```

Results:



Unit Settings: SI K kPa kJ molar deg

cp = 1.005 [kJ/kg-K]
ΔS = -0.04697 [kJ/kg]
p1 = 130 [kPa]
p2 = 100 [kPa]
T1 = 323 [K]
T2 = 286 [K]

We see that the entropy change of fluid = -0.04697 kJ/kg.K

And entropy change of surroundings = 0, since the pipe is insulated.

Therefore: entropy change of universe = 0 + (– 0.04697) = -0.04697 kJ/kg … i.e. < 0
This is impossible.
Therefore, flow is from B to A …. Ans.

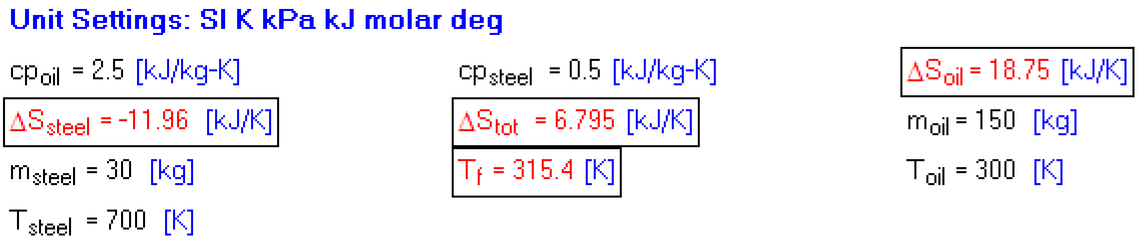
==

"**Prob.7.5.**A 30 kg steel ball at 427 C is dropped in 150 kg of oil at 27 C. Sp. heat of steel and oil are 0.5 kJ/kg.K and 2.5 kJ/kg.K respectively. Estimate the entropy change of steel, the oil and that of the system containing oil and steel. [VTU-March 2001]"

EES Solution:

```
"Data:"

m_steel=30"kg"
m_oil=150"kg"
T_steel=427+273"K"
T_oil=27+273"K"
cp_steel=0.5"kJ/kg.K"
cp_oil=2.5"kJ/kg.K"

"Calculations:"

"Let T_f be the final, equilibrium temp of the system"

"Then, by an energy balance:"

m_steel * cp_steel * (T_steel-T_f) = m_oil * cp_oil * (T_f-T_oil) "...finds final, equilibrium temp, T_f"

DELTAS_steel=m_steel*cp_steel*ln(T_f/(T_steel)) "kJ/K ... change in entropy of steel"

DELTAS_oil=m_oil*cp_oil*ln(T_f/(T_oil))"kJ/K ... change in entropy of oil"

DELTAS_tot=DELTAS_steel+DELTAS_oil"kJ/K ... change in entropy of (oil+steel)"
```

Results:



```
Unit Settings: SI K kPa kJ molar deg
cp_oil = 2.5 [kJ/kg-K]          cp_steel = 0.5 [kJ/kg-K]      ΔS_oil = 18.75 [kJ/K]
ΔS_steel = -11.96 [kJ/K]        ΔS_tot = 6.795 [kJ/K]         m_oil = 150 [kg]
m_steel = 30 [kg]               T_f = 315.4 [K]               T_oil = 300 [K]
T_steel = 700 [K]
```

Thus:

Final, equilibrium temp = Tf = 315.4 K … Ans.
Entropy change of steel = -11.96 kJ/K … Ans.
Entropy change of oil = 18.75 kJ/K … Ans.
Entropy change of (oil + steel) = 6.795 kJ/K … Ans.

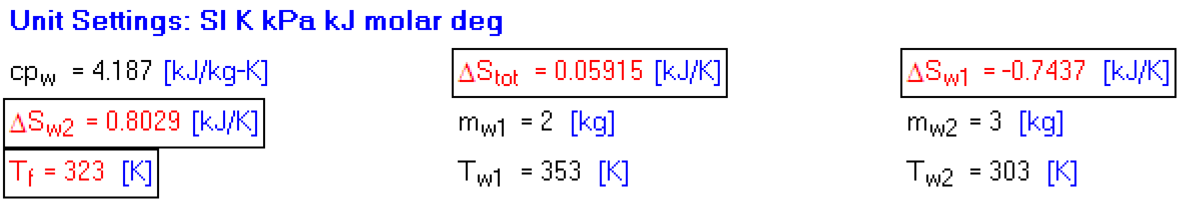
==

"**Prob.7.6.**Two kg of water at 80 C is mixed adiabatically with three kg of water at 30 C in a constant pressure process at 1 atm. Find the increase in entropy of the total mass of water due to mixing process. Assume cp of water = 4.187 kJ/kg.K. [VTU-Aug. 2003]"

EES Solution:

```
"Data:"

m_w1=2"kg"
m_w2=3"kg"
T_w1=80+273"K"
T_w2=30+273"K"
cp_w=4.187"kJ/kg.K"

"Calculations:"

"Let T_f be the final, equilibrium temp of the system"

"Then, by an energy balance:"

m_w1 * cp_w * (T_w1-T_f) = m_w2 * cp_w* (T_f-T_w2) "...finds final, equilibrium temp, T_f"

DELTAS_w1=m_w1*cp_w * ln(T_f/T_w1) "kJ/K ... change in entropy of high temp water"

DELTAS_w2=m_w2 * cp_w * ln(T_f/T_w2)"kJ/K ... change in entropy of low temp water"

DELTAS_tot=DELTAS_w1+DELTAS_w2"kJ/K ... change in entropy of total mass of water"
```

Results:



```
Unit Settings: SI K kPa kJ molar deg
cpw = 4.187 [kJ/kg-K]        ΔStot = 0.05915 [kJ/K]     ΔSw1 = -0.7437 [kJ/K]
ΔSw2 = 0.8029 [kJ/K]         mw1 = 2 [kg]               mw2 = 3 [kg]
Tf = 323 [K]                 Tw1 = 353 [K]              Tw2 = 303 [K]
```

Thus:

Final, equilibrium temp = Tf = 323 K … Ans.
Entropy change of 2kg hot water = ΔS_w1 = -0.7437 kJ/K … Ans.
Entropy change of 3 kg cold water = ΔS_w2 = 0.8029 kJ/K … Ans.
Entropy change of total mass of water = ΔS_tot = 0.05915 kJ/K … Ans.

==

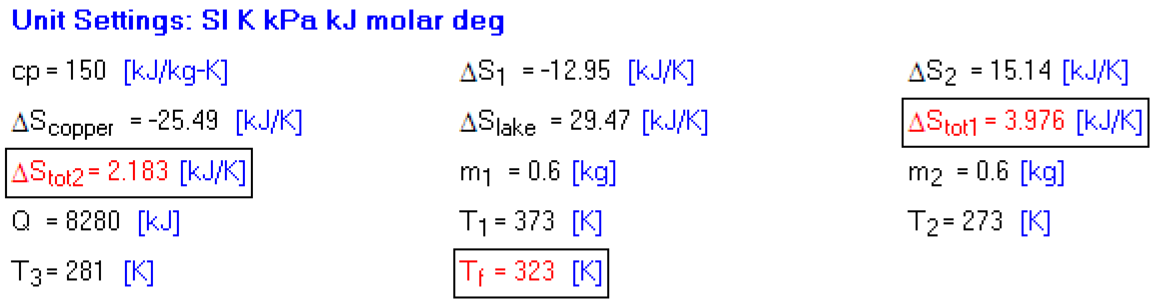
"**Prob.7.7.**Calculate the entropy change of the universe as a result of the following processes:

(i) A copper block of mass 0.6 kg and sp. heat of 150 kJ/kg.K at 100 C is placed in a lake at 8 C
(ii) Two such blocks at 100 C and 0 C are joined together. [VTU-Jan. 2005]"

EES Solution:

```
"Data:"

m_1= 0.6"kg .... mass of first block of copper"
m_2= 0.6"kg ... ... mass of second block of copper"
T_1=100+273"K ... temp of first block of copper"
T_3= 8+273"K ... temp of lake"
T_2 = 0 + 273 "K .... temp of second block of copper"
cp =150"kJ/kg.K"

"Calculations:"

" Case 1: Copper block immersed in the lake:

Temp of the lake will remain constant because of its large mass, i.e. lake is an infinite reservoir."

"And, the heat transferred is:"

Q = m_1 * cp * (T_1 - T_3) "kJ .... heat transferred from copper piece to lake"

"Entropy changes:"

DELTAS_copper = m_1 * cp * ln (T_3/T_1)  "kJ/K ... entropy change of copper block while cooling from
T_1 to T_3"

DELTAS_lake = Q/T_3 "kJ/K ... entropy change of lake"

DELTAS_tot1 = DELTAS_copper + DELTAS_lake "kJ/K ... net entropy change for case 1"

"Case 2: Two such copper blocks are brought together:

Let T_f be the final, equilibrium temp of the system"

"Then, by an energy balance:"

m_1 * cp * (T_1-T_f) = m_2 * cp * (T_f -T_2) "...finds final, equilibrium temp, T_f"

"Entropy changes:"

DELTAS_1=m_1*cp * ln(T_f/T_1) "kJ/K ... change in entropy of high temp block"

DELTAS_2=m_2 * cp * ln(T_f/T_2)"kJ/K ... change in entropy of low temp block"

DELTAS_tot2= DELTAS_1+DELTAS_2"kJ/K ... change in entropy of total mass of copper"
```

Results:



Unit Settings: SI K kPa kJ molar deg

$cp = 150$ [kJ/kg-K] $\Delta S_1 = -12.95$ [kJ/K] $\Delta S_2 = 15.14$ [kJ/K]

$\Delta S_{copper} = -25.49$ [kJ/K] $\Delta S_{lake} = 29.47$ [kJ/K] $\boxed{\Delta S_{tot1} = 3.976}$ [kJ/K]

$\boxed{\Delta S_{tot2} = 2.183}$ [kJ/K] $m_1 = 0.6$ [kg] $m_2 = 0.6$ [kg]

$Q = 8280$ [kJ] $T_1 = 373$ [K] $T_2 = 273$ [K]

$T_3 = 281$ [K] $\boxed{T_f = 323}$ [K]

Thus:

Net entropy change in case 1 = ΔS_tot1 = 3.976 kJ/K …. Ans.

Net entropy change in case 2 = ΔS_tot2 = 2.183 kJ/K …. Ans.

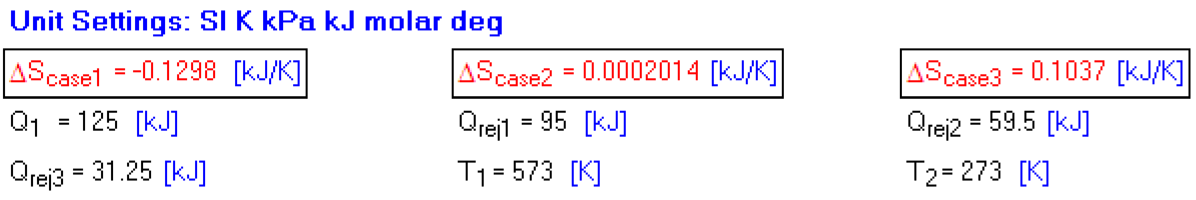
==

"**Prob.7.8.**A heat engine receives 125 kJ of heat per cycle from a reservoir at 300 C and rejects heat to a reservoir at zero deg. C by the following hypothetical amounts: (i) 95 kJ/cycle, (ii) 59.5 kJ/cycle, and (iii) 31.25 kJ/cycle. Which of these represents reversible, irreversible and impossible cycles? [VTU-Aug. 2000]"

EES Solution:

```
"Data:"

Q_1= 125"kJ/cycle .... heat supplied to the reversible (Carnot) engine at the source"
Q_rej1= 95"kJ/cycle .... heat rejected from the reversible (Carnot) engine to the sink, case 1"
Q_rej2= 59.5"kJ/cycle .... heat rejected from the reversible (Carnot) engine to the sink, case 2"
Q_rej3= 31.25"kJ/cycle .... heat rejected from the reversible (Carnot) engine to the sink, case 3"

T_1=300+273"K ... temp of reservoir source"
T_2= 0+273"K ... temp of sink"

"Calculations:"

" We use the Clausius inequality form of Second Law:

Case 1: heat rejected = 95 kJ/cycle:"

DELTAS_case1 = Q_1/T_1 - Q_rej1/T_2

"Case 2: heat rejected = 59.5 kJ/cycle:"

DELTAS_case2 = Q_1/T_1 - Q_rej2/T_2

"Case 3: heat rejected = 31.25 kJ/cycle:"

DELTAS_case3 = Q_1/T_1 - Q_rej3/T_2
```

Results:



```
Unit Settings: SI K kPa kJ molar deg
ΔS_case1 = -0.1298  [kJ/K]     ΔS_case2 = 0.0002014 [kJ/K]     ΔS_case3 = 0.1037  [kJ/K]
Q_1 = 125  [kJ]                Q_rej1 = 95  [kJ]               Q_rej2 = 59.5  [kJ]
Q_rej3 = 31.25 [kJ]            T_1 = 573  [K]                  T_2 = 273  [K]
```

Thus, using Clausius inequality:

For case 1: ΔS < 0 ….therefore, irreversible and possible …. Ans.

For case 2: ΔS = 0 (almost) ….therefore, reversible …. Ans.

For case 3: ΔS > 0 ….therefore, impossible … Ans.

===

"**Prob.7.9.** Ten grams of water at 20 C is converted to ice at -10 C at constant atm. pressure. Assuming sp. heat of liquid water to remain constant at 4.2 kJ/kg.K and that of ice to be half this value and taking the latent heat of fusion of ice at 0 C to be 335 J/g, calculate the total change in entropy. [VTU-Aug. 2000]"

EES Solution:

```
"Data:"

m_w = 0.01 "kg .... mass of water"
T_1=20+273"K ... temp of water"
T_2= 0+273"K ... freezing temp of water"
T_3= -10+273"K ... temp of Ice"
cp_w = 4.2 "kJ/kg.K.... sp. heat of water"
cp_ice = 2.1 "kJ/kg.K .... sp. heat of ice"
h_fg = 335 "kJ/kg... latent heat of fusion for Ice"
```

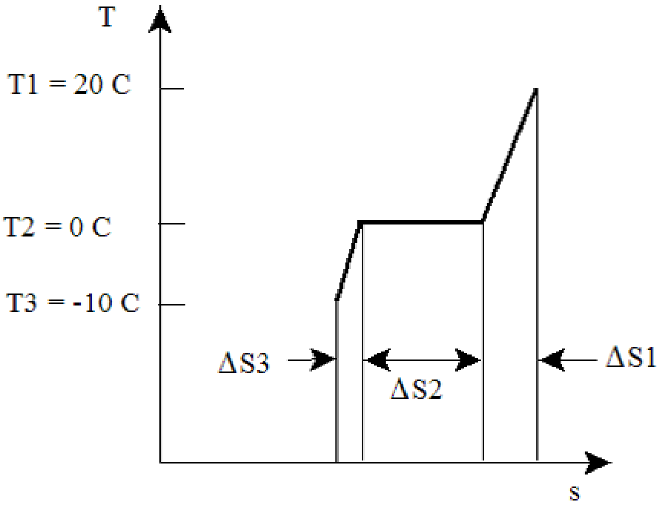
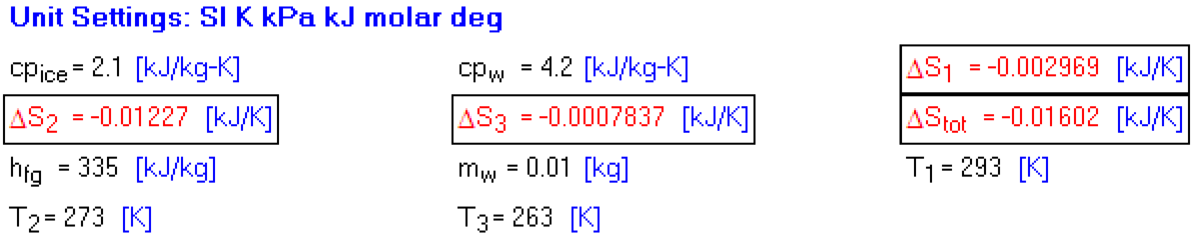


Fig.Prob.7.9

```
"Calculations:"

" We observe that there three steps: first, water is cooled from water at 20 C to water at 0 C, then freezing occurs converting water at 0 C to Ice at 0 C using latent heat of fusion, and the ice at 0 C is cooled further to ice at -10 C."

"Step 1: cooling water from 20 C to 0 C"

DELTAS_1 = m_w * cp_w * ln (T_2 / T_1) "kJ/K"

"Step 2: freezing water at  C to Ice at 0 C"

DELTAS_2 = - m_w * h_fg / T_2 "kJ/K"

"Step 3: cooling of Ice at 0 C to Ice at -10 C"

DELTAS_3 = m_w * cp_ice * ln (T_3/T_2) "kJ/K"

"Total change in entropy:"

DELTAS_tot = DELTAS_1 + DELTAS_2 + DELTAS_3 "kJ/K "
```

Results:



```
Unit Settings: SI K kPa kJ molar deg

cpice = 2.1  [kJ/kg-K]       cpw  = 4.2  [kJ/kg-K]         ΔS1   = -0.002969  [kJ/K]
ΔS2  = -0.01227  [kJ/K]      ΔS3  = -0.0007837  [kJ/K]     ΔStot = -0.01602  [kJ/K]
hfg  = 335  [kJ/kg]          mw = 0.01  [kg]               T1 = 293  [K]
T2 = 273  [K]                T3 = 263  [K]
```

Thus:

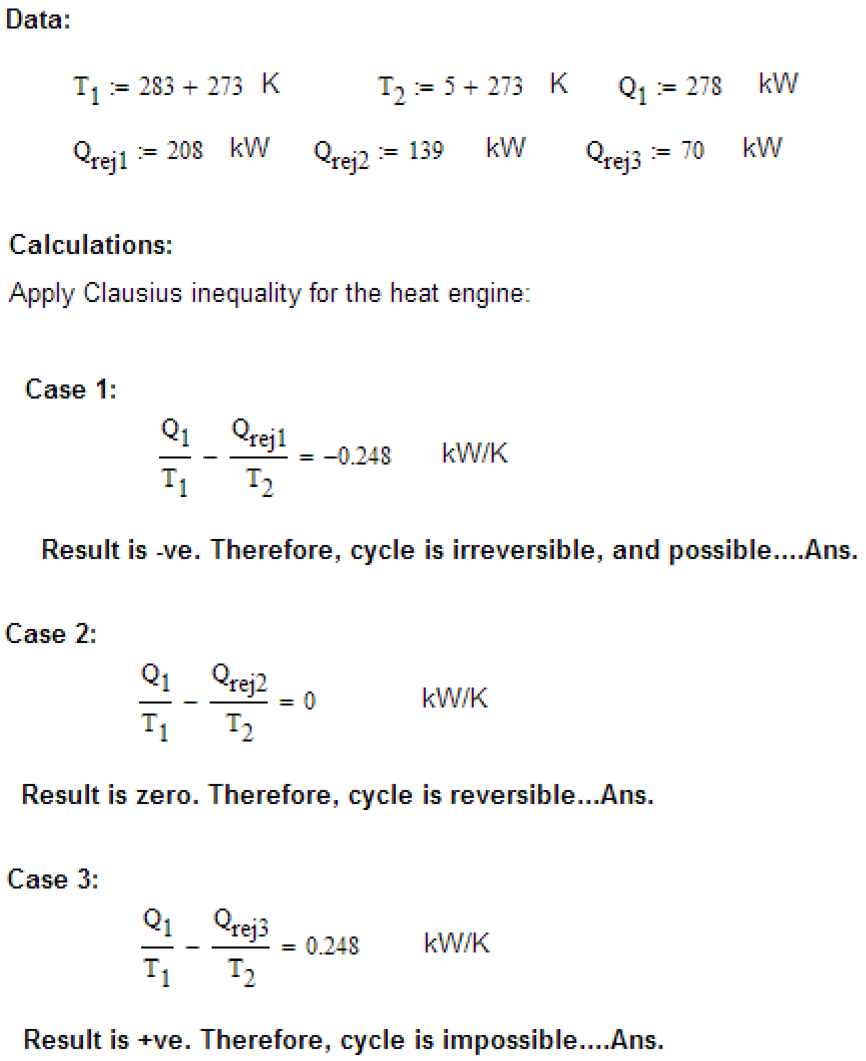
Total change in entropy as water at 20 C is converted to Ice at -10 C =
ΔS_tot = -0.01602 kJ/kg … Ans.
-ve sign indicates that the heat is removed from water.

==

7.3 Problems solved with MathCad:

Prob.7.10. A heat engine is supplied with 278 kJ/s of heat at a constant fixed temp of 283 C and the heat rejections take place at 5 C. The following results were reported:
(i) 208 kJ/s of heat rejected, (ii) 139 kJ/s of heat rejected, (iii) 70 kJ/s of heat rejected.
Classify which of the results report a reversible cycle, irreversible cycle or impossible cycle.
[VTU-BTD-Dec. 2006–Jan. 2007]

Mathcad Solution:



Data:

$T_1 := 283 + 273$ K $\quad T_2 := 5 + 273$ K $\quad Q_1 := 278$ kW

$Q_{rej1} := 208$ kW $\quad Q_{rej2} := 139$ kW $\quad Q_{rej3} := 70$ kW

Calculations:

Apply Clausius inequality for the heat engine:

Case 1:

$$\frac{Q_1}{T_1} - \frac{Q_{rej1}}{T_2} = -0.248 \quad \text{kW/K}$$

Result is -ve. Therefore, cycle is irreversible, and possible....Ans.

Case 2:

$$\frac{Q_1}{T_1} - \frac{Q_{rej2}}{T_2} = 0 \quad \text{kW/K}$$

Result is zero. Therefore, cycle is reversible...Ans.

Case 3:

$$\frac{Q_1}{T_1} - \frac{Q_{rej3}}{T_2} = 0.248 \quad \text{kW/K}$$

Result is +ve. Therefore, cycle is impossible....Ans.

===

Prob.7.11. An inventor claims to have designed a heat engine which absorbs 260 kJ of energy as heat from a reservoir at 52 C and delivers 72 kJ of work. His claim includes that the engine rejects 100 kJ and 88 kJ of energy to the reservoirs at 27 C and 2 C respectively. Verify the claim. How is the temp of the source to be altered in accordance with the verification, if necessary? [VTU-BTD-Dec. 2008–Jan. 2009]

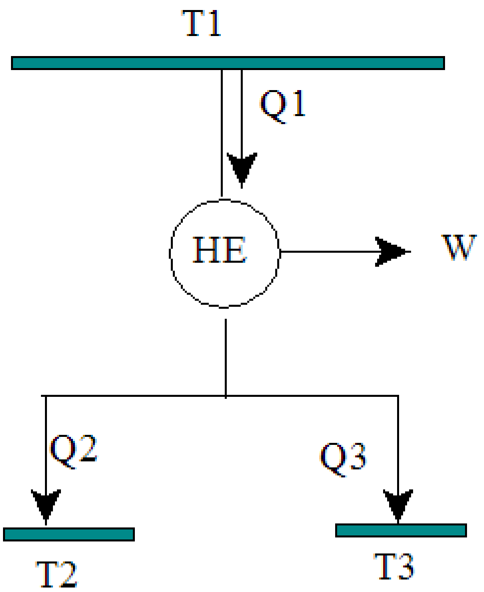


Fig.Prob.7.11

Mathcad Solution:

Data:

$Q_1 := 260$ kJ $\quad Q_2 := 100$ kJ $\quad Q_3 := 88$ kJ $\quad W := 72$ kJ

$T_1 := 52 + 273$ K $\quad T_2 := 27 + 273$ K $\quad T_3 := 2 + 273$ K

Calculations:

Apply I Law as well as Clausius inequality. Both should be satisfied for the process to take place.

$Q_1 - W = 188$ kJ

$Q_2 + Q_3 = 188$ kJ

...they are equal. Therefore, I Law is satisfied.

We have the Clausius inequality:

Considering the usual sign conventions for Heat and Work, (i.e. Heat going In is +ve, Work going Out is +ve)

$\sum \frac{Q}{T} = 0$ ……for a Reversible engine (Carnot Engine) ……eqn. 6.7

$\sum \frac{Q}{T} < 0$ ……for an Irreversible engine ……eqn. 6.8

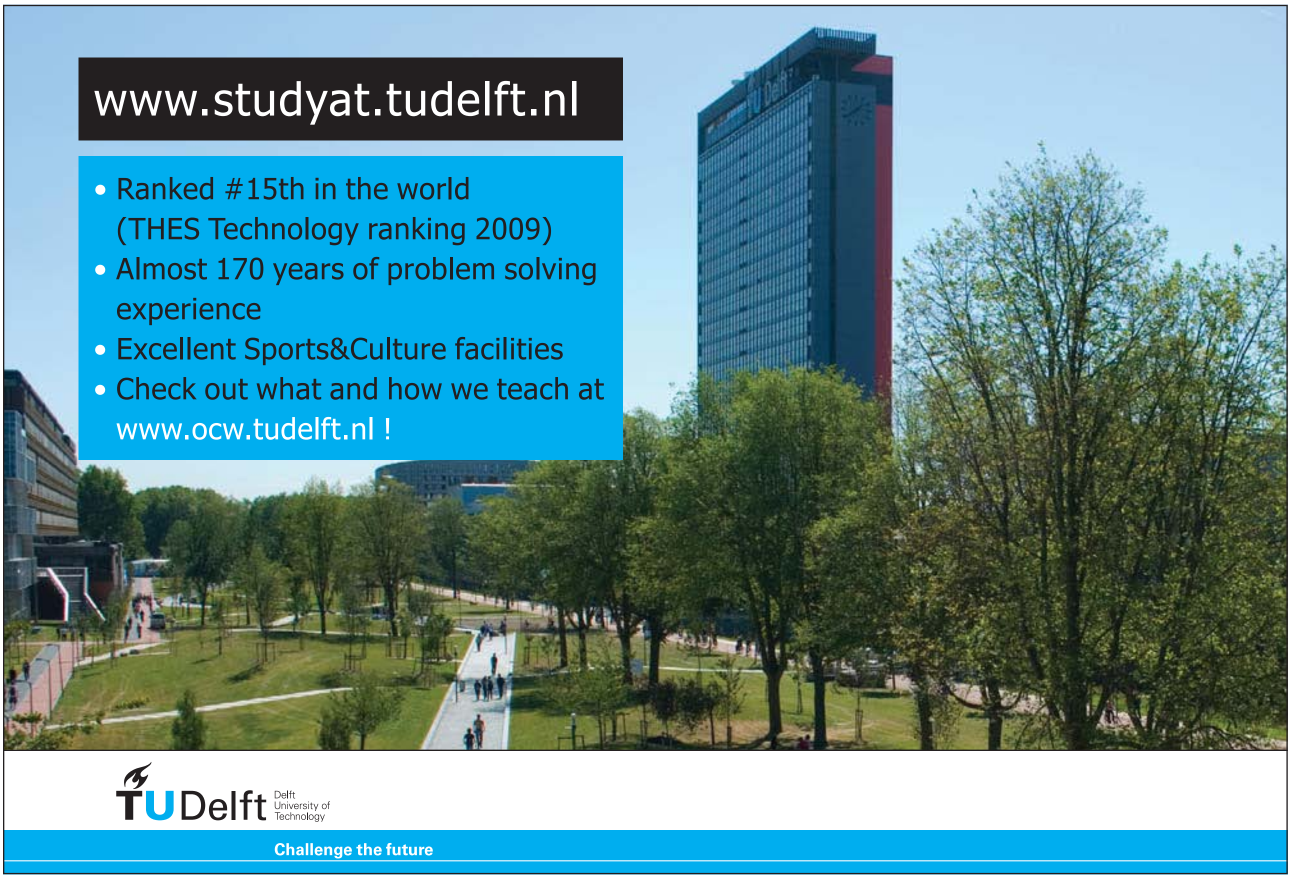
If $\sum \frac{Q}{T} > 0$ ……It is an Impossible engine ……eqn. 6.9

Applying Clausius Inequality to the cycle: heat supplied is positive, heat rej. is negative:

$$\frac{Q_1}{T_1} - \frac{Q_2}{T_2} - \frac{Q_3}{T_3} = 0.147 \quad \text{kJ/K .... eqn.(A)}$$

...This is not equal to zero or -ve, but is +ve. So, II Law is not satisfied.

So, the process is impossible, i.e. the claim is not true...... Ans.



(b) For the claim to be possible, the integral or summation in eqn.(A) above, should be at least equal to zero. Let the new source temp be T_new. Then:

$$\frac{Q_1}{T_{new}} - \frac{Q_2}{T_2} - \frac{Q_3}{T_3} = 0 \qquad \text{kJ/K .... eqn.(B)}$$

Therefore:

$$T_{new} := \frac{Q_1}{\left(\frac{Q_2}{T_2} + \frac{Q_3}{T_3}\right)}$$

i.e.

$T_{new} = 397.959$ **K .... New source temp for the cycle to be possible (reversible) .. Ans.**

==

Prob.7.12. 1.2 m^3 of air is heated reversibly at constant pressure from 300 K to 600 K and is then cooled reversibly at constant volume back to the initial temp. If the initial pressure is 1 bar, calculate the net heat flow and overall change in entropy. Also, represent the processes on a T-s diagram. Take cp = 1.005 kJ/kg.K and R = 0.287 kJ/kg.K [VTU-BTD-Dec. 2008–Jan. 2009]

Mathcad Solution:

Data:

$P1 := 10^5$ Pa .... initial pressure $T1 := 300$ K....initial temp $V1 := 1.2$ m^3...initial vol.

$T2 := 600$ K ... high temp after process 1-2 $P2 := P1$ $T3 := T1$

$cp := 1005$ J/kg.K .... sp. heat $R := 287$ J/kg.K .... Gas const.

Therefore, $cv := cp - R$ since $cp - cv = R$

i.e. $cv = 718$ J/kg.K

Calculations:

$m := \frac{P1 \cdot V1}{R \cdot T1}$ ....mass of air, by Gas Law

i.e. $m = 1.394$ kg

Process 1-2 at constant volume:

$\frac{P1 \cdot V1}{T1} = \frac{P2 \cdot V2}{T2}$ ....from Ideal gas law. Here, P2 = P1

Then:

$V2 := \frac{V1}{T1} \cdot T2$

i.e. $V2 = 2.4$ m^3 .... volume after process 1-2

For heat flow in Process 1-2:

From I Law for a closed system:

$Q1 = \Delta U + W$

Now, $W := P1 \cdot (V2 - V1)$ i.e. $W = 1.2 \times 10^5$ J....work done

and: $\Delta U := m \cdot cv \cdot (T2 - T1)$

i.e. $\Delta U = 3.002 \times 10^5$ J.... change in Internal energy

And:. $Q1 := \Delta U + W$

or: $Q1 = 4.202 \times 10^5$ **J..+ve, i.e. heat is supplied**

For heat flow in Process 2-3:

Process 2-3 is at constant volume V2. i.e. V3 = V2.

We have: $V3 := V2$

Apply I Law to process 2-3:

$$Q2 = \Delta U + W$$

W = 0 since it is a const. vol. process.

Therefore,

$$Q2 = \Delta U = m \cdot cv \cdot (T3 - T2)$$

i.e. $Q2 := m \cdot cv \cdot (T3 - T2)$

i.e. $Q2 = -3.002 \times 10^{5}$ **J.... heat rej.. in process 2-3.. rejected since -ve.**

Therefore, net heat transfer Qnet:

$$Q_{net} := Q1 + Q2$$

i.e. $Q_{net} = 1.2 \times 10^{5}$ **J .....net heat transfer while going from State 1 to State 3....Ans.**

Entropy changes:

ΔS in process 1-2 at const. pressure:

We have:

$$s_2 - s_1 = c_p \cdot \ln\left(\frac{T_2}{T_1}\right) - R \cdot \ln\left(\frac{P_2}{P_1}\right) \qquad \text{....eqn. 7.16, a}$$

i.e. $\Delta S_{12} := m \cdot cp \cdot \ln\left(\frac{T2}{T1}\right)$

i.e. $\Delta S_{12} = 970.889$ **J/K......entropy change from State 1 to 2 ...Ans.**

ΔS in process 2-3 at const. volume:

We have:

$$s_3 - s_2 = c_v \cdot \ln\left(\frac{T3}{T2}\right) + R \cdot \ln\left(\frac{v3}{v2}\right) \qquad \text{....eqn. 7.15, a}$$

i.e. $\Delta S_{23} := m \cdot cv \cdot \ln\left(\frac{T3}{T2}\right)$

i.e. $\Delta S_{23} = -693.63$ **J/K......entropy change from State 2 to 3 ...Ans..**

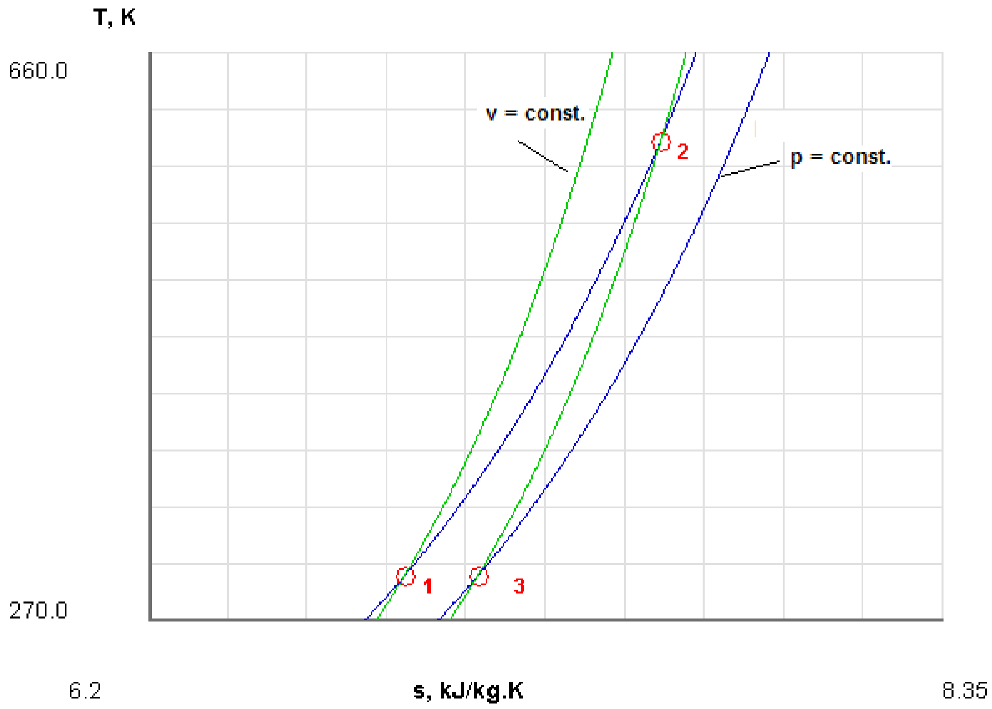
Therefore, net entropy change while going from State 1 to State 3:

$\Delta S_{net} := \Delta S_{12} + \Delta S_{23}$

i.e. $\Delta S_{net} = 277.259$ **J/K ...net entropy change ... Ans.**

T-s diagram:

Processes 1–2 (const. pressure) and 2–3 (const. volume) are plotted on a T-s diagram using TEST:



Note that s3 > s1 i.e. (s3 – s1) is +ve.

===

Prob.7.13. A 5 kg copper block at a temp of 200 C is dropped in to an insulated tank containing 100 kg of oil at a temp of 30 C. Find the increase in the entropy of the universe due to this process when the copper block and the oil reach thermal equilibrium. Assume sp. heats of copper and oil are 0.4 kJ/kg.K and 2.1 kJ/kg.K respectively. [VTU-BTD-July 2006]

Mathcad Solution:

Data:

$m_{cu} := 5$ kg $\quad m_{oil} := 100$ kg $\quad cp_{cu} := 0.4$ kJ/kg.K $\quad cp_{oil} := 2.1$ kJ/kg.K

$T_{cu} := 200 + 273$ K $\quad T_{oil} := 30 + 273$ K

Calculations:

Let the final equilibrium temp be T_f.

Then, by an energy balance:

$$m_{cu}\cdot cp_{cu}\cdot\left(T_{cu}-T_f\right) = m_{oil}\cdot cp_{oil}\cdot\left(T_f-T_{oil}\right)$$

i.e. $$T_f := \frac{m_{cu}\cdot cp_{cu}\cdot T_{cu}+m_{oil}\cdot cp_{oil}\cdot T_{oil}}{m_{oil}\cdot cp_{oil}+m_{cu}\cdot cp_{cu}}$$

i.e. $T_f = 304.604$ **K ...equilibrium temp.**

Entropy changes:

$\Delta S_{cu} := m_{cu} \cdot cp_{cu} \cdot \ln\left(\frac{T_f}{T_{cu}}\right)$ **kJ/K .... entropy change of copper while cooling from T_{cu} to T_f**

i.e. $\Delta S_{cu} = -0.88$ kJ/K

$\Delta S_{oil} := m_{oil} \cdot cp_{oil} \cdot \ln\left(\frac{T_f}{T_{oil}}\right)$ **kJ/K .... entropy change of oil while heating from T_{oil} to T_f**

i.e. $\Delta S_{oil} = 1.109$ kJ/K

Therefore net entropy change of the system of (copper + oil):

$\Delta S_{sys} := \Delta S_{cu} + \Delta S_{oil}$ **kJ/K .... entropy change of system of (copper + oil)**

i.e. $\Delta S_{sys} = 0.228$ **kJ/K..... note that this is +ve**

Entropy change of the universe:

$\Delta S_{universe} = \Delta S_{sys} + \Delta S_{surr}$ where $\Delta S_{surr} = 0$ since the system is insulated.

Therefore:

$\Delta S_{universe} := \Delta S_{sys} + 0$

i.e. $\Delta S_{universe} = 0.228$ **kJ/K .... entropy change ofuniverse (i.e. system + surr.)... Ans.**

===

Prob.7.14. 1 kg of water at 273 K is brought in to contact with a heat reservoir at 373 K. When water has reached 373 K, find the entropy change of water, of the heat reservoir and of the universe. [VTU-BTD-June–July 2008]

Mathcad Solution:

Data:

$T_1 := 273$ K $T_2 := 373$ K $m := 1$ kg $cp := 4.18$ kJ/kg.K

Calculations:

Note that water gets heated and its temp increases, and the entropy also increases.

The reservoir loses heat, but its temp remains const, and its entropy decreases.

Net entropy change for (water + reservoir) will be +ve since the process is irreversible.

Entropy change of water:

$\Delta S_{water} := m \cdot cp \cdot \ln\left(\frac{T_2}{T_1}\right)$ kJ/K.... entropy change of water

i.e. $\Delta S_{water} = 1.305$ kJ/K

Heat supplied to water by the reservoir:

$Q := m \cdot cp \cdot (T_2 - T_1)$ kJ

i.e. $Q = 418$ kJ

Therefore, entropy change of reservoir:

$\Delta S_{res} := \frac{-Q}{T_2}$ kJ/K

i.e. $\Delta S_{res} = -1.121$ kJ/K

Therefore, entropy change of universe:

$\Delta S_{univ} := \Delta S_{water} + \Delta S_{res}$ kJ/K

i.e. $\Delta S_{univ} = 0.184$ **kJ/K....... Ans.**

==

Prob.7.15. 1 kg of ice at -5 C is exposed to atmosphere, which is at 20 C. The ice melts and comes into thermal equilibrium with the atmosphere. Determine the entropy increase of the universe. Take cp of ice = 2.093 kJ/kg.K and latent heat of fusion of ice = 334 kJ/kg. [VTU-BTD- May–June, 2010]

Mathcad Solution:

Data:

$T_1 := -5 + 273$ K $\quad m := 1$ kg $\quad cp_w := 4.187$ kJ/kg.K

$cp_{ice} := 2.093$ kJ/kg.K $\quad T_2 := 20 + 273$ K $\quad h_{fg} := 334$ kJ/kg

Calculations:

Note that ice gets warmed up to zero degree C, melts using the latent heat of fusion in to water at zero deg. C and then this water warms up to 20 deg. C. Entropy increases in these stages.

The reservoir (atmosphere) loses heat, but its temp remains const, and its entropy decreases.

Net entropy change for (water + reservoir) will be +ve since the process is irreversible.

Heat supplied to Ice by the reservoir:

$$Q := m\cdot\left[cp_{ice}\cdot(273 - T_1) + h_{fg} + cp_w\cdot(T_2 - 273)\right] \quad \text{kJ}$$

i.e. $Q = 428.205$ kJ

Entropy change of Ice as it warms to water at zero deg. C:

$$\Delta S_1 := m\cdot cp_{ice}\cdot\ln\left(\frac{273}{T_1}\right)$$ kJ/K.... entropy change of water

i.e. $\Delta S_1 = 0.039$ kJ/K

Entropy change of water melting in to ice at 273 K:

$$\Delta S_2 := \frac{m\cdot h_{fg}}{273}$$ kJ/K.... entropy change during melting at const. temp of 273 K

i.e. $\Delta S_2 = 1.223$ kJ/K

Entropy change of water as it warms from zero deg. C to 20 C:

$$\Delta S_3 := m\cdot cp_w\cdot\ln\left(\frac{T_2}{273}\right)$$ kJ/K.... entropy change of water

i.e. $\Delta S_3 = 0.296$ kJ/K

Therefore, total entropy change of system (i.e. Ice/water):

$$\Delta S_{sys} := \Delta S_1 + \Delta S_2 + \Delta S_3$$

i.e. $\Delta S_{sys} = 1.558$ **kJ/K .... total entropy change of system**

Now, entropy change of reservoir:

$$\Delta S_{res} := \frac{-Q}{T_2}$$ kJ/K

i.e. $\Delta S_{res} = -1.461$ kJ/K

Therefore, entropy change of universe:

$\Delta S_{univ} := \Delta S_{sys} + \Delta S_{res}$ kJ/K

i.e. $\Delta S_{univ} = 0.097$ **kJ/K....... Ans.**

===

Prob.7.16. Refrigerant 134a is throttled from 1200 kPa, 40 C to 200 kPa. Heat is lost from the refrigerant in the amount of 0.5 kJ/kg to surroundings at 25 C. Determine: (i) the exit temp of the refrigerant, and (ii) the entropy generation during this process. [Ref: 1]

Mathcad Solution:

Data:

$m := 1$ kg $P_1 := 1200$ kPa $P_2 := 200$ kPa $T_1 := 40$ C $T_{surr} := 25 + 273$ K

$q := 0.5$ kJ/kg

Properties of R134a, from EES:

$h_1 := 108.2$ kJ/kg $s_1 := 0.394$ kJ/kg.K

Applying the I Law to the flow system, we have, with usual notations:

$$q - w = \Delta h + \Delta ke + \Delta pe$$

Here, Δke = 0, Δpe = 0, w = 0 and q = - 0.5 kJ/kg. negative since heat is flowing out.

i.e. $-0.5 - 0 = h_2 - h_1$

Therefoe, $h_2 := h_1 - 0.5$

i.e. $h_2 = 107.7$ kJ/kg

With h2 = 107.7 kJ/kg and P2 = 200 kPa, find the temp, T2 after the throttling, using EES:

$T_2 := -10.1$ **C....temp after throttling .. Ans.**

and, $s_2 := 0.418$ kJ/kg.K

Entropy generation:

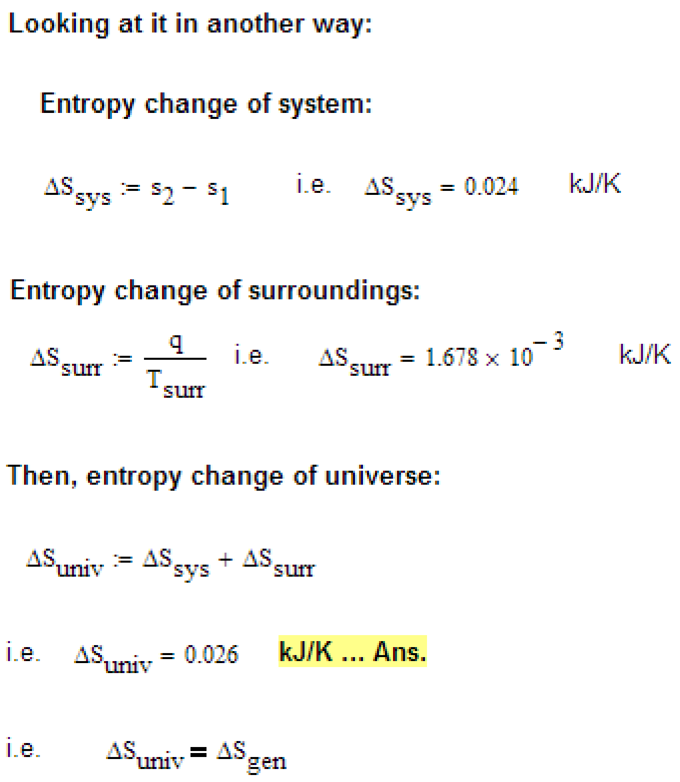
For Steady Flow system, we have the Entropy balance equation:

$$\mathrm{Sdot}_{in} - \mathrm{Sdot}_{out} + \mathrm{Sdot}_{gen} = 0$$

i.e. $$m \cdot s_1 - m \cdot s_2 - \frac{q}{T_{surr}} + \mathrm{Sdot}_{gen} = 0$$

i.e. $$\mathrm{Sdot}_{gen} := m \cdot s_2 - m \cdot s_1 + \frac{q}{T_{surr}}$$

i.e. $\mathrm{Sdot}_{gen} = 0.026$ kJ/K ... Ans.



Looking at it in another way:

Entropy change of system:

$\Delta S_{sys} := s_2 - s_1$ i.e. $\Delta S_{sys} = 0.024$ kJ/K

Entropy change of surroundings:

$\Delta S_{surr} := \frac{q}{T_{surr}}$ i.e. $\Delta S_{surr} = 1.678 \times 10^{-3}$ kJ/K

Then, entropy change of universe:

$\Delta S_{univ} := \Delta S_{sys} + \Delta S_{surr}$

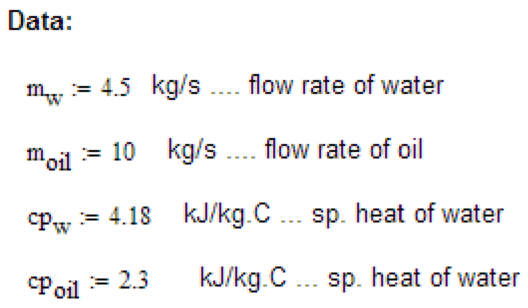
i.e. $\Delta S_{univ} = 0.026$ **kJ/K ... Ans.**

i.e. $\Delta S_{univ} = \Delta S_{gen}$

==

Prob.7.17. A well insulated Shell & Tube heat exchanger is used to heat water (cp = 4.18 kJ/kg.C) in the tubes from 20 to 70 C at a rate of 4.5 kg/s. Heat is supplied by hot oil (cp = 2.3 kJ/kg.C) that enters the shell side at 170 C at a rate of 10 kg/s. Disregarding any heat loss from the heat exchanger, determine: (i) the exit temp of the oil, and (ii) the rate of entropy generation in the heat exchanger. [Ref: 1]

Mathcad Solution:



Data:

$m_w := 4.5$ kg/s .... flow rate of water

$m_{oil} := 10$ kg/s .... flow rate of oil

$cp_w := 4.18$ kJ/kg.C ... sp. heat of water

$cp_{oil} := 2.3$ kJ/kg.C ... sp. heat of water

$T_{w1} := 20$ C... inlet temp of water

$T_{w2} := 70$ C... exit temp of water

$T_{oil1} := 170$ C... inlet temp of oil

Let T_oil2 be the exit temp of oil

Calculations:

Exit temp of oil is found out by making a heat balance:

$$m_w \cdot cp_w \cdot (T_{w2} - T_{w1}) = m_{oil} \cdot cp_{oil} \cdot (T_{oil1} - T_{oil2})$$

Then, exit temp of oil is given by:

$$T_{oil2} := T_{oil1} - \frac{m_w \cdot cp_w \cdot (T_{w2} - T_{w1})}{m_{oil} \cdot cp_{oil}}$$

i.e. $T_{oil2} = 129.109$ **C .... exit temp of oil .... Ans.**

To find the entropy changes:

Entropy change (increase) of water:

$$\Delta S_w := m_w \cdot cp_w \cdot \ln\left(\frac{T_{w2} + 273}{T_{w1} + 273}\right) \quad \text{kJ/K}$$

i.e. $\Delta S_w = 2.964$ kJ/K

Entropy change (decrease) of oil:

$$\Delta S_{oil} := m_{oil} \cdot cp_{oil} \cdot \ln\left(\frac{T_{oil2} + 273}{T_{oil1} + 273}\right) \quad \text{kJ/K}$$

i.e. $\Delta S_{oil} = -2.227$ kJ/K

Therefore, net entropy change in the heat exchanger (system):

$\Delta S_{sys} := \Delta S_w + \Delta S_{oil}$ kJ/K

i.e. $\Delta S_{sys} = 0.736$ kJ/K

Entropy change of surroundings:

$\Delta S_{surr} := 0$ since the HX is insulated, Q = 0

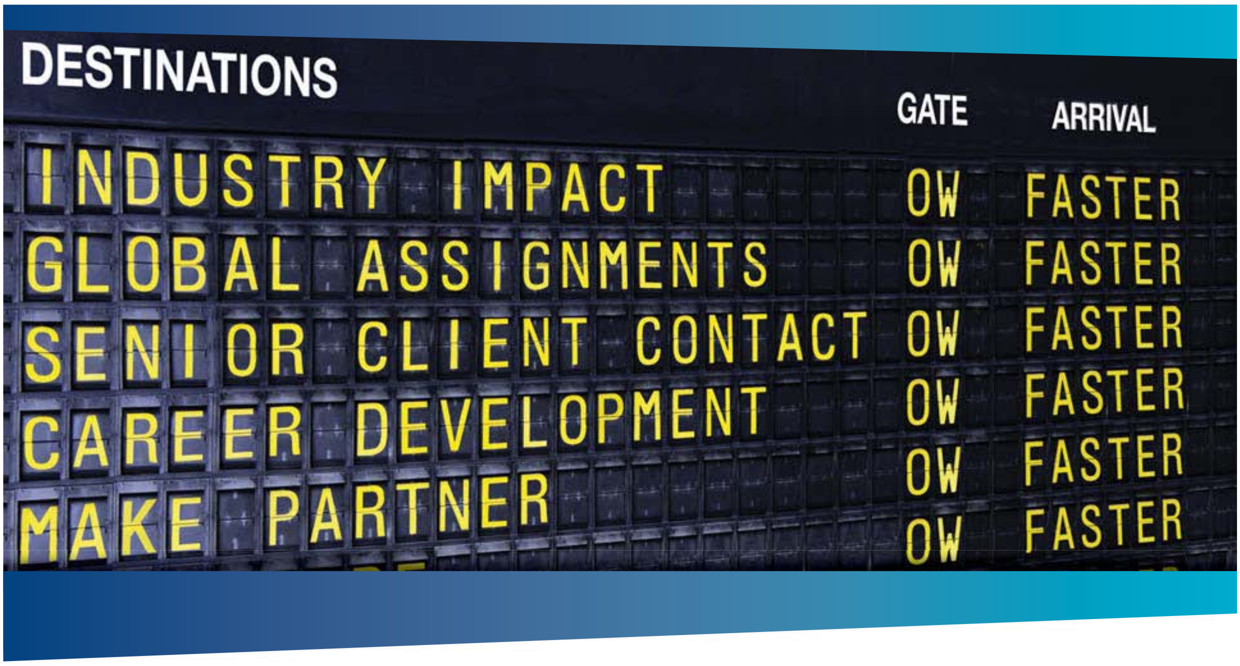
Therefore, entropy change of universe:

$\Delta S_{univ} := \Delta S_{sys} + \Delta S_{surr}$ kJ/K

i.e. $\Delta S_{univ} = 0.736$ **kJ/K ...... Ans.**

Note: $S_{gen} = \Delta S_{univ}$

===



7.4 Problems solved with The Expert System for Thermodynamics (TEST):

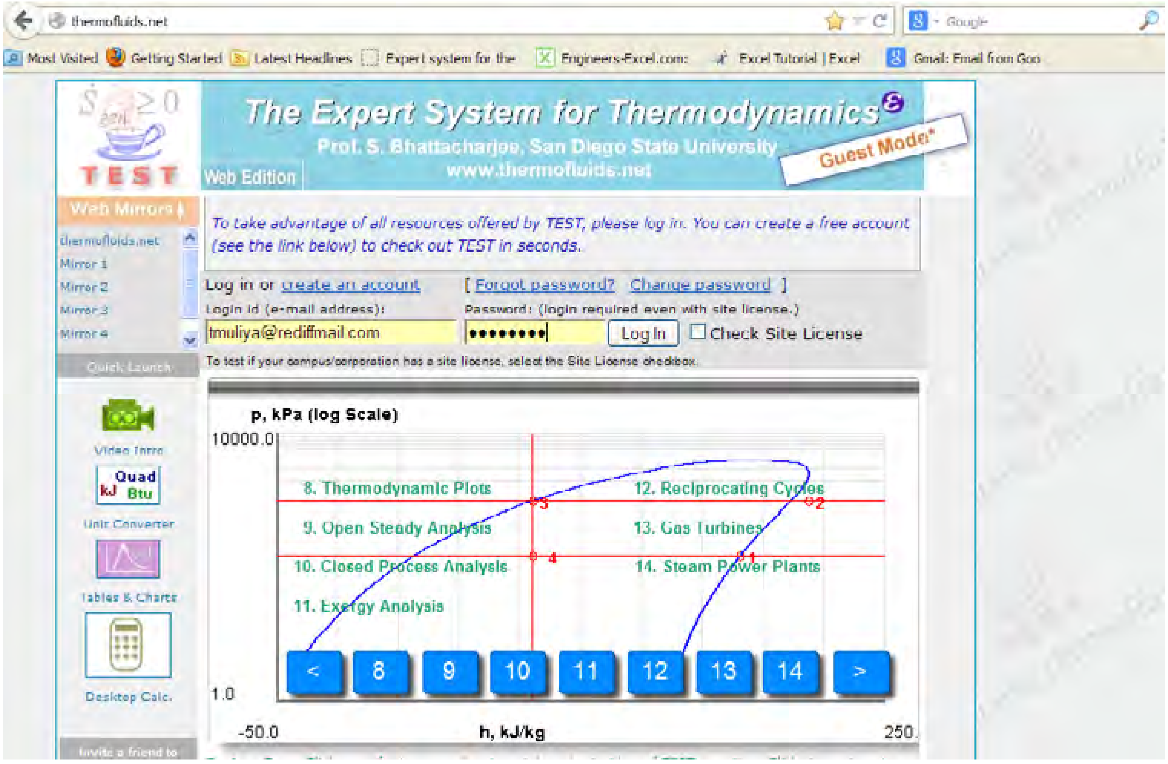
Prob.7.18. 1.2 m^3 of air is heated reversibly at constant pressure from 300 K to 600 K and is then cooled reversibly at constant volume back to the initial temp. If the initial pressure is 1 bar, calculate the net heat flow and overall change in entropy. Also, represent the processes on a T-s diagram. Take cp = 1.005 kJ/kg.K and R = 0.287 kJ/kg.K [VTU-BTD-June-July 2009]

Note: This is the same as Prob.7.12, solved with Mathcad.

TEST Solution:

Following are the steps:

1. Go to www.thermofluids.net. Following screen appears.



To take advantage of all resources offered by TEST, please log in. You can create a free account (see the link below) to check out TEST in seconds.

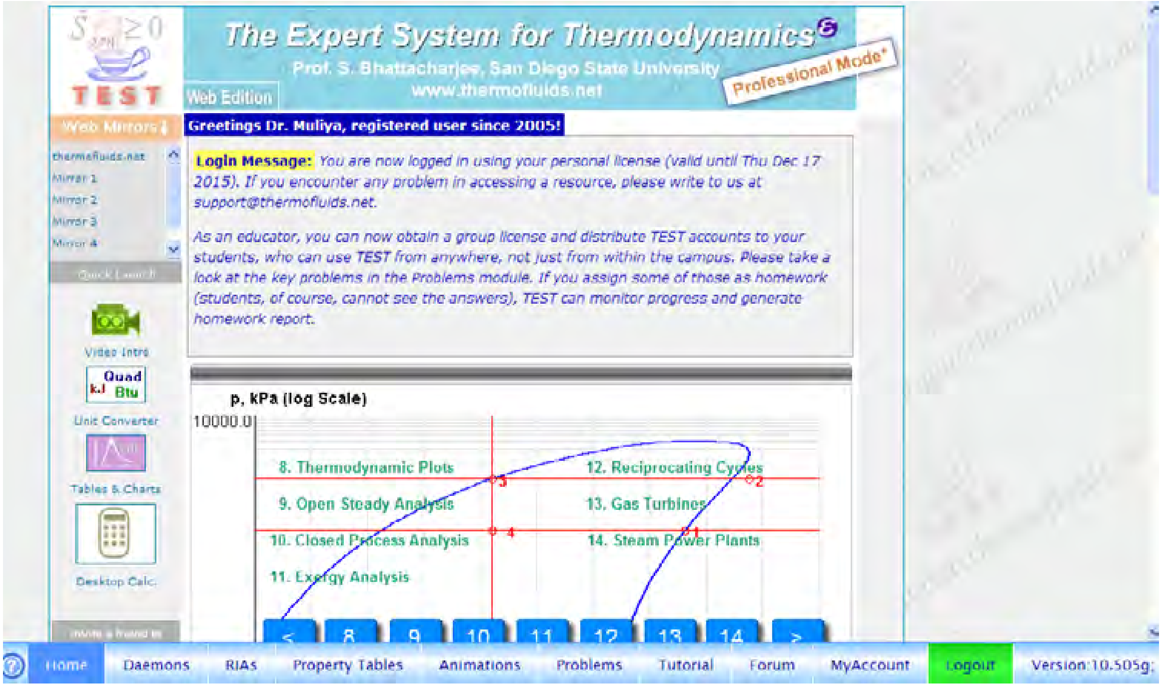
Log in or create an account [Forgot password? Change password]

Login id (e-mail address): tmuliya@rediffmail.com

Password: (login required even with site license.) ••••••••

To test if your campus/corporation has a site license, select the Site License checkbox.

2. Enter the e-mail address and password, press Enter, and following greeting screen appears:

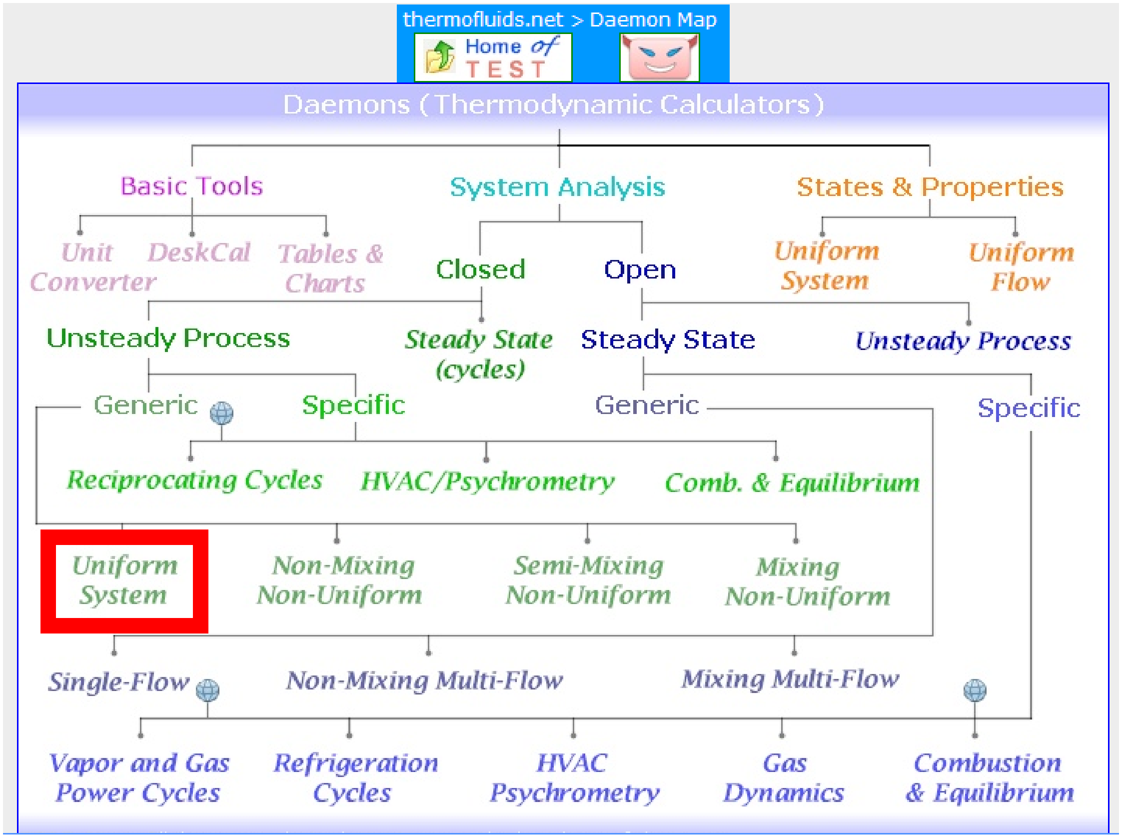


Greetings Dr. Muliya, registered user since 2005!

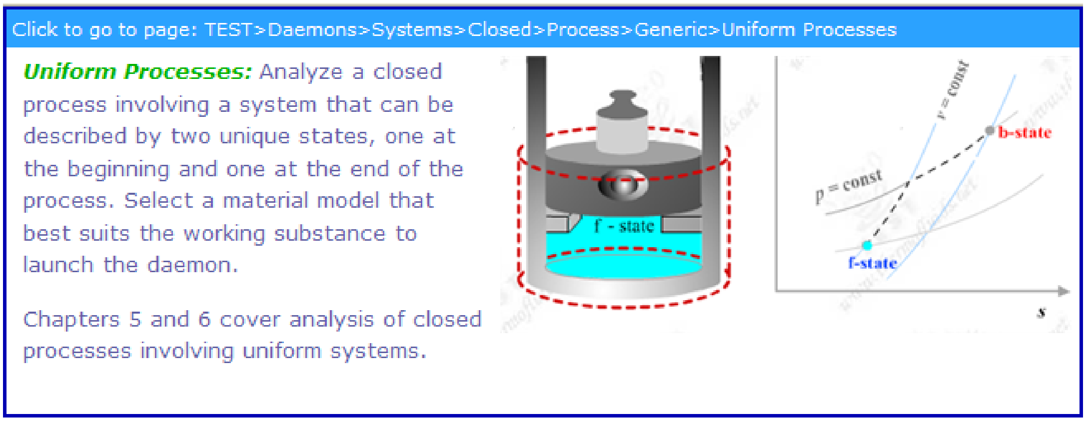
Login Message: *You are now logged in using your personal license (valid until Thu Dec 17 2015). If you encounter any problem in accessing a resource, please write to us at support@thermofluids.net.*

As an educator, you can now obtain a group license and distribute TEST accounts to your students, who can use TEST from anywhere, not just from within the campus. Please take a look at the key problems in the Problems module. If you assign some of those as homework (students, of course, cannot see the answers), TEST can monitor progress and generate homework report.

3. Click on Daemons tab, at the bottom of above screen. We get:



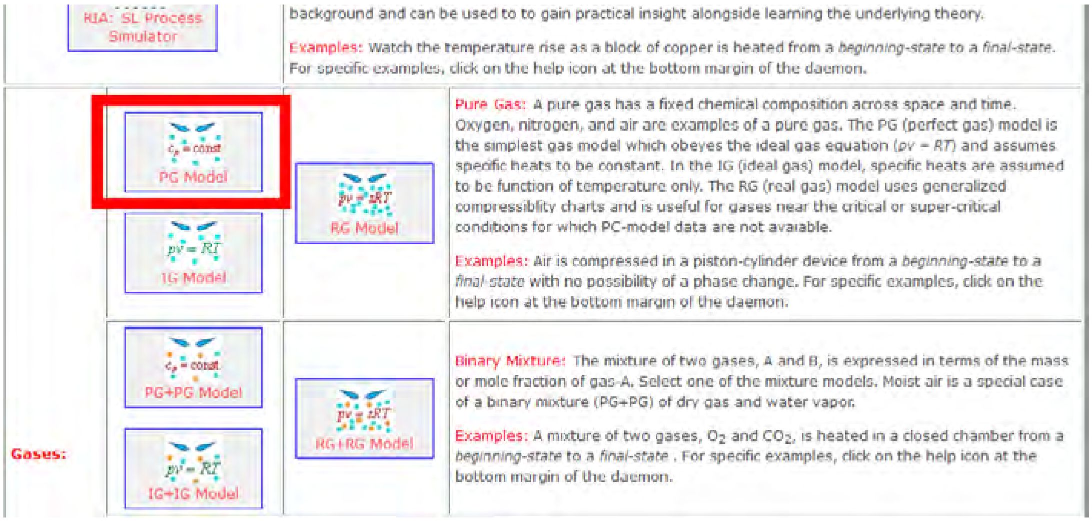
4. Hover the mouse pointer on System Analysis-Closed-Generic-Uniform System (marked above). We get the pop-up:


Click to go to page: TEST>Daemons>Systems>Closed>Process>Generic>Uniform Processes

Uniform Processes: Analyze a closed process involving a system that can be described by two unique states, one at the beginning and one at the end of the process. Select a material model that best suits the working substance to launch the daemon.

Chapters 5 and 6 cover analysis of closed processes involving uniform systems.

5. Click on Uniform System, and we get the following for material model selection:



background and can be used to to gain practical insight alongside learning the underlying theory.

Examples: Watch the temperature rise as a block of copper is heated from a *beginning-state* to a *final-state*. For specific examples, click on the help icon at the bottom margin of the daemon.

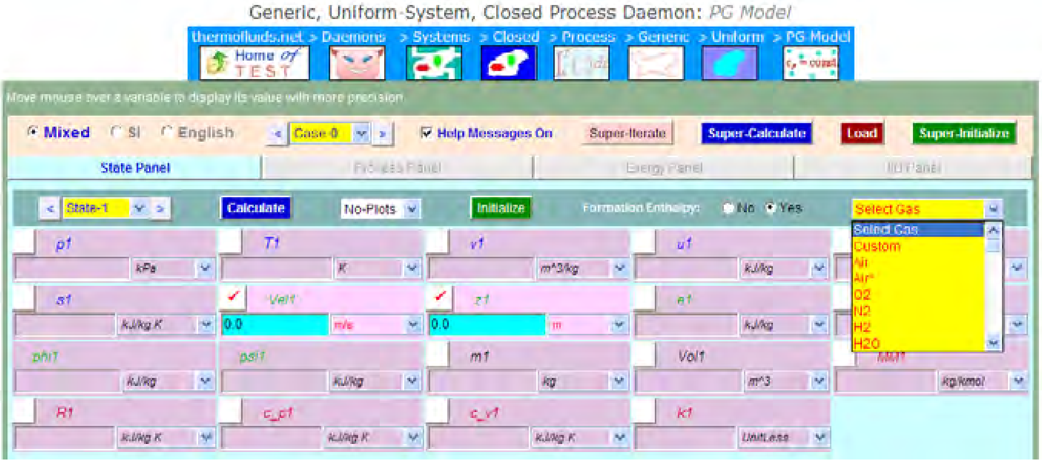
Pure Gas: A pure gas has a fixed chemical composition across space and time. Oxygen, nitrogen, and air are examples of a pure gas. The PG (perfect gas) model is the simplest gas model which obeys the ideal gas equation ($pv = RT$) and assumes specific heats to be constant. In the IG (ideal gas) model, specific heats are assumed to be function of temperature only. The RG (real gas) model uses generalized compressiblity charts and is useful for gases near the critical or super-critical conditions for which PC-model data are not avaiable.

Examples: Air is compressed in a piston-cylinder device from a *beginning-state* to a *final-state* with no possibility of a phase change. For specific examples, click on the help icon at the bottom margin of the daemon.

Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: A mixture of two gases, O_2 and CO_2, is heated in a closed chamber from a *beginning-state* to a *final-state* . For specific examples, click on the help icon at the bottom margin of the daemon.

6. Select the PG Model as shown above, and we get:


Generic, Uniform-System, Closed Process Daemon: *PG Model*

thermofluids.net > Daemons > Systems > Closed > Process > Generic > Uniform > PG Model

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English · Case-0 · ☑ Help Messages On

Formation Enthalpy: ○ No ● Yes

Select Gas: Select Gas, Custom, Air, Air*, O2, N2, H2, H2O

Vel1: 0.0 m/s · z1: 0.0 m

7. Select Air as the substance, as shown in the above screen. We get the following screen. Enter for State 1 values for P1, T1, Vol1 as shown and click on Calculate (or, press Enter). We get:


Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English · Case 0 · ☑ Help Messages On

@State-1 · No-Plots · Formation Enthalpy: ○ No ● Yes · Air

✓ p1: 100.0 kPa
✓ T1: 300.0 K
v1: 0.86096 m^3/kg
u1: -84.2395 kJ/kg
h1: 1.85646 kJ/kg
s1: 6.8929 kJ/kg.K
✓ Vel1: 0.0 m/s
✓ z1: 0.0 m
e1: -84.2395 kJ/kg
j1: 1.85646 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
m1: 1.39379 kg
✓ Vol1: 1.2 m^3
MM1: 28.97 kg/kmol
R1: 0.28699 kJ/kg.K
c_p1: 1.00349 kJ/kg.K
c_v1: 0.71651 kJ/kg.K
k1: 1.40054 UnitLess

Note in the above screen that other parameters such as m1, s1 u1, h1 etc for State 1 are immediately calculated.

8. Now, select State 2, and enter values for P2 = P1, T2 = 600 K, m2 = m1 and click enter. Immediately all other parameters for State 2 are calculated:

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

@State-2

No Plots

Formation Enthalpy: ○ No ● Yes

Air

☑ p2: =p1 kPa

☑ T2: 600.0 K

☐ v2: 1.72192 m^3/kg

☐ u2: 130.71274 kJ/kg

☐ h2: 302.90466 kJ/kg

☐ s2: 7.58847 kJ/kg.K

☑ Vel2: 0.0 m/s

☑ z2: 0.0 m

☐ e2: 130.71274 kJ/kg

☐ j2: 302.90466 kJ/kg

phi2: kJ/kg

psi2: kJ/kg

☑ m2: =m1 kg

☐ Vol2: 2.4 m^3

MM2: 28.97 kg/kmol

R2: 0.28699 kJ/kg.K

c_p2: 1.00349 kJ/kg.K

c_v2: 0.71651 kJ/kg.K

k2: 1.40054 UnitLess

9. Similarly, select State 3, enter T3= T1, v3 = v2, m3 = m2 and press Enter. We get:

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

@State-3

No-Plots

Formation Enthalpy: ○ No ● Yes

Air

☐ p3: 50.0 kPa

☑ T3: =T1 K

☑ v3: =v2 m^3/kg

☐ u3: -84.2395 kJ/kg

☐ h3: 1.85646 kJ/kg

☐ s3: 7.09102 kJ/kg.K

☑ Vel3: 0.0 m/s

☑ z3: 0.0 m

☐ e3: -84.2395 kJ/kg

☐ j3: 1.85646 kJ/kg

phi3: kJ/kg

psi3: kJ/kg

☑ m3: =m2 kg

☐ Vol3: 2.4 m^3

MM3: 28.97 kg/kmol

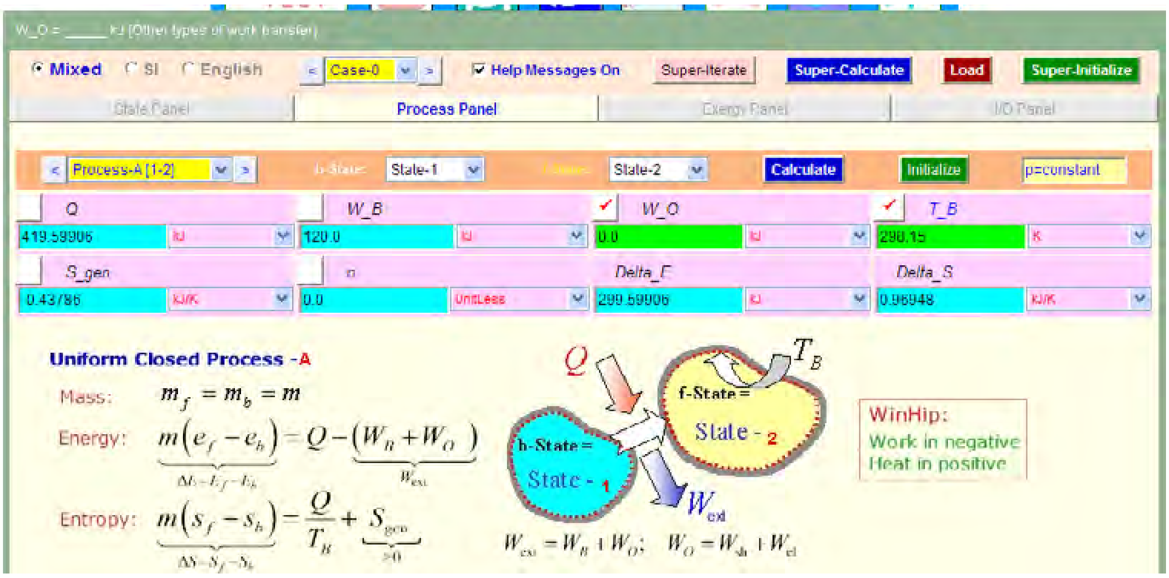
R3: 0.28699 kJ/kg.K

c_p3: 1.00349 kJ/kg.K

c_v3: 0.71651 kJ/kg.K

k3: 1.40054 UnitLess

10. Now, go to Process panel. For Process A (1–2), enter State 1 for b-State and State 2 for f-State (i.e. begin and finish States). Enter zero for W_O (i.e. other work… means… other than Boundary work or Pdv work). Click on Calculate; we get:



b-State: State-1; f-State: State-2

☐ Q	☐ W_B	✓ W_O	✓ T_B
419.59906 kJ	120.0 kJ	0.0 kJ	298.15 K
☐ S_gen	☐ n	Delta_E	Delta_S
0.43786 kJ/K	0.0 UnitLess	299.59906 kJ	0.96948 kJ/K

Uniform Closed Process -A

Mass: $m_f = m_b = m$

Energy: $\underbrace{m(e_f - e_b)}_{\Delta E = E_f - E_b} = Q - \underbrace{(W_B + W_O)}_{W_{ext}}$

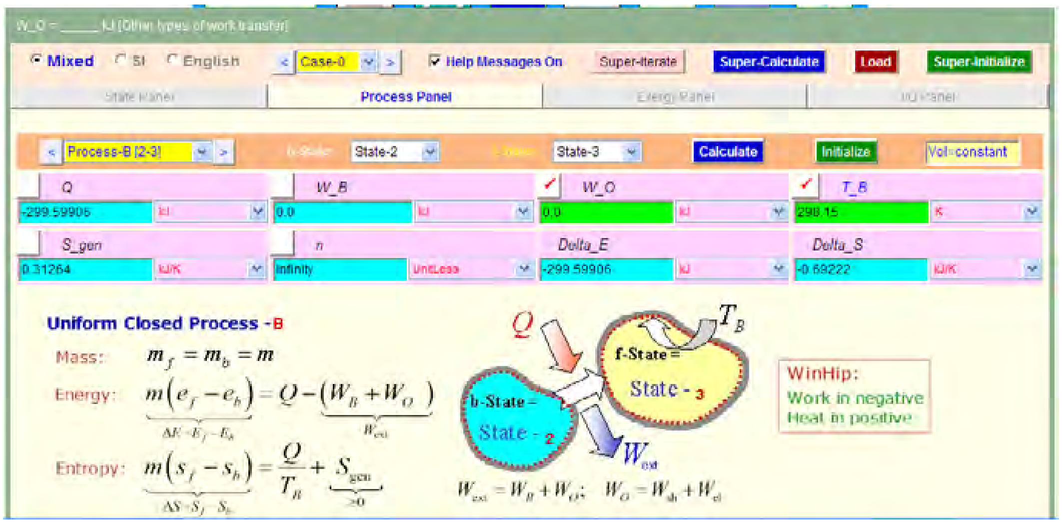
Entropy: $\underbrace{m(s_f - s_b)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{gen}}_{\geq 0}$

$W_{ext} = W_B + W_O; \quad W_O = W_{sh} + W_{el}$

WinHip:
Work in negative
Heat in positive

Note from the above screen that heat transfer Q and work W_B (i.e. boundary work), and change in entropy for process 1–2 are immediately calculated.

11. Now, in the Process panel, select the Process B (2–3), enter State 2 for b-State and State 3 for f-State and enter W_O = 0, and hit Enter. We get:



W_O = _____ kJ [Other types of work transfer]

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

Process-B [2-3]

b-State: State-2

f-State: State-3

Vol=constant

Q: -299.59906 kJ

W_B: 0.0 kJ

✓ W_O: 0.0 kJ

✓ T_B: 298.15 K

S_gen: 0.31264 kJ/K

n: Infinity UnitLess

Delta_E: -299.59906 kJ

Delta_S: -0.69222 kJ/K

Uniform Closed Process - B

Mass: $m_f = m_b = m$

Energy: $m\underbrace{(e_f - e_b)}_{\Delta E = E_f - E_b} = Q - \underbrace{(W_B + W_O)}_{W_{ext}}$

Entropy: $m\underbrace{(s_f - s_b)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{gen}}_{\geq 0}$

$W_{ext} = W_B + W_O$; $W_O = W_{sh} + W_{el}$

WinHip:
Work in negative
Heat in positive

Note again from the above screen that heat transfer Q and work W_B (i.e. boundary work), and change in entropy for process 2-3 are immediately calculated.

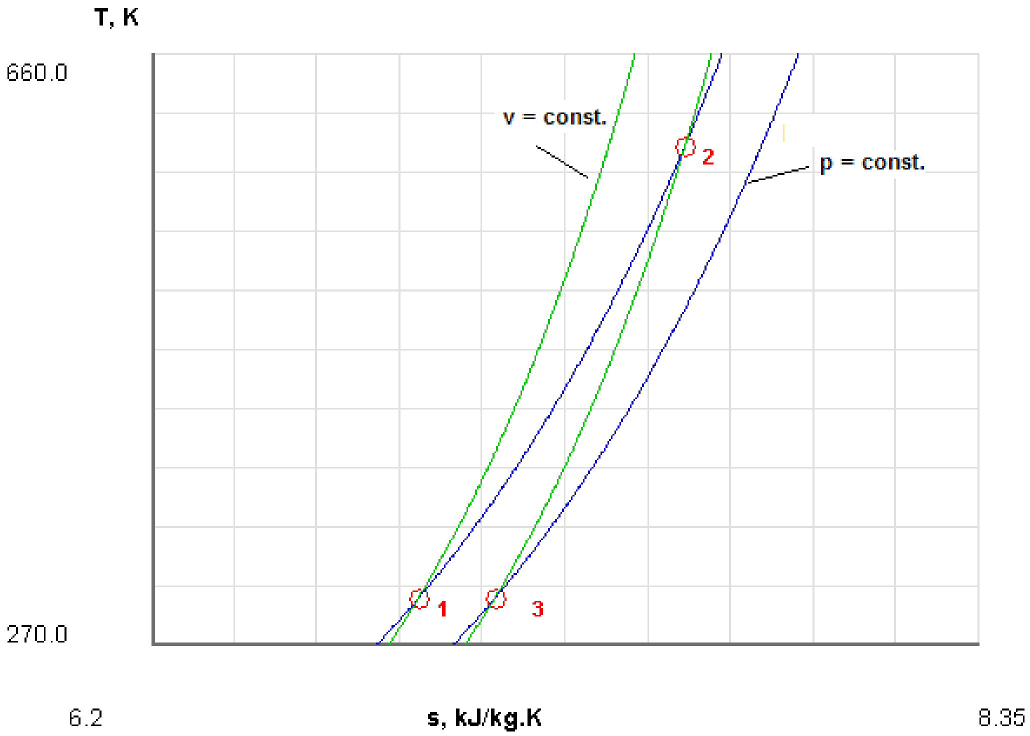
12. Therefore, net heat transfer and net entropy changes are calculated as follows:

Q_net = Q for process 1–2 + Q for process 2–3 = 419.599 – 299.599 = 120 kJ …. Ans.

ΔS_net = Delta_S for process 1–2 + Delta_S for process 2–3 = 0.96948 – 0.69222
= 0.27726 kJ/K …. Ans.

Note: Above values match very well with those obtained in Prob.7.12, using Mathcad.

13. **T-s plot is obtained easily by going to States tab, and choosing T-s plot:**



14. **To get TEST code etc, click on SuperCalculate, and go to I/O panel:**

```
#*******ANALYST: Dr. Muliya; TEST License: Professional*******

#	Solution logged at: Mar 30, 2014 11:02:25 AM

#*******TEST-code: To save the solution, copy the codes generated below into a text file. To reproduce the solution at a later time, launch:

#	Daemon Path: Systems>Closed>Process>Generic>Uniform>PG-Model; v-10.ca08

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

States {
	State-1: Air;
	Given: { p1= 100.0 kPa; T1= 300.0 K; Vel1= 0.0 m/s; z1= 0.0 m; Vol1= 1.2 m^3; }

	State-2: Air;
	Given: { p2= “p1” kPa; T2= 600.0 K; Vel2= 0.0 m/s; z2= 0.0 m; m2= “m1” kg; }
```

```
        State-3: Air;
        Given: { T3= “T1” K; v3= “v2” m^3/kg; Vel3= 0.0 m/s; z3= 0.0 m; m3= “m2” kg; }
        }
Analysis {

        Process-A: b-State = State-1; f-State = State-2;
        Given: { W_O= 0.0 kJ; T_B= 298.15 K; }

        Process-B: b-State = State-2; f-State = State-3;
        Given: { W_O= 0.0 kJ; T_B= 298.15 K; }

        Process-C: b-State = State-3; f-State = State-1;
        Given: { W_O= 0.0 kJ; T_B= 298.15 K; }
        }
#----------------------End of TEST-code ------------------------------------------
```

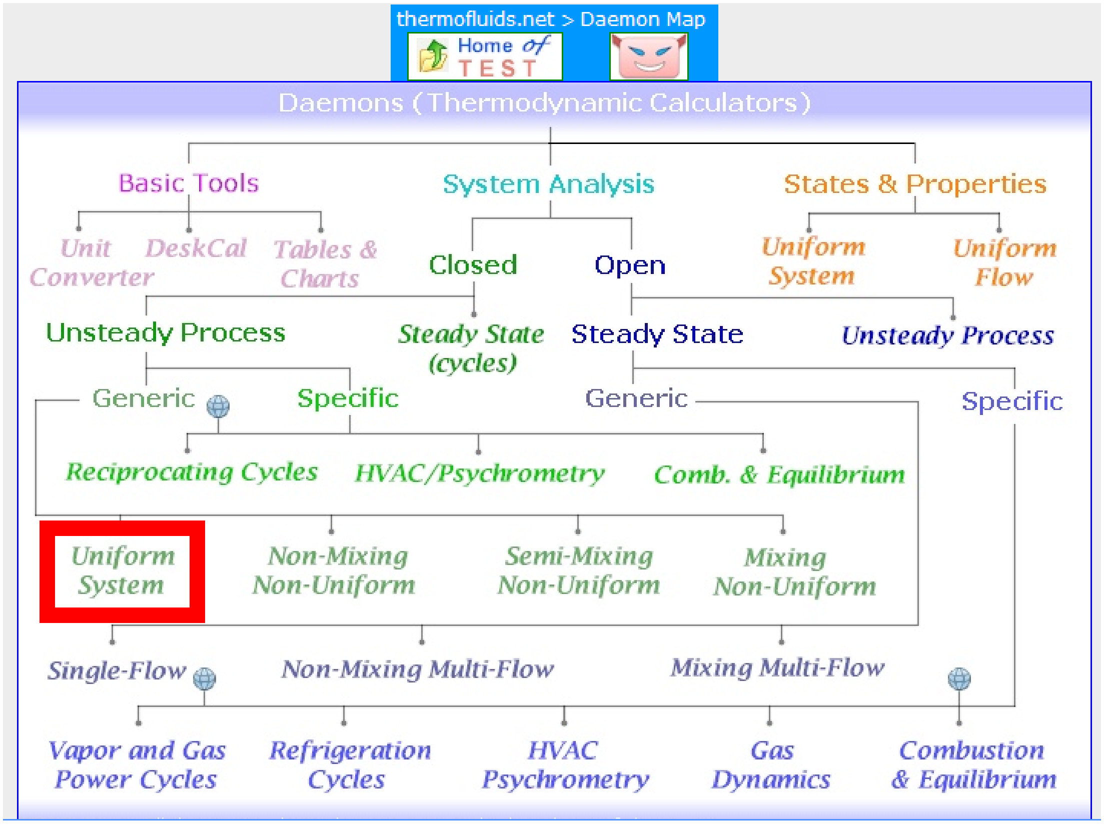
```
#--------Property spreadsheet starts:

#     State    p(kPa)    T(K)     v(m^3/kg)   u(kJ/kg)   h(kJ/kg)   s(kJ/kg)
#      1       100.0     300.0    0.861       -84.24      1.86      6.893
#      2       100.0     600.0    1.7219      130.71      302.9     7.588
#      3       50.0      300.0    1.7219      -84.24      1.86      7.092

# Mass, Energy, and Entropy Analysis Results:
#      Process-A: b-State = State-1; f-State = State-2;
#            Given: W_O= 0.0 kJ; T_B= 298.15 K;
#      Calculated: Q= 419.59906 kJ; W_B= 120.0 kJ; S_gen= -0.43786246 kJ/K; n= 0.0 UnitLess;
#     Delta_E= 299.59906 kJ; Delta_S= 0.9694797 kJ/K;
#
#      Process-B: b-State = State-2; f-State = State-3;
#            Given: W_O= 0.0 kJ; T_B= 298.15 K;
#      Calculated: Q= -299.59906 kJ; W_B= 0.0 kJ; S_gen= 0.31263936 kJ/K; n= Infinity UnitLess;
#     Delta_E= -299.59906 kJ; Delta_S= -0.6922208 kJ/K;
#
#      Process-C: b-State = State-3; f-State = State-1;
#            Given: W_O= 0.0 kJ; T_B= 298.15 K;
#      Calculated: Q= -83.17766 kJ; W_B= -83.17766 kJ; S_gen= 0.001720372 kJ/K; n= 1.0 UnitLess;
#     Delta_E= -0.0 kJ; Delta_S= -0.27725887 kJ/K;
#==================================================================
```

Prob.7.19. Air at 20 C and 1.05 bar occupies 0.025 m^3. The air is heated at constant volume until the pressure is 4.5 bar, and then cooled at constant pressure back to original temp. Calculate: (i) the net heat flow from air, and (ii) the net entropy change. Also, represent the processes on a T-s diagram. [VTU-BTD-Dec. 2007–Jan. 2008]

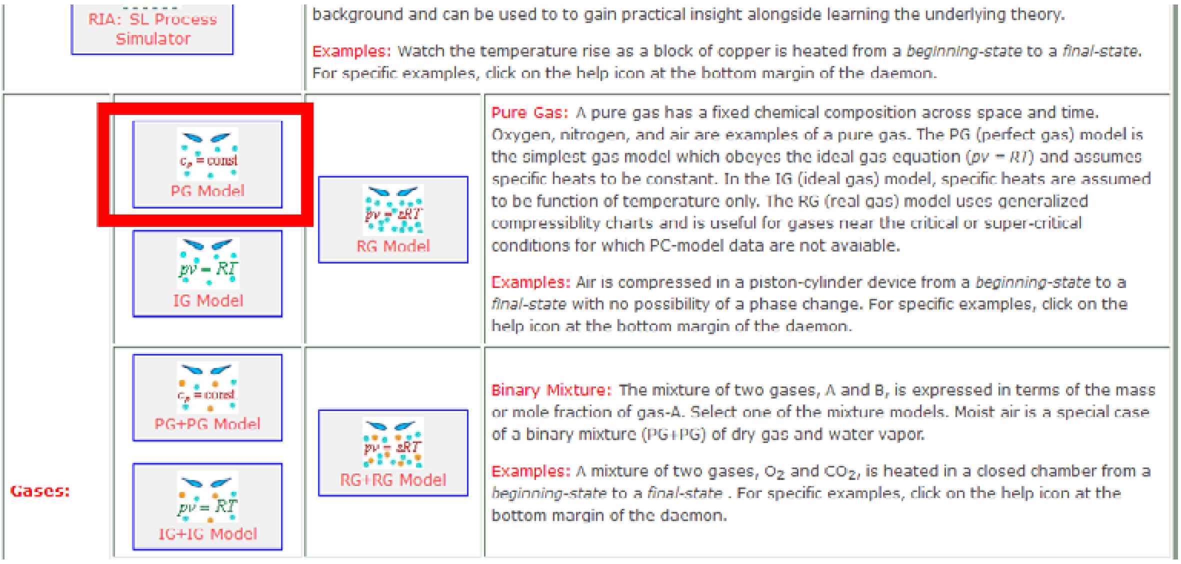
TEST Solution:

Following are the steps:

1. In the Daemons tree, locate the Closed – Uniform System daemon:



2. Click on Uniform System, and we get the following for material model selection:



background and can be used to to gain practical insight alongside learning the underlying theory.

Examples: Watch the temperature rise as a block of copper is heated from a *beginning-state* to a *final-state*. For specific examples, click on the help icon at the bottom margin of the daemon.

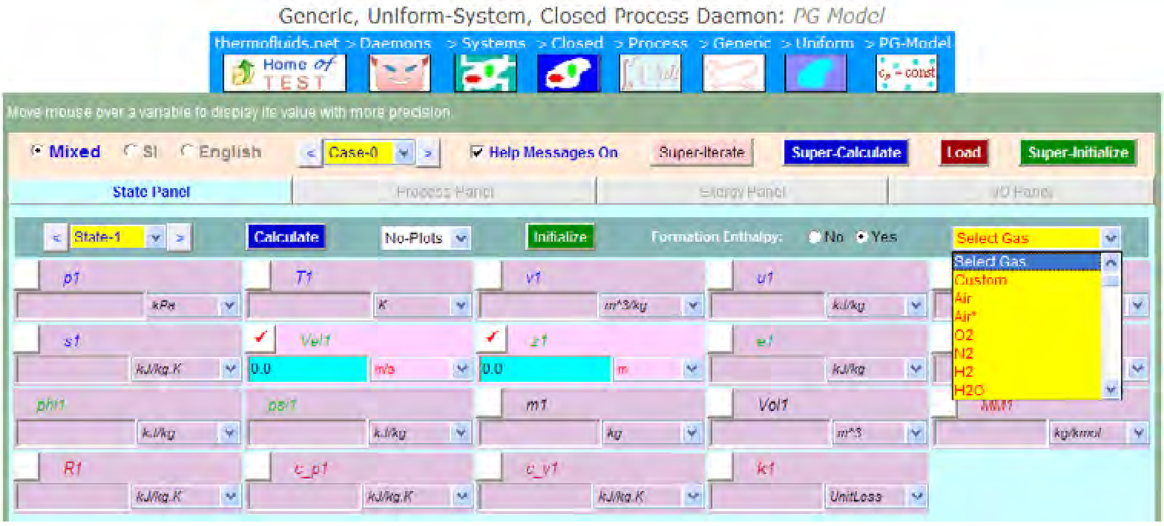
Pure Gas: A pure gas has a fixed chemical composition across space and time. Oxygen, nitrogen, and air are examples of a pure gas. The PG (perfect gas) model is the simplest gas model which obeyes the ideal gas equation ($pv = RT$) and assumes specific heats to be constant. In the IG (ideal gas) model, specific heats are assumed to be function of temperature only. The RG (real gas) model uses generalized compressiblity charts and is useful for gases near the critical or super-critical conditions for which PG-model data are not avaiable.

Examples: Air is compressed in a piston-cylinder device from a *beginning-state* to a *final-state* with no possibility of a phase change. For specific examples, click on the help icon at the bottom margin of the daemon.

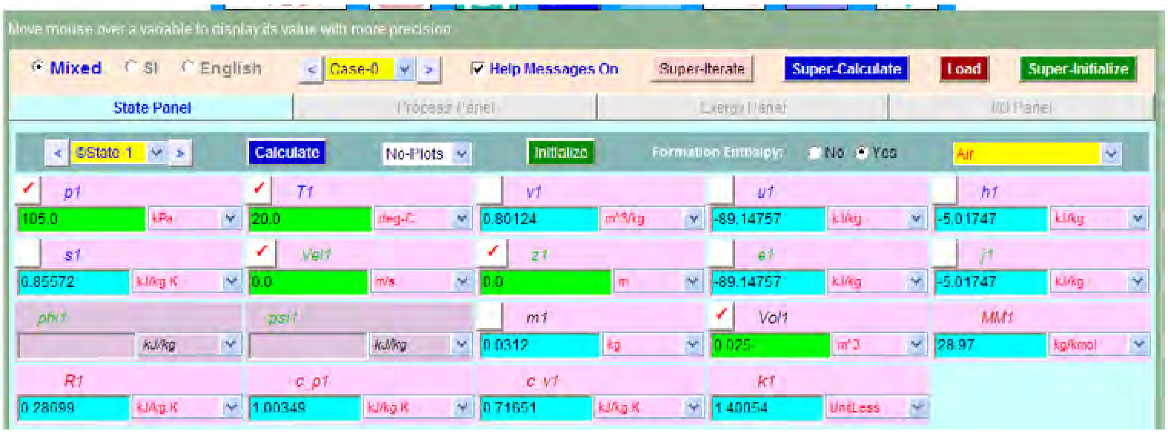
Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: A mixture of two gases, O_2 and CO_2, is heated in a closed chamber from a *beginning-state* to a *final-state* . For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select the PG Model as shown above, and we get:



4. Select Air as the substance, as shown in the above screen. We get the following screen. Enter for State 1 values for P1, T1, Vol1 as shown and click on Calculate (or, press Enter). We get:



● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

@State 1 | No-Plots | Formation Enthalpy: ○ No ● Yes | Air

✓ p1	✓ T1	☐ v1	☐ u1	☐ h1
105.0 kPa	20.0 deg-C	0.80124 m^3/kg	-89.14757 kJ/kg	-5.01747 kJ/kg
☐ s1	✓ Vel1	✓ z1	☐ e1	☐ j1
0.85572 kJ/kg.K	0.0 m/s	0.0 m	-89.14757 kJ/kg	-5.01747 kJ/kg
phi1	psi1	☐ m1	✓ Vol1	MM1
kJ/kg	kJ/kg	0.0312 kg	0.025 m^3	28.97 kg/kmol
R1	c_p1	c_v1	k1	
0.28699 kJ/kg.K	1.00349 kJ/kg.K	0.71651 kJ/kg.K	1.40054 UnitLess	

Note in the above screen that other parameters such as m1, s1 u1, h1 etc for State 1 are immediately calculated.

5. Now, select State 2, and enter values for P2, v2 = v1, m2 = m1, and click enter. Immediately, all other parameters for State 2 are calculated:

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

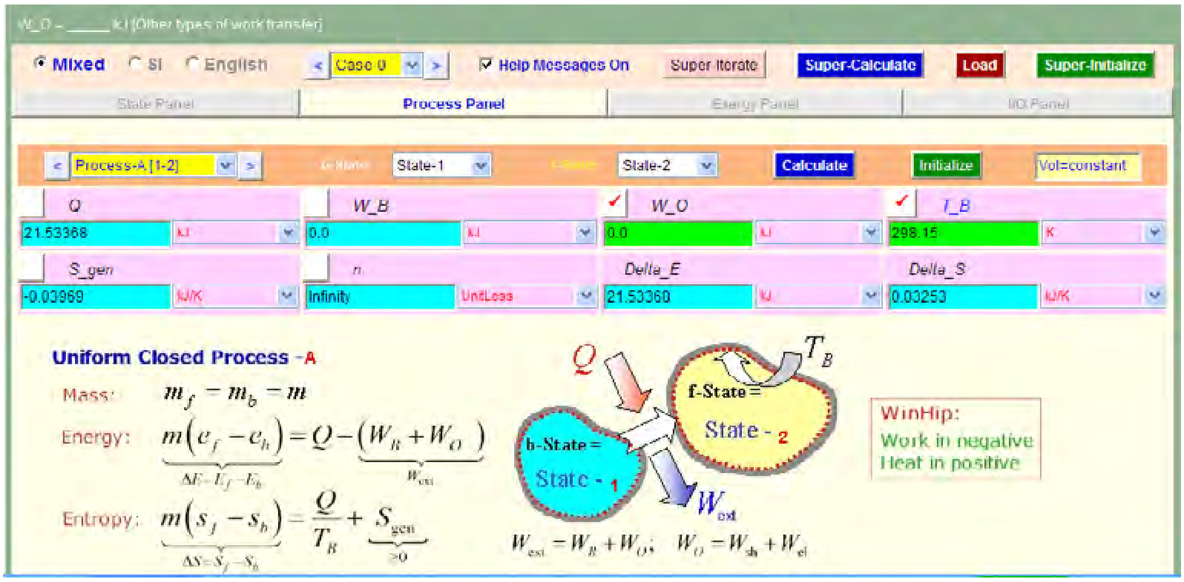
@State-2 | No-Plots | Formation Enthalpy: ○ No ● Yes | Air

✓ p2	☐ T2	✓	☐ u2	☐ h2
450.0 kPa	983.20715 deg C	=v1 m^3/kg	600.99756 kJ/kg	961.5551 kJ/kg
☐ s2	✓ Vel2	✓ z2	☐ e2	☐ j2
7.09044 kJ/kg.K	0.0 m/s	0.0 m	600.99756 kJ/kg	961.5551 kJ/kg
phi2	psi2	✓ m2	☐ Vol2	MM2
kJ/kg	kJ/kg	=m1 kg	0.025 m^3	28.97 kg/kmol
R2	c_p2	c_v2	k2	
0.28699 kJ/kg.K	1.00349 kJ/kg.K	0.71651 kJ/kg.K	1.40054 UnitLess	

6. Similarly, select State 3, enter T3 = T1, p3 = p2, m3 = m2, and press Enter. We get:

p3: =p2 kPa
T3: =T1 deg-C
v3: 0.10696 m^3/kg
u3: -89.14757 kJ/kg
h3: -5.01747 kJ/kg
s3: 6.43807 kJ/kg.K
Vel3: 0.0 m/s
z3: 0.0 m
e3: -89.14757 kJ/kg
j3: -5.01747 kJ/kg
pm3: kJ/kg
ps3: kJ/kg
m3: =m2 kg
Vol3: 0.00503 m^3
MM3: 28.97 kg/kmol
R3: 0.28699 kJ/kg.K
c_p3: 1.00349 kJ/kg.K
c_v3: 0.71651 kJ/kg.K
k3: 1.40054 UnitLess

7. Now, go to Process panel. For Process A (1–2), enter State 1 for b-State and State 2 for f-State (i.e. begin and finish States). Enter zero for W_O (i.e. other work… means… other than Boundary work or Pdv work). Click on Calculate; we get:



b-State: State-1
f-State: State-2
Vol=constant

Q: 21.53368 kJ
W_B: 0.0 kJ
W_O: 0.0 kJ
T_B: 298.15 K
S_gen: -0.03969 kJ/K
n: Infinity UnitLess
Delta_E: 21.53368 kJ
Delta_S: 0.03253 kJ/K

$$m_f = m_b = m$$

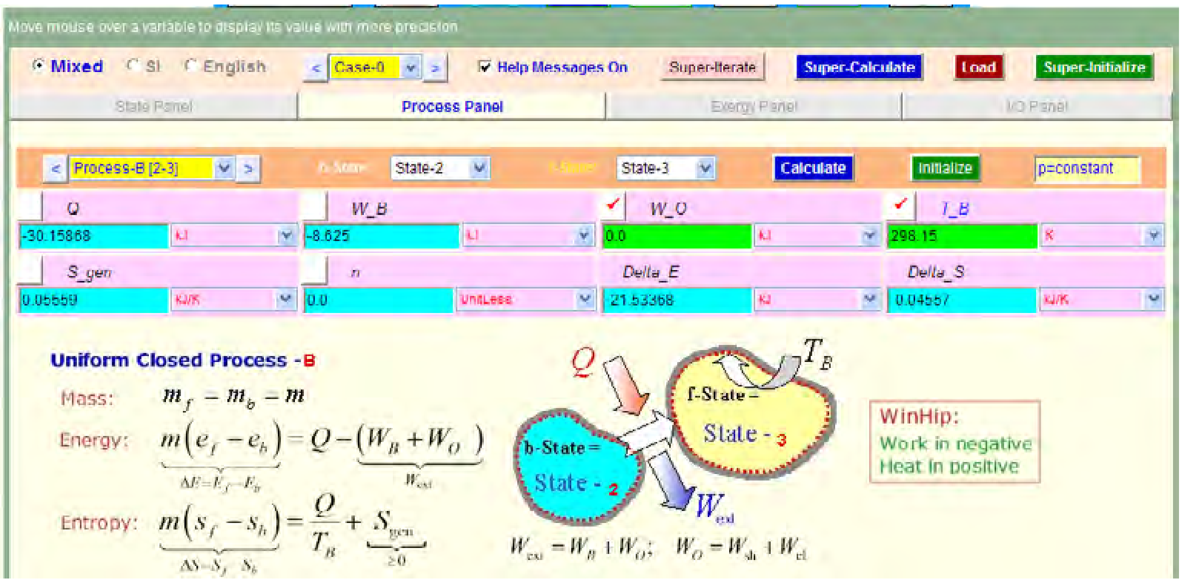
$$\underbrace{m(e_f - e_b)}_{\Delta E = E_f - E_b} = Q - \underbrace{(W_B + W_O)}_{W_{ext}}$$

$$\underbrace{m(s_f - s_b)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{gen}}_{\geq 0}$$

$$W_{ext} = W_B + W_O; \quad W_O = W_{sh} + W_{el}$$

Note from the above screen that heat transfer Q and work W_B (i.e. boundary work = 0 for const. vol.), and change in entropy for process 1–2 are immediately calculated.

8. Now, in the Process panel, select the Process B (2–3), enter State 2 for b-State and State 3 for f-State and enter W_O = 0, and hit Enter. We get:



Move mouse over a variable to display its value with more precision

● Mixed ○ SI ○ English · Case-0 · ☑ Help Messages On

Process Panel: Process-B [2-3] · b-State: State-2 · f-State: State-3 · p=constant

Q: -30.15868 kJ
W_B: -8.625 kJ
☑ W_O: 0.0 kJ
☑ T_B: 298.15 K
S_gen: 0.05559 kJ/K
n: 0.0 UnitLess
Delta_E: 21.53368 kJ
Delta_S: 0.04557 kJ/K

Uniform Closed Process -B

Mass: $m_f = m_b = m$

Energy: $\underbrace{m(e_f - e_b)}_{\Delta E = E_f - E_b} = Q - \underbrace{(W_B + W_O)}_{W_{ext}}$

Entropy: $\underbrace{m(s_f - s_b)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{gen}}_{\geq 0}$

$W_{ext} = W_B + W_O;\quad W_O = W_{sh} + W_{el}$

WinHip:
Work in negative
Heat in positive

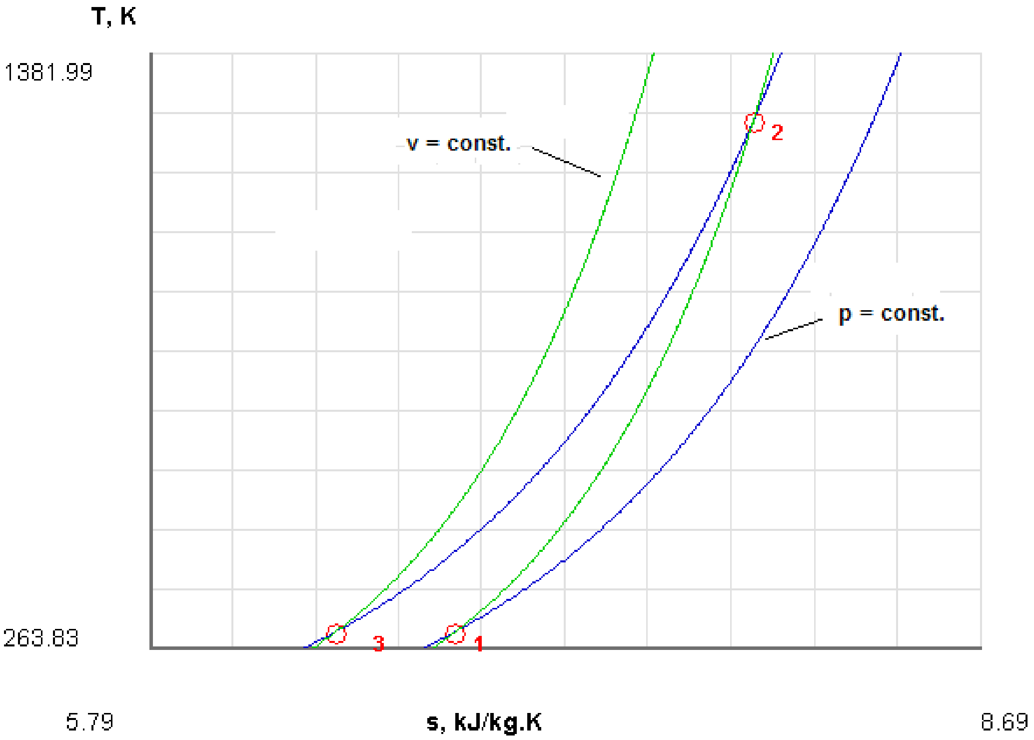
Note again from the above screen that heat transfer Q and work W_B (i.e. boundary work), and change in entropy for process 2–3 are immediately calculated.

9. Therefore, net heat transfer and net entropy changes are calculated as follows:

Q_net = Q for process 1–2 + Q for process 2–3 = 21.53368 – 30.15868 = -8.625 kJ …negative sign indicates that heat is rejected while going from State 1 to State 3…. Ans.

ΔS_net = Delta_S for process 1–2 + Delta_S for process 2–3 = 0.03253 – 0.04557
= – 0.01304 kJ/K ….entropy decreases from State 1 to State 3…. Ans.

10. **T-s plot is obtained easily by going to States tab, and choosing T-s plot:**



11. **To get TEST code etc, click on SuperCalculate, and go to I/O panel:**

 # Daemon Path: Systems>Closed>Process>Generic>Uniform>PG-Model; v-10.ca08

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

States  {
            State-1: Air;
            Given: { p1= 105.0 kPa; T1= 20.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; Vol1= 0.025 m^3; }
            State-2: Air;
            Given: { p2= 450.0 kPa; v2= “v1” m^3/kg; Vel2= 0.0 m/s; z2= 0.0 m; m2= “m1” kg; }
            State-3: Air;
            Given: { p3= “p2” kPa; T3= “T1” deg-C; Vel3= 0.0 m/s; z3= 0.0 m; m3= “m2” kg; }
            }
```

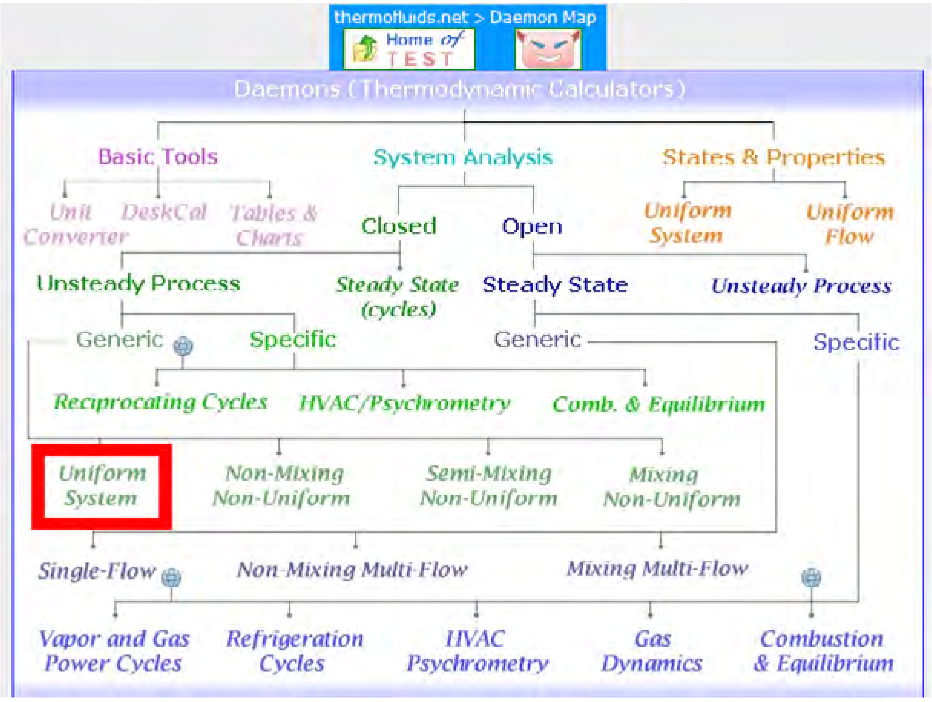
```
Analysis {
        Process-A: b-State = State-1; f-State = State-2;
        Given: { W_O= 0.0 kJ; T_B= 298.15 K; }
        Process-B: b-State = State-2; f-State = State-3;
        Given: { W_O= 0.0 kJ; T_B= 298.15 K; }
        }

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

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

#         State    p(kPa)    T(K)      v(m^3/kg)   u(kJ/kg)  h(kJ/kg)   s(kJ/kg)
#         1        105.0     293.2     0.8012      -89.15    -5.02      6.856
#         2        450.0     1256.4    0.8012      601.0     961.56     7.898
#         3        450.0     293.2     0.187       -89.15    -5.02      6.438

#--------Property spreadsheet ends-----------------------------------------------------------------

# Mass, Energy, and Entropy Analysis Results:

#         Process-A: b-State = State-1; f-State = State-2;
#         Given: W_O= 0.0 kJ; T_B= 298.15 K;
# Calculated: Q= 21.533682 kJ; W_B= 0.0 kJ; S_gen= -0.039689586 kJ/K; n= Infinity UnitLess;
#        Delta_E= 21.533682 kJ; Delta_S= 0.032534737 kJ/K;
#
#         Process-B: b-State = State-2; f-State = State-3;
#         Given: W_O= 0.0 kJ; T_B= 298.15 K;
#Calculated: Q= -30.158682 kJ; W_B= -8.625 kJ; S_gen= 0.055586666 kJ/K; n= 0.0 UnitLess;
#        Delta_E= -21.533682 kJ; Delta_S= -0.04556605 kJ/K;

==================================================================
```

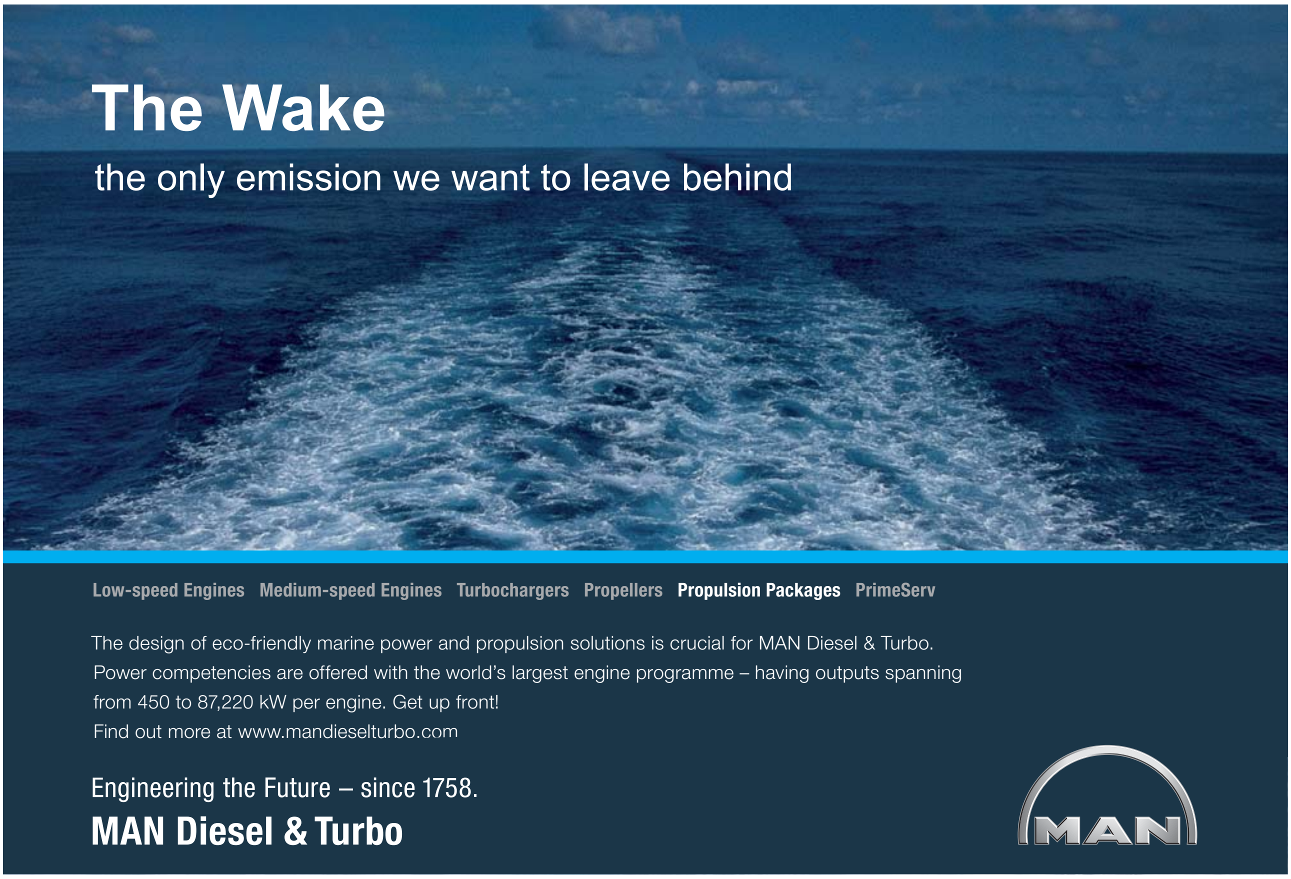
Prob.7.20. A rigid tank contains air at 35 C and is stirred by a paddle wheel which does 500 kJ of work on the air. During the stirring process the temp of air remains constant because of heat transfer to surroundings at 15 C. Estimate the change in entropy of air in the tank and the change in entropy of the surroundings. [VTU-BTD-Jan.–Feb. 2004]

TEST Solution:

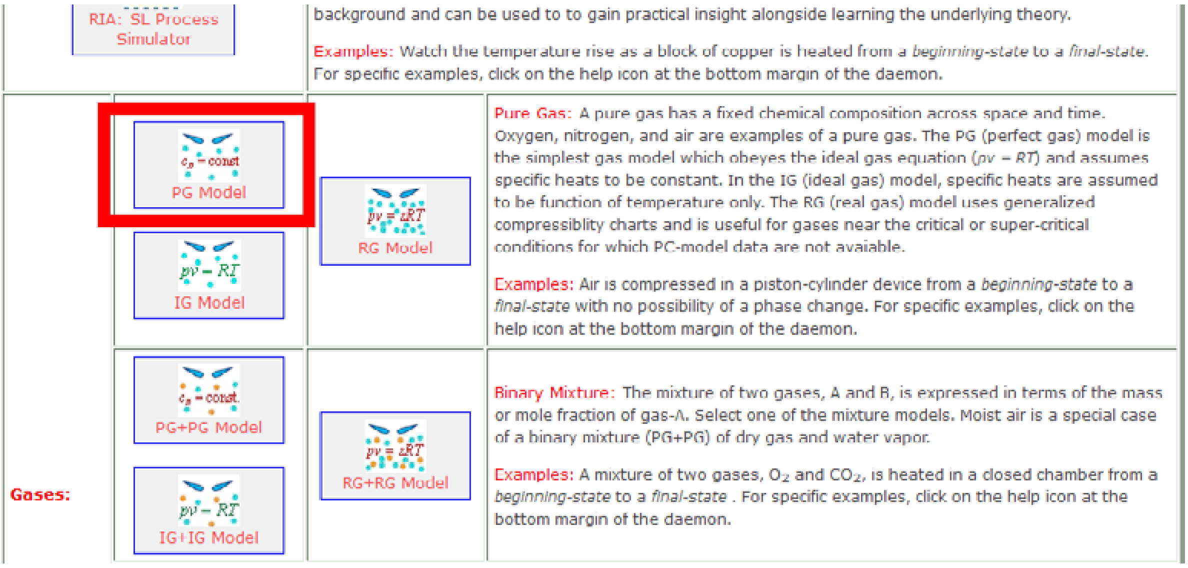
Following are the steps:

1. In the Daemons tree, locate the Closed – Uniform System daemon:





2. Click on Uniform System, and we get the following for material model selection:



background and can be used to to gain practical insight alongside learning the underlying theory.

Examples: Watch the temperature rise as a block of copper is heated from a *beginning-state* to a *final-state*. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Gas: A pure gas has a fixed chemical composition across space and time. Oxygen, nitrogen, and air are examples of a pure gas. The PG (perfect gas) model is the simplest gas model which obeyes the ideal gas equation (*pv = RT*) and assumes specific heats to be constant. In the IG (ideal gas) model, specific heats are assumed to be function of temperature only. The RG (real gas) model uses generalized compressiblity charts and is useful for gases near the critical or super-critical conditions for which PC-model data are not avaiable.

Examples: Air is compressed in a piston-cylinder device from a *beginning-state* to a *final-state* with no possibility of a phase change. For specific examples, click on the help icon at the bottom margin of the daemon.

Binary Mixture: The mixture of two gases, A and B, is expressed in terms of the mass or mole fraction of gas-A. Select one of the mixture models. Moist air is a special case of a binary mixture (PG+PG) of dry gas and water vapor.

Examples: A mixture of two gases, O_2 and CO_2, is heated in a closed chamber from a *beginning-state* to a *final-state* . For specific examples, click on the help icon at the bottom margin of the daemon.

3. Select the PG Model as shown above, and select Air for working substance, and enter for State 1 values for P1 = 100 kPa, T1 = 35 C, m1 = 1 kg as shown and click on Calculate (or, press Enter). We get:

Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English

@Case 0

☑ Help Messages On

@State-1

No-Plots

Formation Enthalpy: ○ No ● Yes

Air

✓ p1: 100.0 kPa

✓ T1: 35.0 deg-C

☐ v1: 0.88435 m^3/kg

☐ u1: -78.39996 kJ/kg

☐ h1: 10.03494 kJ/kg

☐ s1: 6.9198 kJ/kg.K

✓ Vel1: 0.0 m/s

✓ z1: 0.0 m

☐ e1: -70.39996 kJ/kg

☐ j1: 10.03494 kJ/kg

phi1: kJ/kg

psi1: kJ/kg

✓ m1: 1.0 kg

☐ Vol1: 0.88435 m^3

MM1: 28.97 kg/kmol

R1: 0.28699 kJ/kg.K

c_p1: 1.00349 kJ/kg.K

c_v1: 0.71651 kJ/kg.K

k1: 1.40054 UnitLess

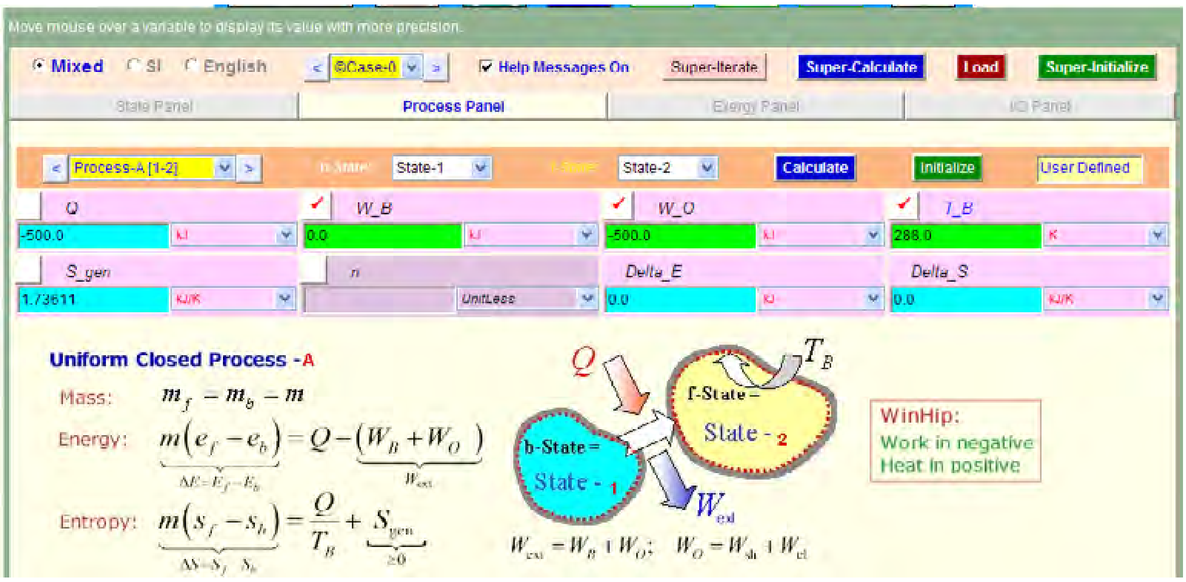
Note in the above screen that other parameters such as Vol1, s1, u1, h1 etc for State 1 are immediately calculated.

4. Similarly, enter parameters for State 2, i.e. P2 = P1, T2 = T1, m2 = m1, press Enter:

Air

☑ p2 =p1 kPa	☑ T2 =T1 deg-C	☐ v2 0.88435 m^3/kg	☐ u2 -78.39996 kJ/kg	☐ h2 10.03494 kJ/kg
☐ s2 6.9198 kJ/kg.K	☑ Vel2 0.0 m/s	☑ z2 0.0 m	☐ e2 -78.39996 kJ/kg	☐ j2 10.03494 kJ/kg
phi2 kJ/kg	psi2 kJ/kg	☑ m2 =m1 kg	☐ Vol2 0.88435 m^3	MM2 28.97 kg/kmol
R2 0.28699 kJ/kg.K	c_p2 1.00349 kJ/kg.K	c_v2 0.71651 kJ/kg.K	k2 1.40054 UnitLess	

5. Go to Process Panel, enter State 1 for b-State and State 2 for f-State. Also, W_O = – 500 kJ (i.e. other work, such as paddle work, -ve since work is done on the system), and W_B = 0 since volume is const. Press Enter:



b-State: State-1
f-State: State-2

☐ Q -500.0 kJ	☑ W_B 0.0 kJ	☑ W_O -500.0 kJ	☑ T_B 288.0 K
☐ S_gen 1.73611 kJ/K	☐ n UnitLess	Delta_E 0.0 kJ	Delta_S 0.0 kJ/K

Uniform Closed Process -A

Mass: $m_f = m_b = m$

Energy: $\underbrace{m(e_f - e_b)}_{\Delta E = E_f - E_b} = Q - \underbrace{(W_B + W_O)}_{W_{ext}}$

Entropy: $\underbrace{m(s_f - s_b)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{gen}}_{\geq 0}$

$W_{ext} = W_B + W_O; \quad W_O = W_{sh} + W_{el}$

Thus:

Entropy change of air = 0, entropy change of atmosphere = Q/ T_B = 1.73611 kJ/K , and Entropy change of universe = S_gen = 1.73611 kJ/K …. Ans.

6. Press SuperCalculate, and see the TEST code etc. in the I/O panel:

```
#*******TEST-code:

#       Daemon Path: Systems>Closed>Process>Generic>Uniform>PG-Model; v-10.ca08

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

States   {
            State-1: Air;
            Given: { p1= 100.0 kPa; T1= 35.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 1.0 kg; }

            State-2: Air;
            Given: { p2= “p1” kPa; T2= “T1” deg-C; Vel2= 0.0 m/s; z2= 0.0 m; m2= “m1” kg; }
            }

Analysis {
            Process-A: b-State = State-1; f-State = State-2;
            Given: { W_B= 0.0 kJ; W_O= 500.0 kJ; T_B= 288.0 K; }
            }

#---------------------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   p(kPa)      T(K)    v(m^3/kg)    u(kJ/kg)     h(kJ/kg)     s(kJ/kg)
#        1      100.0       308.2   0.8843       -78.4        10.03        6.92
#        2      100.0       308.2   0.8843       -78.4        10.03        6.92
#

#--------Property spreadsheet ends------------------------------------------------------------------

# Mass, Energy, and Entropy Analysis Results:

#       Process-A: b-State = State-1; f-State = State-2;
#               Given: W_B= 0.0 kJ; W_O= -500.0 kJ; T_B= 288.0 K;
#       Calculated: Q= -500.0 kJ; S_gen= 1.7361112 kJ/K; Delta_E= -0.0 kJ; Delta_S= -0.0 kJ/K;
================================================================================
```

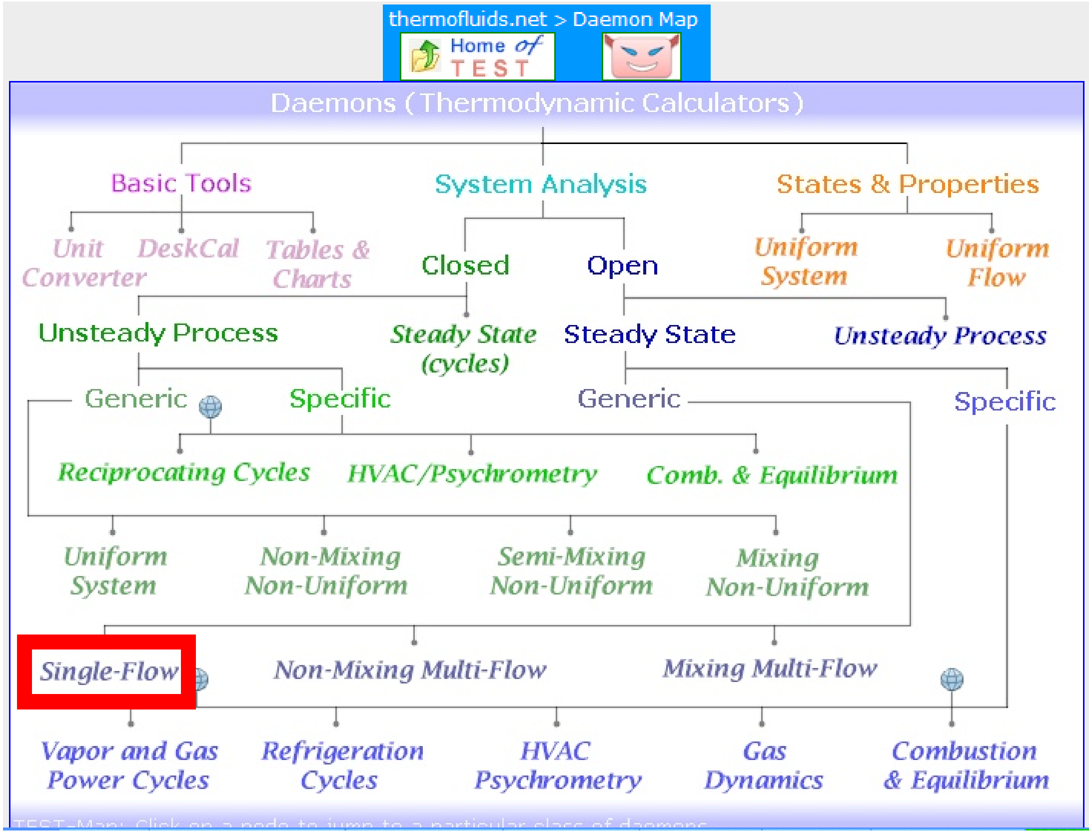
Prob.7.21. Refrigerant 134a is throttled from 1200 kPa, 40 C to 200 kPa. Heat is lost from the refrigerant in the amount of 0.5 kJ/kg to surroundings at 25 C. Determine: (i) the exit temp of the refrigerant, and (ii) the entropy generation during this process. [Ref: 1]

Note: This is the same as Prob.7.16, solved with Mathcad.

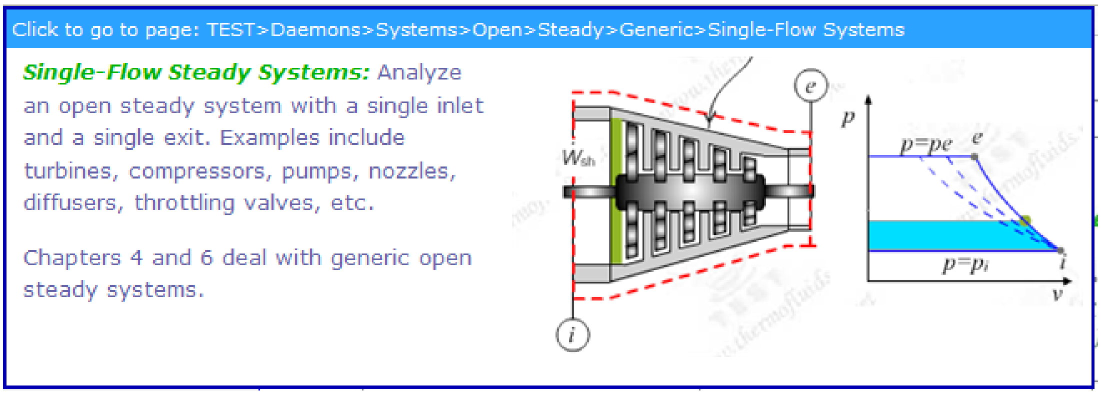
TEST Solution:

Following are the steps:

1. From the Daemons tree, select System Analysis – Open – Single Flow daemon:



Hovering the mouse pointer over ‘Single Flow’ in the above fig. brings up the following explanatory pop up:

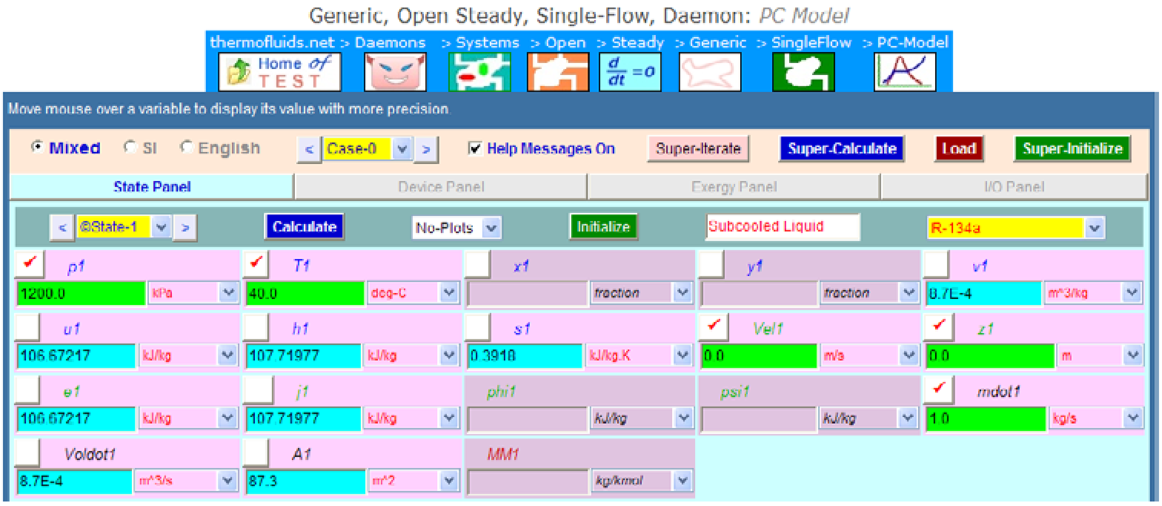


Click to go to page: TEST>Daemons>Systems>Open>Steady>Generic>Single-Flow Systems

Single-Flow Steady Systems: Analyze an open steady system with a single inlet and a single exit. Examples include turbines, compressors, pumps, nozzles, diffusers, throttling valves, etc.

Chapters 4 and 6 deal with generic open steady systems.

2. For Material model, select PC model, select R134a for substance, and fill in the parameters for State 1, i.e. P1 = 1200 kPa, T1 = 40 C, mdot1 = 1 kg/s. Press Enter; immediately, other properties are calculated:



Generic, Open Steady, Single-Flow, Daemon: *PC Model*

Subcooled Liquid

R-134a

	Variable	Value	Unit
✓	p1	1200.0	kPa
✓	T1	40.0	deg-C
☐	x1		fraction
☐	y1		fraction
☐	v1	8.7E-4	m^3/kg
☐	u1	106.67217	kJ/kg
☐	h1	107.71977	kJ/kg
☐	s1	0.3918	kJ/kg.K
✓	Vel1	0.0	m/s
✓	z1	0.0	m
☐	e1	106.67217	kJ/kg
☐	j1	107.71977	kJ/kg
	phi1		kJ/kg
	psi1		kJ/kg
✓	mdot1	1.0	kg/s
☐	Voldot1	8.7E-4	m^3/s
☐	A1	87.3	m^2
	MM1		kg/kmol

3. Similarly, for State 2, enter P2 = 200 kPa, mdot2 = mdot1 and press Enter:

Move mouse over a variable to display its value with more precision.

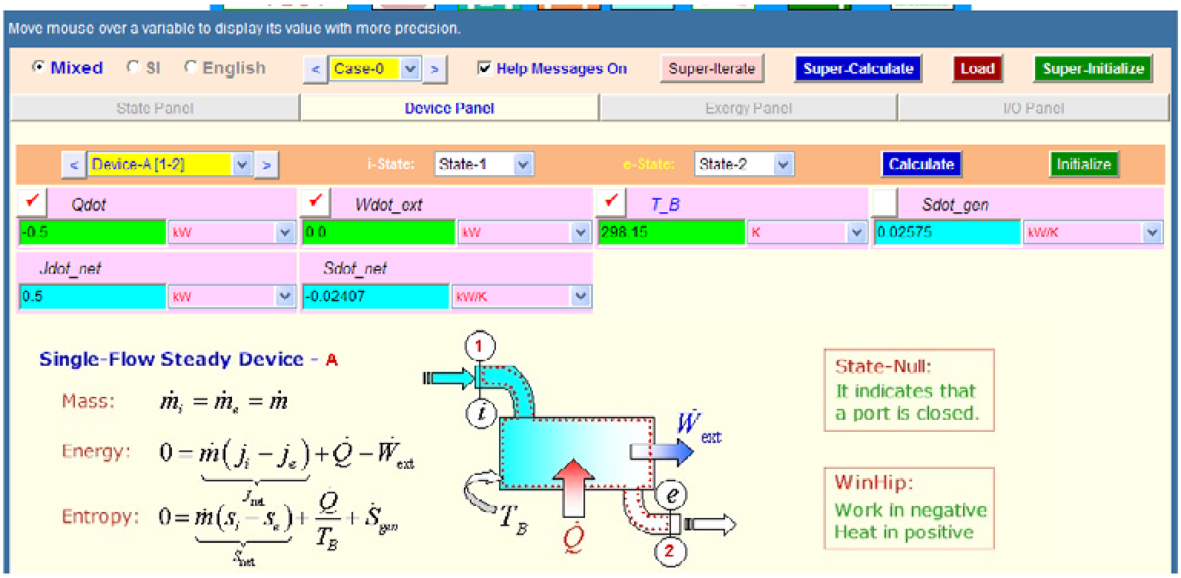
● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

@State-2 | No-Plots | Unknown Phase | R-134a

☑ p2: 200.0 kPa
☐ T2: deg-C
☐ x2: fraction
☐ y2: fraction
☐ v2: m^3/kg
☐ u2: kJ/kg
☐ h2: kJ/kg
☐ s2: kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: kJ/kg
☐ j2: kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☑ mdot2: =mdot1 kg/s
☐ Voldot2: m^3/s
☐ A2: m^2
MM2: kg/kmol

All properties are not calculated, since data is not enough. But, after we go to Device panel and SuperCalculate, the calculated properties will be posted back.

4. Go to Device Panel. Fill in State 1 for i-State and State 2 for e-State, Q = -0.5 kW and Wdot_ext = 0 and press Calculate, and Super Calculate. We get:



Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

Device-A [1-2] | i-State: State-1 | e-State: State-2

☑ Qdot: -0.5 kW
☑ Wdot_ext: 0.0 kW
☑ T_B: 298.15 K
☐ Sdot_gen: 0.02575 kW/K
Jdot_net: 0.5 kW
Sdot_net: -0.02407 kW/K

Single-Flow Steady Device - A

Mass: $\dot{m}_i = \dot{m}_e = \dot{m}$

Energy: $0 = \underbrace{\dot{m}(j_i - j_e)}_{\dot{J}_{net}} + \dot{Q} - \dot{W}_{ext}$

Entropy: $0 = \underbrace{\dot{m}(s_i - s_e)}_{\dot{S}_{net}} + \frac{\dot{Q}}{T_B} + \dot{S}_{gen}$

State-Null: It indicates that a port is closed.

WinHip: Work in negative Heat in positive

5. **Now, go back to State Panel, and see State 2 and observe that calculations for State 2 are completed:**

Saturated Mixture
R-134a

☑ p2: 200.0 kPa
T2: 10.22257 deg C
x2: 0.33016 fraction
y2: 0.98552 fraction
v2: 0.03444 m^3/kg
u2: 100.33614 kJ/kg
h2: 107.21977 kJ/kg
s2: 0.41587 kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
e2: 100.33614 kJ/kg
☑ j2: 107.21977 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☑ mdot2: =mdot1 kg/s
Voldot2: 0.03444 m^3/s
A2: 3444.3965 m^2
MM2: 102.03 kg/kmol

Thus:

Temp after throttling = T2 = -10.22 C….. Ans.

Entropy generated = Sdot_gen = 0.02575 kJ/K …from Device Panel… Ans.

Note: These values match well with those obtained using Mathcad.

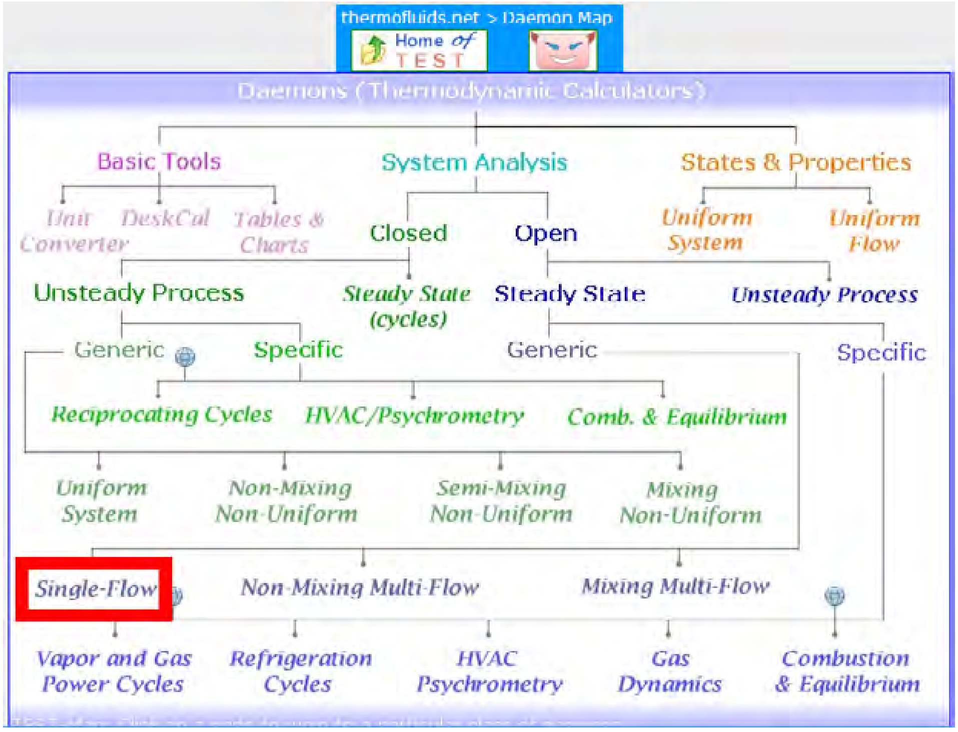
===

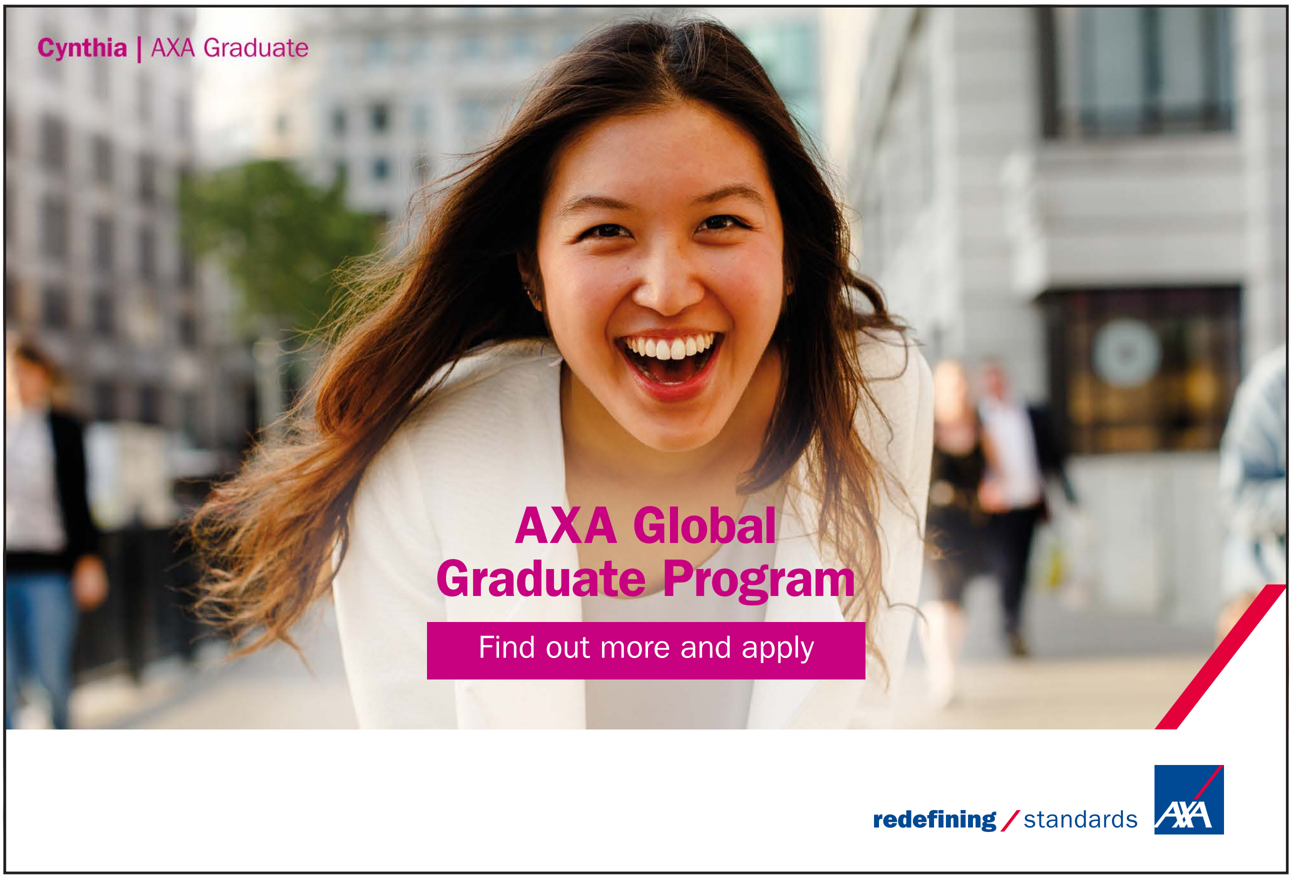
Prob.7.22. Refrigerant 134a enters a steady flow, adiabatic turbine as a saturated vapour at 1200 kPa and expands to 100 kPa. The power produced by the turbine is found to be 100 kW when the process is also reversible. (a) Sketch the T-s diagram (b) Determine the volume flow rate of R134a at the turbine exit. [Ref: 1]

TEST Solution:

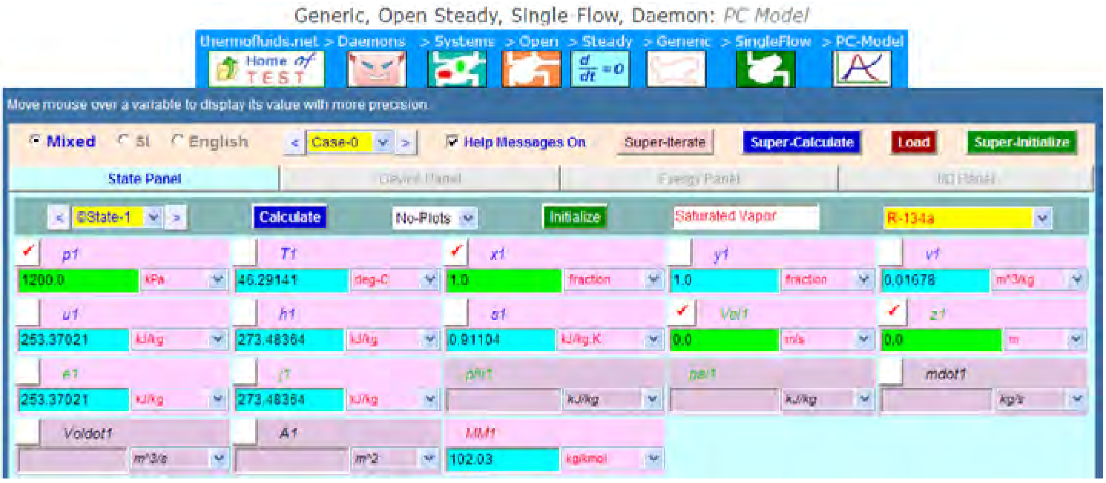
Following are the steps:

1. From the Daemons tree, select System Analysis – Open – Single Flow daemon:





1. For Material model, select PC model, select R134a for substance, and fill in the parameters for State 1, i.e. P1 = 1200 kPa, x1 = 1. Press Enter; immediately, other properties are calculated:



● Mixed ○ SI ○ English — Case-0 — ☑ Help Messages On

State-1 — No-Plots — Saturated Vapor — R-134a

✓ p1	T1	✓ x1	y1	v1
1200.0 kPa	46.29141 deg-C	1.0 fraction	1.0 fraction	0.01678 m^3/kg
u1	h1	s1	✓ Vel1	✓ z1
253.37021 kJ/kg	273.48364 kJ/kg	0.91104 kJ/kg.K	0.0 m/s	0.0 m
e1	j1	phi1	psi1	mdot1
253.37021 kJ/kg	273.48364 kJ/kg	kJ/kg	kJ/kg	kg/s
Voldot1	A1	MM1		
m^3/s	m^2	102.03 kg/kmol		

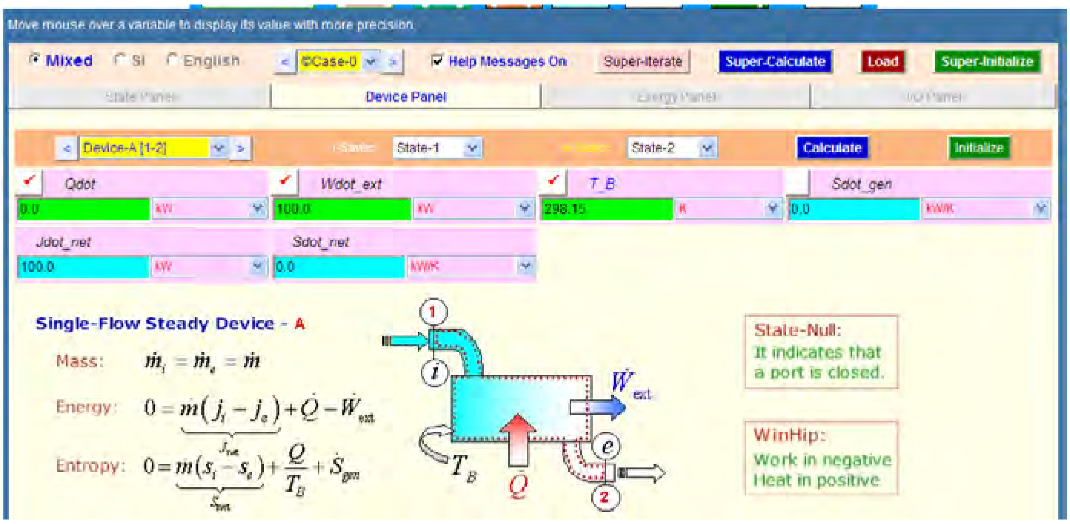
2. For State2, enter p2 = 100 kPa, s2 = s1 (since rev. adiabatic) and mdot2 = mdot1. Hit Enter. We get:

● Mixed ○ SI ○ English — Case-0 — ☑ Help Messages On

State-2 — No-Plots — Sat.Mixture: Liq.+Vap. — R-134a

✓ p2	T2	x2	y2	v2
100.0 kPa	-26.5866 deg-C	0.9596 fraction	0.99984 fraction	0.18494 m^3/kg
u2	h2	✓ s2	✓ Vel2	✓ z2
205.7723 kJ/kg	224.24907 kJ/kg	=s1 kJ/kg.K	0.0 m/s	0.0 m
e2	j2	phi2	psi2	✓ mdot2
205.7723 kJ/kg	224.24907 kJ/kg	kJ/kg	kJ/kg	=mdot1 kg/s
Voldot2	A2	MM2		
m^3/s	m^2	102.03 kg/kmol		

3. Go to Device Panel. Enter State 1 for i-State and State 2 for e-State. Also enter Qdot = 0, Wdot_ext = 100 kW, and press Enter. And also click on SuperCalculate. We get:



i-State: State-1
e-State: State-2

✓ Qdot: 0.0 kW
✓ Wdot_ext: 100.0 kW
✓ T_B: 298.15 K
Sdot_gen: 0.0 kW/K
Jdot_net: 100.0 kW
Sdot_net: 0.0 kW/K

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

$$0 = \underbrace{\dot{m}(j_i - j_e)}_{\dot{J}_{net}} + \dot{Q} - \dot{W}_{ext}$$

$$0 = \underbrace{\dot{m}(s_i - s_e) + \frac{\dot{Q}}{T_B}}_{\dot{S}_{net}} + \dot{S}_{gen}$$

4. Go back to State Panel. See State 2:

Saturated Mixture
R-134a

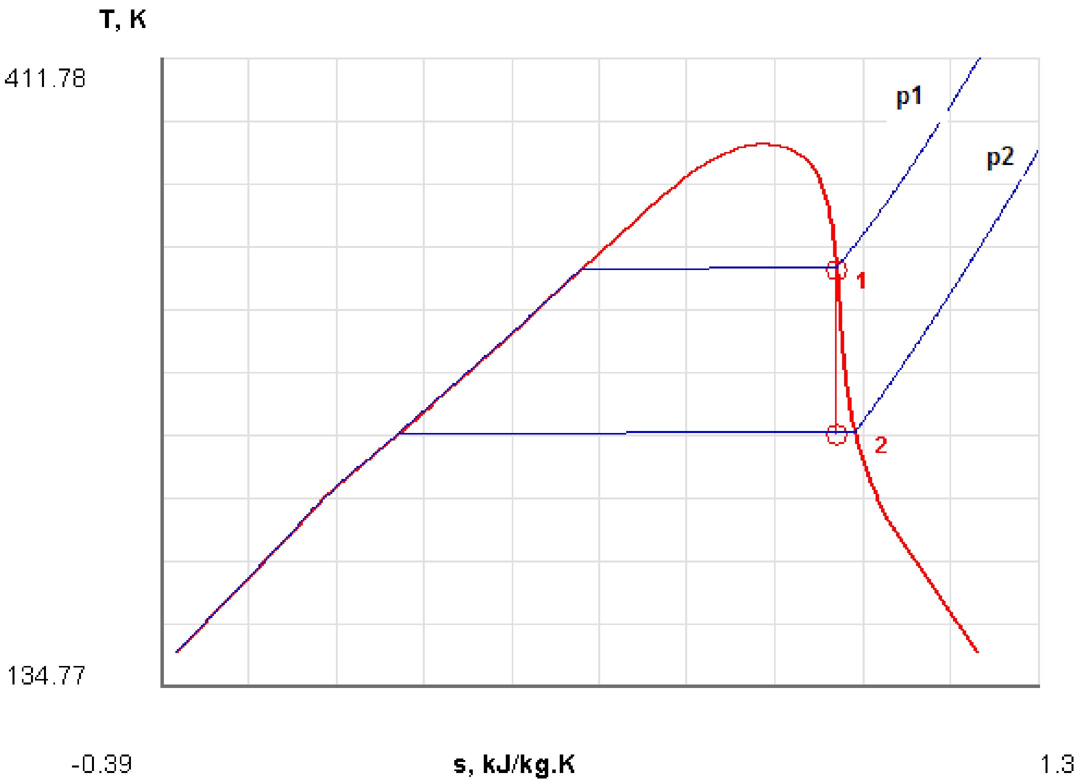
✓ p2: 100.0 kPa
T2: -26.5866 deg-C
x2: 0.9590 fraction
y2: 0.99984 fraction
v2: 0.18494 m^3/kg
u2: 205.7723 kJ/kg
h2: 224.24907 kJ/kg
✓ s2: =s1 kJ/kg.K
✓ Vel2: 0.0 m/s
✓ z2: 0.0 m
e2: 205.7723 kJ/kg
j2: 224.24907 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
✓ mdot2: =mdot1 kg/s
Voldot2: 0.37562 m^3/s
A2: 37562.438 m^2
MM2: 102.03 kg/kmol

Thus:

Temp after expansion in turbine = T2 = -26.59 C … Ans.

Volume flow rate at the exit = Voldot2 = 0.37562 m^3/s …. Ans.

5. T-s plot: choose the T-s plot from the plots widget. We get:



6. **TEST code etc: See the I/O panel:**

#*******TEST-code: To save the solution, copy the codes generated below into a text file. To reproduce the solution at a later time, launch

```
#          Daemon Path: Systems>Open>SteadyState>Generic>SingleFlow>PC-Model; v-10.cb01

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

States    {
            State-1: R-134a;
            Given: { p1= 1200.0 kPa; x1= 1.0 fraction; Vel1= 0.0 m/s; z1= 0.0 m; }

            State-2: R-134a;
            Given: { p2= 100.0 kPa; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= "mdot1" kg/s; }
            }

Analysis {
            Device-A: i-State = State-1; e-State = State-2;
            Given: { Qdot= 0.0 kW; Wdot_ext= 100.0 kW; T_B= 298.15 K; }
            }

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

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

 # Evaluated States:

```
#          State-1: R-134a > Saturated Mixture;
#                    Given: p1= 1200.0 kPa; x1= 1.0 fraction; Vel1= 0.0 m/s;
#                           z1= 0.0 m;
#                    Calculated: T1= 46.2914 deg-C; y1= 1.0 fraction; v1= 0.0168 m^3/kg;
#                           u1= 253.3702 kJ/kg; h1= 273.4836 kJ/kg; s1= 0.911 kJ/kg.K;
#                           e1= 253.3702 kJ/kg; j1= 273.4836 kJ/kg; mdot1= 2.0311 kg/s;
#                           Voldot1= 0.0341 m^3/s; A1= 3408.1953 m^2; MM1= 102.03 kg/kmol;
#          State-2: R-134a > Saturated Mixture;
#                    Given: p2= 100.0 kPa; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s;
#                           z2= 0.0 m; mdot2= "mdot1" kg/s;
```

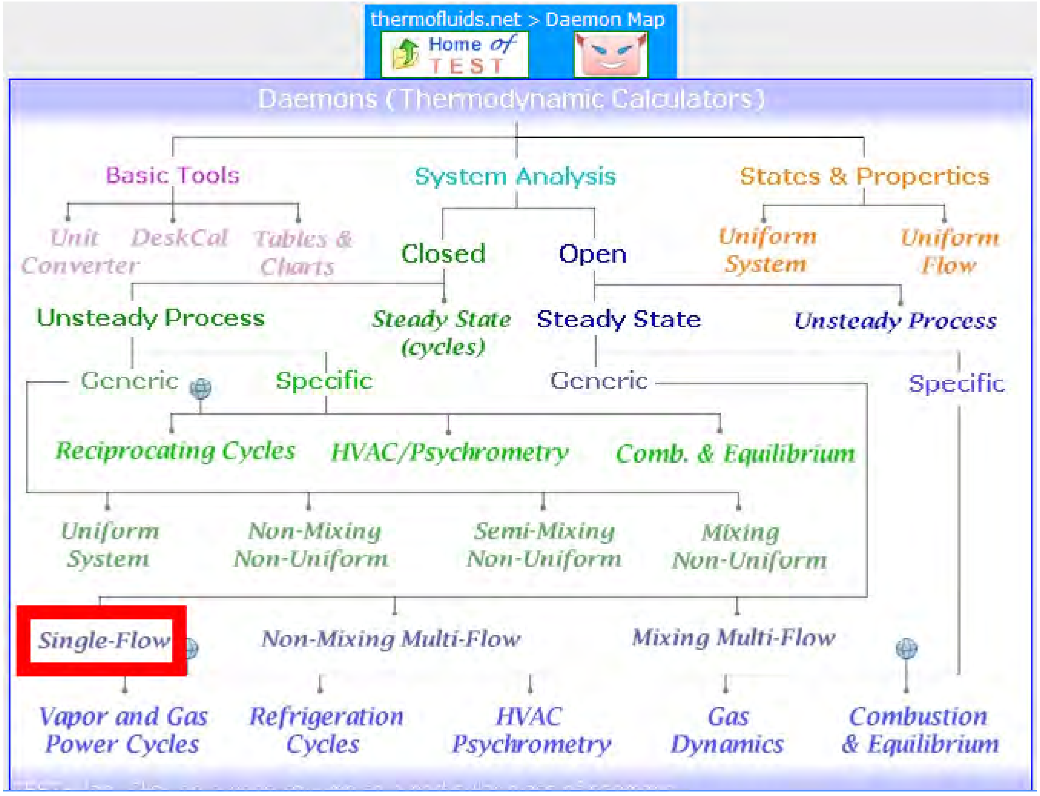
```
#                 Calculated: T2= -26.5866 deg-C; x2= 0.9596 fraction; y2= 0.9998 fraction;
#                         v2= 0.1849 m^3/kg; u2= 205.7723 kJ/kg; h2= 224.2491 kJ/kg;
#                         e2= 205.7723 kJ/kg; j2= 224.2491 kJ/kg; Voldot2= 0.3756 m^3/s;
#                         A2= 37562.438 m^2; MM2= 102.03 kg/kmol;
#--------Property spreadsheet starts:

# State  p(kPa)        T(K)    x     v(m3/kg)    u(kJ/kg)    h(kJ/kg)    s(kJ/kg)
# 01     1200.0        319.4   1.0   0.0168      253.37      273.48       0.911
# 02     100.0         246.6   1.0   0.1849      205.77      224.25       0.911

# Mass, Energy, and Entropy Analysis Results:

#
#         Device-A: i-State = State-1; e-State = State-2;
#                 Given: Qdot= 0.0 kW; Wdot_ext= 100.0 kW; T_B= 298.15 K;
#                 Calculated: Sdot_gen= -0.0 kW/K; Jdot_net= 100.0 kW; Sdot_net= 0.0 kW/K;

=================================================================================
```

Prob.7.23. Methane (CH_4) at 280 K, 1 bar enters a compressor operating at steady state and exits at 380 K, 3.5 bar. Ignoring heat transfer with the surroundings, and employing Ideal gas model, determine the rate of entropy production within the compressor, in kJ/kg.K. [Ref: 3]

TEST Solution:

Following are the steps:

1. From the Daemons tree, select System Analysis – Open – Single Flow daemon:



2. For Material model, select IG model, select CH4 for substance, and fill in the parameters for State-1, i.e. P1 = 100 kPa, T1=280 K, mdot1 = 1 kg/s. Press Enter; immediately, other properties are calculated:

Formation Enthalpy: ○ No ● Yes

Methane(CH4)

✓ p1	✓ T1	rho1	v1	u1
100.0 kPa	280.0 K	0.68903 kg/m^3	1.45132 m^3/kg	-4853.2886 kJ/kg
h1	s1	✓ Vel1	✓ z1	e1
-4708.1567 kJ/kg	11.47914 kJ/kg.K	0.0 m/s	0.0 m	-4853.2886 kJ/kg
j1	phi1	psi1	✓ mdot1	Voldot1
-4708.1567 kJ/kg	kJ/kg	kJ/kg	1.0 kg/s	1.45132 m^3/s
A1	MM1	R1	c_p1	
145132.17 m^2	16.04 kg/kmol	0.51833 kJ/kg.K	2.22216 kJ/kg.K	

3. For State-2, enter P2, T2 and mdot2 (=mdot1). Hit Enter. We get:

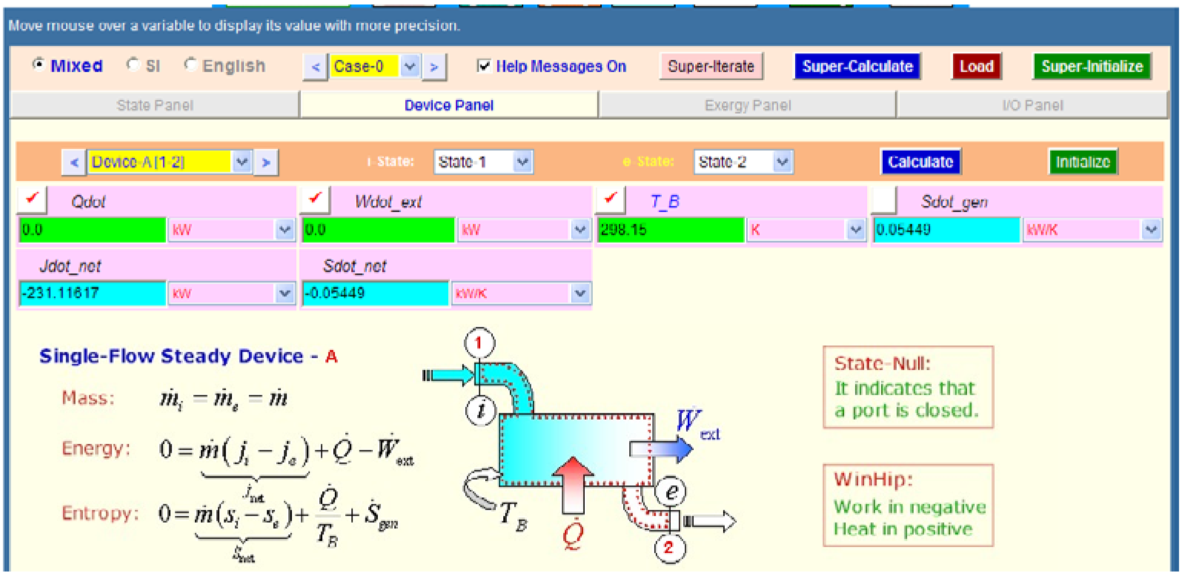
Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English; Case-0; ☑ Help Messages On

State Panel; @State-2; No-Plots; Formation Enthalpy: ○ No ● Yes; Methane(CH4)

☑ p2: 350.0 kPa
☑ T2: 380.0 K
☐ rho2: 1.77696 kg/m^3
☐ v2: 0.56276 m^3/kg
☐ u2: -4674.0054 kJ/kg
☐ h2: -4477.0405 kJ/kg
☐ s2: 11.53363 kJ/kg.K
☑ Vel2: 0.0 m/s
☑ z2: 0.0 m
☐ e2: -4674.006 kJ/kg
☐ j2: -4477.0405 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☑ mdot2: =mdot1 kg/s
☐ Voldot2: 0.56276 m^3/s
☐ A2: 56275.74 m^2
MM2: 16.04 kg/kmol
R2: 0.51833 kJ/kg.K
☐ c_p2: 2.45631 kJ/kg.K

4. Go to Device Panel. Enter State 1 and State 2 for i-State and e-State respectively. Also Qdot = o since compressor is taken as insulated (i.e. no heat transfer), and Wdot-ext = 0 = external work. Press Enter. We get:



< Device-A[1-2] >   i-State: State-1   e-State: State-2

✓ Qdot	✓ Wdot_ext	✓ T_B	Sdot_gen
0.0 kW	0.0 kW	298.15 K	0.05449 kW/K
Jdot_net	Sdot_net		
-231.11617 kW	-0.05449 kW/K		

Single-Flow Steady Device - A

Mass: $\dot m_i = \dot m_e = \dot m$

Energy: $0 = \underbrace{\dot m(j_i - j_e)}_{\dot J_{net}} + \dot Q - \dot W_{ext}$

Entropy: $0 = \underbrace{\dot m(s_i - s_e)}_{\dot S_{net}} + \frac{\dot Q}{T_B} + \dot S_{gen}$

Thus:

Entropy generated in compressor = Sdot_gen = 0.05449 kW/K …. Ans.

Note: Entropy change of surrounding is zero, since there is no heat transfer to surroundings. And, entropy change of universe = entropy change of system (i.e. compressor) + entropy change of surroundings = 0.05449 kW/K.

5. **SuperCalculate** to get the TEST code etc. from the I/O panel:

 # Daemon Path: Systems>Open>SteadyState>Generic>SingleFlow>IG-Model; v-10.ca08

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

States {
State-1: Methane(CH4);
Given: { p1= 100.0 kPa; T1= 280.0 K; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 1.0 kg/s; }

State-2: Methane(CH4);
Given: { p2= 350.0 kPa; T2= 380.0 K; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= “mdot1” kg/s; }
}

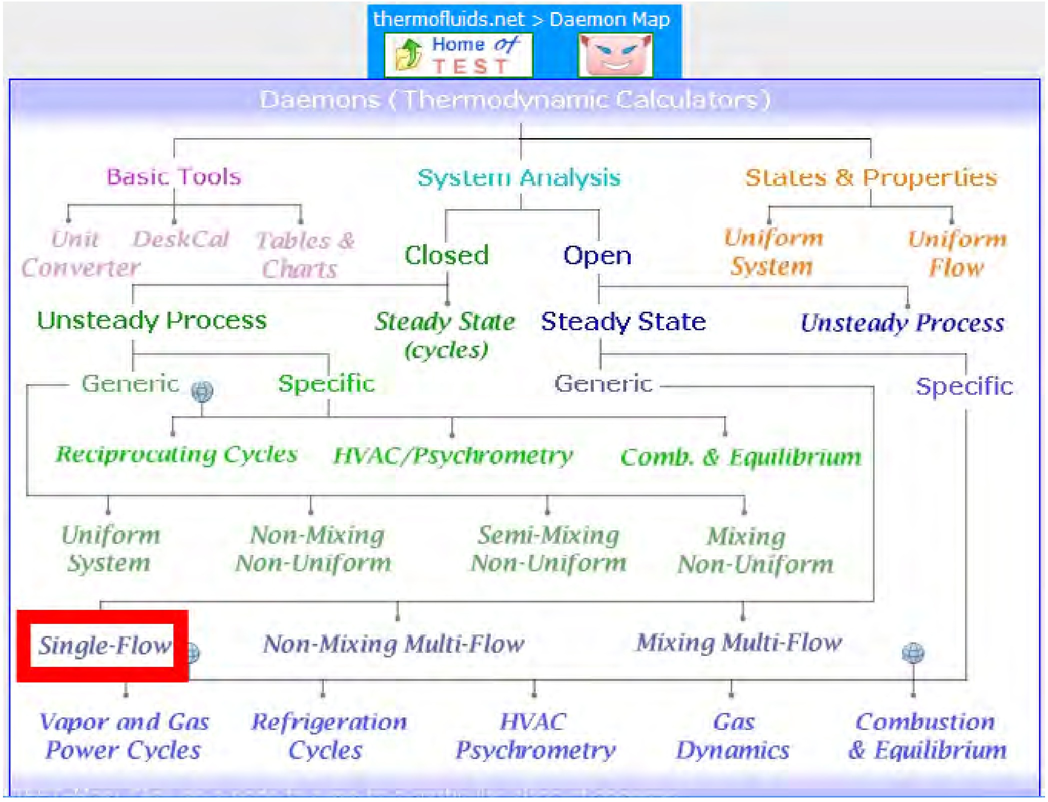
```
Analysis {
            Device-A: i-State = State-1; e-State = State-2;
            Given: { Qdot= 0.0 kW; Wdot_ext= 0.0 kW; T_B= 298.15 K; }
            }

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

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

#      State   p(kPa)        T(K)    v(m^3/kg)     u(kJ/kg)      h(kJ/kg)      s(kJ/kg)
#       1      100.0         280.0   1.4513        -4853.29      -4708.16      11.479
#       2      350.0         380.0   0.5628        -4674.01      -4477.04      11.534

#--------Property spreadsheet ends-------------------------------------------------------------------------

# Mass, Energy, and Entropy Analysis Results:
#       Device-A: i-State = State-1; e-State = State-2;
#       Given: Qdot= 0.0 kW; Wdot_ext= 0.0 kW; T_B= 298.15 K;
#       Calculated: Sdot_gen= 0.05448742 kW/K; Jdot_net= -231.11617 kW; Sdot_net= -0.05448742
       kW/K;

======================================================================================
```

Prob.7.24. Air at 500 kPa and 400 K enters an adiabatic nozzle at a velocity of 30 m/s and leaves at 300 kPa and 350 K. Using variable specific heats, determine: (a) the isentropic efficiency (b) the exit velocity, and (c) the entropy generation. [Ref: 1]

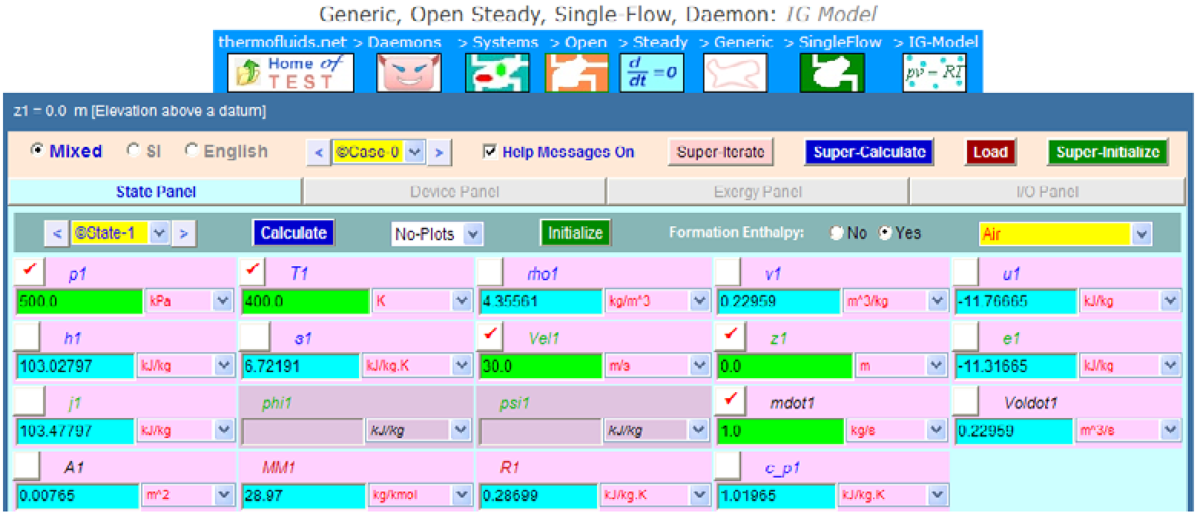
TEST Solution:

Following are the steps:

1. From the Daemons tree, select System Analysis – Open – Single Flow daemon:



2. For Material model, select IG model (i.e. sp. heat varies with temp), select Air for substance, and fill in the parameters for State- 1, i.e. P1 = 500 kPa, T1=400 K, Vel1 = 30 m/s, mdot1 = 1 kg/s. Press Enter; immediately, other properties are calculated:



z1 = 0.0 m [Elevation above a datum]

● Mixed ○ SI ○ English   @Case-0   ☑ Help Messages On

@State-1   No-Plots   Formation Enthalpy: ○ No ● Yes   Air

☑ p1: 500.0 kPa
☑ T1: 400.0 K
☐ rho1: 4.35561 kg/m^3
☐ v1: 0.22959 m^3/kg
☐ u1: -11.76665 kJ/kg
☐ h1: 103.02797 kJ/kg
☐ s1: 6.72191 kJ/kg.K
☑ Vel1: 30.0 m/s
☑ z1: 0.0 m
☐ e1: -11.31665 kJ/kg
☐ j1: 103.47797 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
☑ mdot1: 1.0 kg/s
☐ Voldot1: 0.22959 m^3/s
☐ A1: 0.00765 m^2
MM1: 28.97 kg/kmol
R1: 0.28699 kJ/kg.K
☐ c_p1: 1.01965 kJ/kg.K

3. Similarly, for State 2, enter P2, T2, mdot1. Also enter j2 = j1, remember: j is defined as:

4.

j = h + Vel²/2 + g.z

i.e. it is a statement of I Law.

Hit Enter, and we get:

Move mouse over a variable to display its value with more precision.

@State-2

Formation Enthalpy: ○ No ● Yes

Air

☑ p2: 300.0 kPa
☑ T2: 350.0 K
☐ rho2: 2.9867 kg/m^3
☐ v2: 0.33482 m^3/kg
☐ u2: -48.19359 kJ/kg
☐ h2: 52.2517 kJ/kg
☐ s2: 0.73292 kJ/kg.K
☐ Vel2: 320.0821 m/s
☑ z2: 0.0 m
☐ e2: 3.03208 kJ/kg
☑ j2: =j1 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
☑ mdot2: =mdot1 kg/s
☐ Voldot2: 0.33482 m^3/s
☐ A2: 0.00105 m^2
MM2: 28.97 kg/kmol
R2: 0.28699 kJ/kg.K
☐ c_p2: 1.01147 kJ/kg.K

5. Now, for Isentropic expansion: let it be designated as State 3. For this State, enter P3, s3 = s1and j3 = j1. Hit Enter. We get:

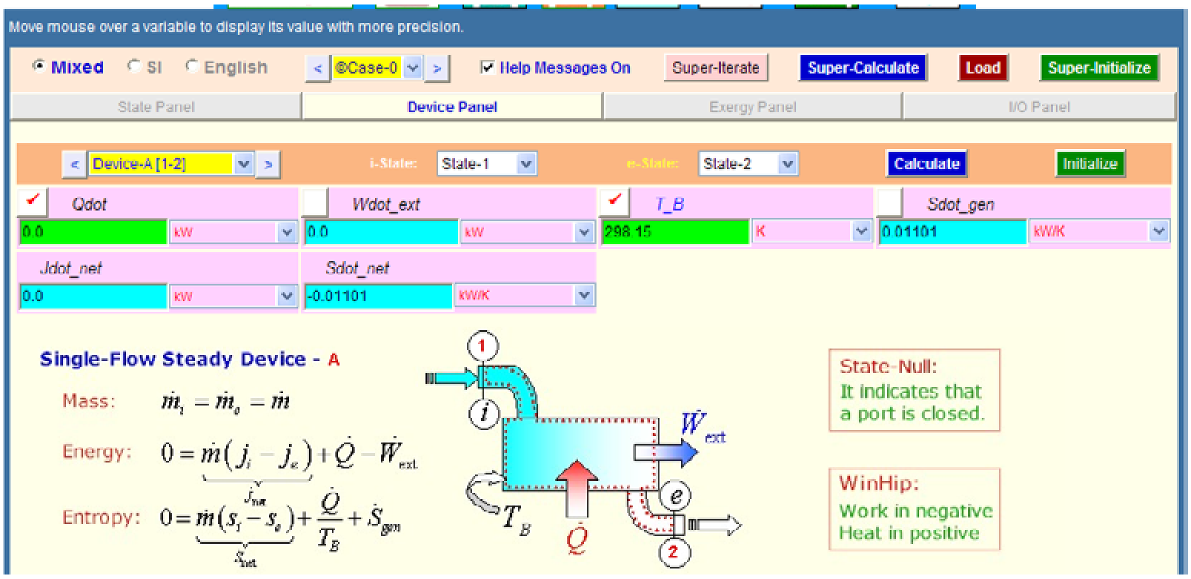
rho3 = 3.0193915 kg/m^3 (Density)

● Mixed ○ SI ○ English | @Case-0 | ☑ Help Messages On

@State-3 | h-s | Formation Enthalpy: ○ No ● Yes | Air

☑ p3: =p2 kPa
☐ T3: 346.21054 K
☐ rho3: 3.01939 kg/m^3
☐ v3: 0.33119 m^3/kg
☐ u3: -50.93787 kJ/kg
☐ h3: 48.4199 kJ/kg
☑ s3: =s1 kJ/kg.K
☐ Vel3: 331.83752 m/s
☑ z3: 0.0 m
☐ e3: 4.12021 kJ/kg
☑ j3: =j1 kJ/kg
phi3: kJ/kg
psi3: kJ/kg
☑ mdot3: =mdot1 kg/s
☐ Voldot3: 0.33119 m^3/s
☐ A3: 0.001 m^2
MM3: 28.97 kg/kmol
R3: 0.28699 kJ/kg.K
☐ c_p3: 1.01087 kJ/kg.K

6. Now, go to Device Panel. Enter State 1 and State 2 for i-State and e-State respectively. Also, Qdot = 0 and Wdot_ext = 0. Hit Enter. We get:



Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | @Case-0 | ☑ Help Messages On

Device-A [1-2] | i-State: State-1 | e-State: State-2

☑ Qdot: 0.0 kW
☐ Wdot_ext: 0.0 kW
☑ T_B: 298.15 K
☐ Sdot_gen: 0.01101 kW/K
Jdot_net: 0.0 kW
Sdot_net: -0.01101 kW/K

Single-Flow Steady Device - A

Mass: $\dot{m}_i = \dot{m}_e = \dot{m}$

Energy: $0 = \dot{m}(j_i - j_e) + \dot{Q} - \dot{W}_{ext}$

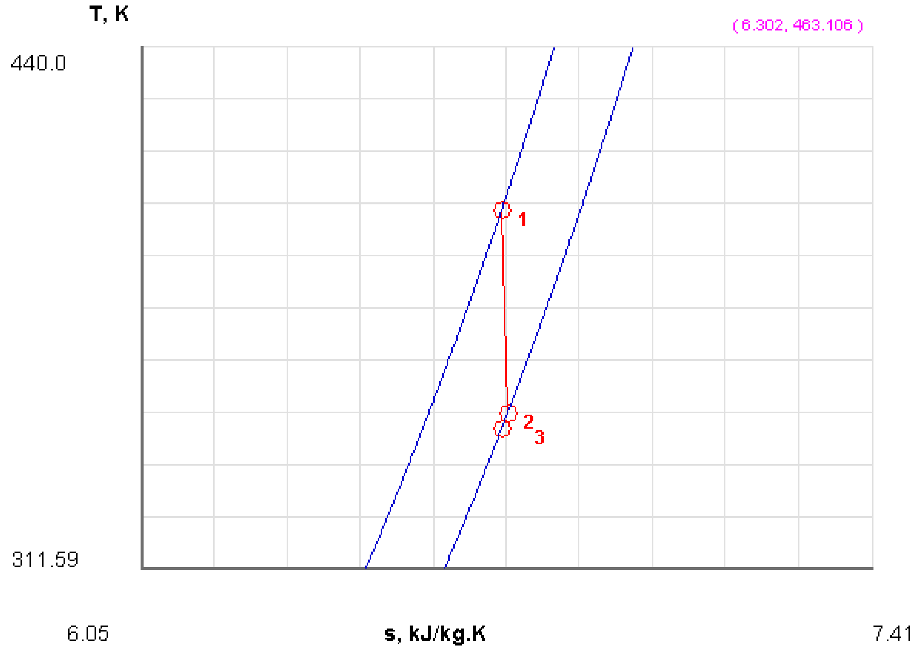
Entropy: $0 = \dot{m}(s_i - s_e) + \frac{\dot{Q}}{T_B} + \dot{S}_{gen}$

State-Null: It indicates that a port is closed.

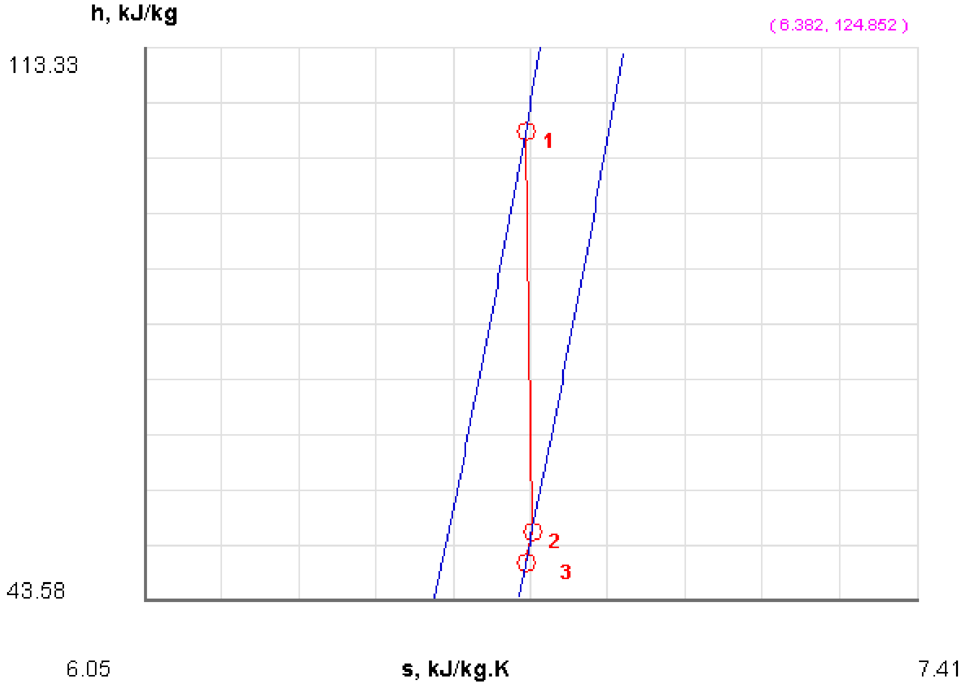
WinHip: Work in negative Heat in positive

Note that: Entropy generated = Sdot_gen = 0.01101 kW/K …. Ans.

7. From the Plots tab, get T-s diagram. Here const. pressure lines are shown in blue and the State points 1, 2 and 3 are also shown marked. Process 1–2 is the actual and Process 1–3 is isentropic process.



8. Also, get the h-s plot: Again, processes 1–2 and 1–3 are shown. Const. pressure lines are shown in blue.



9. **Isentropic efficiency of Nozzle:**

   η_s = (h1 – h2a) / (h1-h2s) = (h1-h2) / (h1 – h3) where

   h1 is the enthalpy of fluid entering the nozzle.
   h2a is the enthalpy after actual expansion in nozzle, and
   h3 is the enthalpy after expansion if the expansion were isentropic.

#Isentropic effcy:
= (h1-h2) / (h1-h3)

i.e. (h1-h2) / (h1-h3) = 0.9298308065807511 = 0.93 = 93% …. Ans.

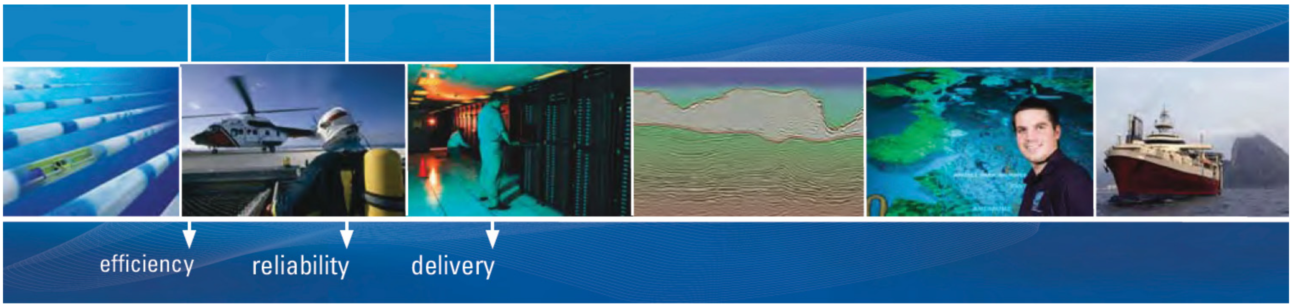
9. Click on **SuperCalculate** to get TEST code etc. in the I/O Panel:

TEST code:

 # Daemon Path: Systems>Open>SteadyState>Generic>SingleFlow>IG-Model; v-10.ca08

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

States {
            State-1: Air;
            Given: { p1= 500.0 kPa; T1= 400.0 K; Vel1= 30.0 m/s; z1= 0.0 m; mdot1= 1.0 kg/s; }
            State-2: Air;
            Given: { p2= 300.0 kPa; T2= 350.0 K; z2= 0.0 m; j2= "j1" kJ/kg; mdot2= "mdot1" kg/s; }
            State-3: Air;
            Given: { p3= "p2" kPa; s3= "s1" kJ/kg.K; z3= 0.0 m; j3= "j1" kJ/kg; mdot3= "mdot1" kg/s; }
            }

Analysis {
            Device-A: i-State = State-1; e-State = State-2;
            Given: { Qdot= 0.0 kW; T_B= 298.15 K; }
            }

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

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

#       State   p(kPa)      T(K)    v(m^3/kg)    u(kJ/kg)     h(kJ/kg)     s(kJ/kg)
#         1     500.0       400.0    0.2296      -11.77        103.03      6.722
#         2     300.0       350.0    0.3348      -48.19        52.25       6.733
#         3     300.0       346.2    0.3312      -50.94        48.42       6.722

#--------Property spreadsheet ends------------------------------------------------------------------------

# Mass, Energy, and Entropy Analysis Results:

#          Device-A: i-State = State-1; e-State = State-2;
#          Given: Qdot= 0.0 kW; T_B= 298.15 K;
#          Calculated: Wdot_ext= 0.0 kW; Sdot_gen= 0.011007705 kW/K; Jdot_net= 0.0 kW; Sdot_net=
-0.011007705 kW/K;

======================================================================
```

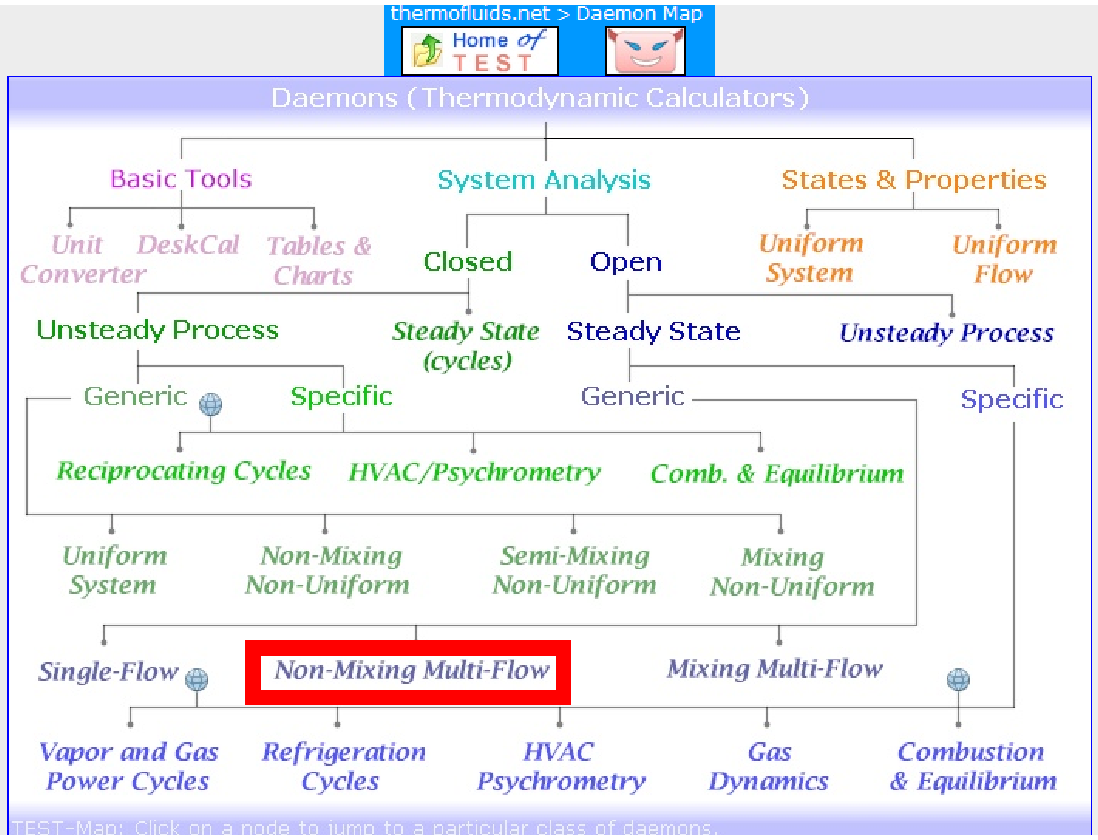


Prob.7.25. Cold water leading to a shower enters a well insulated, thin walled, double pipe counter flow heat exchanger at 10 C at a rate of 0.9 kg/s and is heated to 70 C by hot water that enters at 85 C at a rate of 1.5 kg/s. Determine: (a) the rate of heat transfer, and (b) rate of entropy generation in the heat exchanger. Assume that both the streams are at 1.5 bar pressure. (c) In addition, plot the variation of exit temp of hot water and Entropy generation rate against hot water flow rate, mdot3 as it varies from 1 kg/s to 2 kg/s.

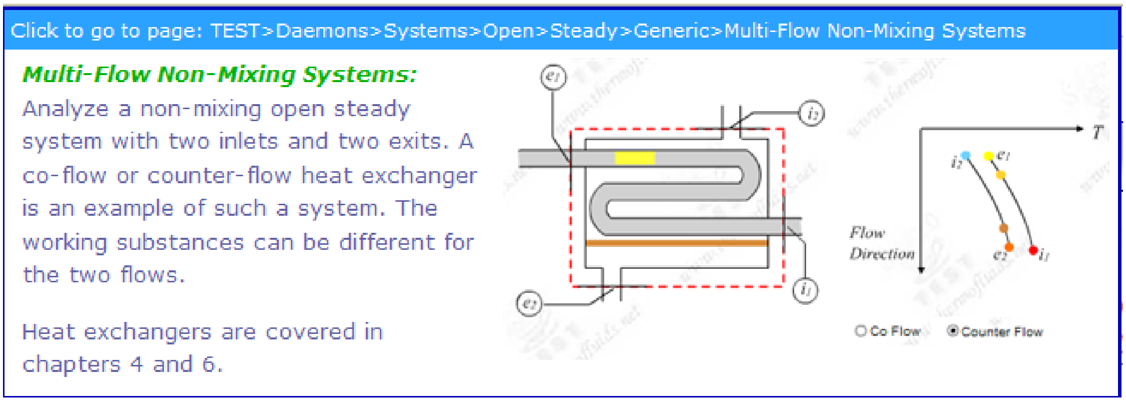
TEST Solution:

Following are the steps:

1. From the Daemon tree, select System Analysis – Open – Non-mixing Multi-flow, shown below:



Hovering the mouse po inter over ‘Non-mixing Multi-flow’ brings up the following explanatory pop-up:



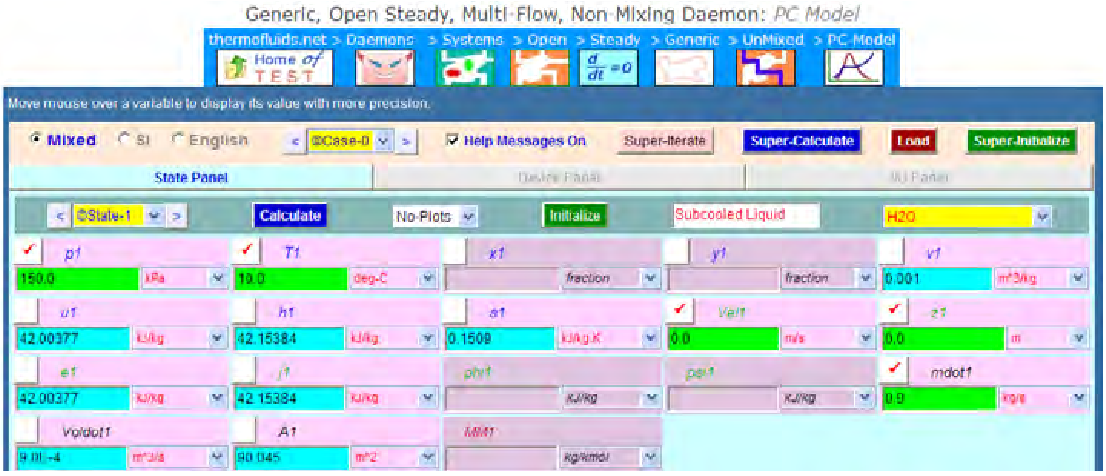
Click to go to page: TEST>Daemons>Systems>Open>Steady>Generic>Multi-Flow Non-Mixing Systems

Multi-Flow Non-Mixing Systems: Analyze a non-mixing open steady system with two inlets and two exits. A co-flow or counter-flow heat exchanger is an example of such a system. The working substances can be different for the two flows.

Heat exchangers are covered in chapters 4 and 6.

○ Co Flow ● Counter Flow

2. For Material model, select PC Model and select H2O as the working substance. Enter values for P1, T1and mdot1 representing State 1. Hit Enter, and all other parameters are immediately calculated:



Subcooled Liquid

H2O

p1: 150.0 kPa
T1: 10.0 deg-C
x1: fraction
y1: fraction
v1: 0.001 m^3/kg
u1: 42.00377 kJ/kg
h1: 42.15384 kJ/kg
s1: 0.1509 kJ/kg.K
Vel1: 0.0 m/s
z1: 0.0 m
e1: 42.00377 kJ/kg
j1: 42.15384 kJ/kg
phi1: kJ/kg
psi1: kJ/kg
mdot1: 0.9 kg/s
Voldot1: 9.0E-4 m^3/s
A1: 90.045 m^2
MM1: kg/kmol

3. Similarly for State 2, i.e. exit of cold water, enter P2, T2 and mdot2 = mdot1. Hit Enter. We get:

Subcooled Liquid

H2O

p2: =p1 kPa
T2: 70.0 deg-C
x2: fraction
y2: fraction
v2: 0.00102 m^3/kg
u2: 292.9481 kJ/kg
h2: 293.10153 kJ/kg
s2: 0.9549 kJ/kg.K
Vel2: 0.0 m/s
z2: 0.0 m
e2: 292.9481 kJ/kg
j2: 293.10153 kJ/kg
phi2: kJ/kg
psi2: kJ/kg
mdot2: =mdot1 kg/s
Voldot2: 9.2E-4 m^3/s
A2: 92.07 m^2
MM2: kg/kmol

4. Now, for State 3, i.e. inlet of hot water stream: enter P3, T3 and mdot3. Hit Enter. We get:

Subcooled Liquid

H2O

p3: =p1 kPa
T3: 85.0 deg-C
x3: fraction
y3: fraction
v3: 0.00103 m^3/kg
u3: 355.84024 kJ/kg
h3: 355.99518 kJ/kg
s3: 1.1343 kJ/kg.K
Vel3: 0.0 m/s
z3: 0.0 m
e3: 355.84024 kJ/kg
j3: 355.99518 kJ/kg
phi3: kJ/kg
psi3: kJ/kg
mdot3: 1.5 kg/s
Voldot3: 0.00155 m^3/s
A3: 154.95 m^2
MM3: kg/kmol

5. Next for State 4, exit of hot water stream: enter P4 = P3, mdot4 = mdot3, and T4 is calculated by heat balance as: T4 = T3 – (mdot1/mdot3)*(T2-T1) = 49.0 C. Hit Enter. We get:

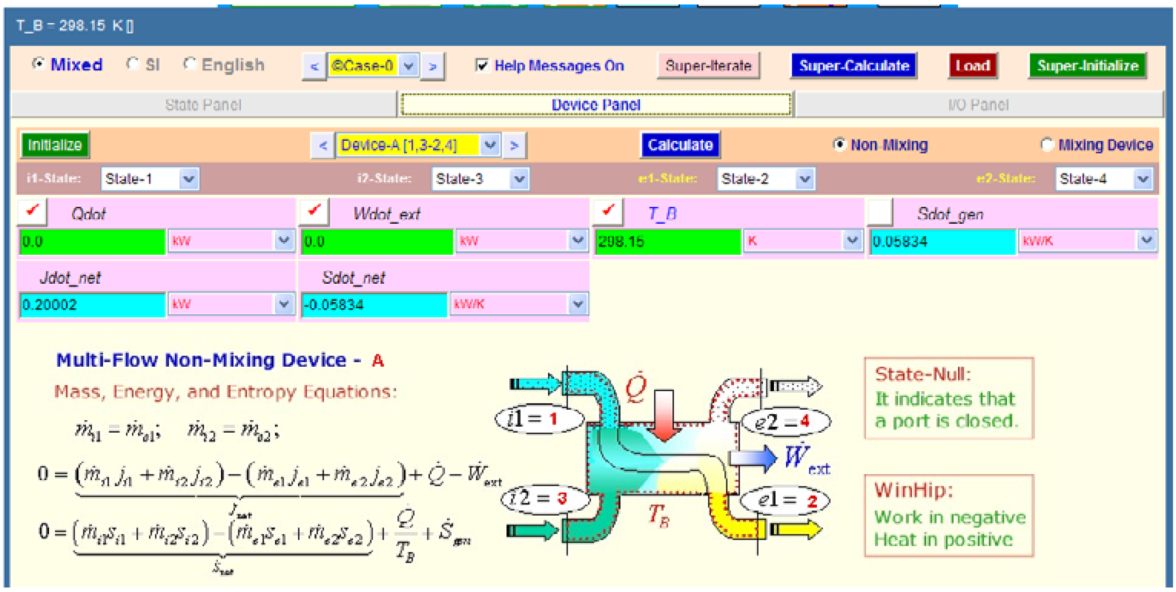
Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | @Case-0 | ☑ Help Messages On

@State-4 | No-Plots | Subcooled Liquid | H2O

☑ p4: =p3 kPa
☑ T4: =T3-(mdot1/mdot deg-C
☐ x4: fraction
☐ y4: fraction
☐ v4: 0.00101 m^3/kg
☐ u4: 205.1415 kJ/kg
☐ h4: 205.29321 kJ/kg
☐ s4: 0.69079 kJ/kg.K
☑ Vel4: 0.0 m/s
☑ z4: 0.0 m
☐ e4: 205.1415 kJ/kg
☐ j4: 205.29321 kJ/kg
phi4: kJ/kg
psi4: kJ/kg
☑ mdot4: =mdot3 kg/s
☐ Voldot4: 0.00152 m^3/s
☐ A4: 151.72841 m^2
MM4: kg/kmol

6. Now, go to Device Panel. Select Non-Mixing type redio button. Enter State 1 and State 3 for i-1 and i-2 States, and State 2 and State 4 for e-1 and e-2 States. (i --- inlet, e …. Exit). And, Qdot = 0 since it is an insulated heat exchanger) and Wdot_ext = o since there is no work transfer. Hit Enter. We get:



T_B = 298.15 K

● Mixed ○ SI ○ English | @Case-0 | ☑ Help Messages On

Device-A [1,3-2,4] | ● Non-Mixing ○ Mixing Device

i1-State: State-1 | i2-State: State-3 | e1-State: State-2 | e2-State: State-4

☑ Qdot: 0.0 kW
☑ Wdot_ext: 0.0 kW
☑ T_B: 298.15 K
☐ Sdot_gen: 0.05834 kW/K
Jdot_net: 0.20002 kW
Sdot_net: -0.05834 kW/K

Multi-Flow Non-Mixing Device - A

Mass, Energy, and Entropy Equations:

$$\dot{m}_{i1} = \dot{m}_{e1}; \quad \dot{m}_{i2} = \dot{m}_{e2};$$

$$0 = \underbrace{(\dot{m}_{i1} j_{i1} + \dot{m}_{i2} j_{i2}) - (\dot{m}_{e1} j_{e1} + \dot{m}_{e2} j_{e2})}_{\dot{J}_{net}} + \dot{Q} - \dot{W}_{ext}$$

$$0 = \underbrace{(\dot{m}_{i1} s_{i1} + \dot{m}_{i2} s_{i2}) - (\dot{m}_{e1} s_{e1} + \dot{m}_{e2} s_{e2})}_{\dot{S}_{net}} + \frac{\dot{Q}}{T_B} + \dot{S}_{gen}$$

State-Null: It indicates that a port is closed.

WinHip: Work in negative Heat in positive

Thus:

Heat transfer in the heat exchanger = mdot1 * (h2 – h1) =225.85 kW …. Ans.

Entropy generated = Sdot_gen = 0.05834 kW/K …(see Device panel)… Ans.

7. **SuparCalculate** to get the TEST code etc in the I/O panel:

```
#*******TEST-code:

#         Daemon Path: Systems>Open>SteadyState>Generic>MultiFlowUnmixed>PC-Model; v-10.cb01

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

States   {
            State-1: H2O;
            Given: { p1= 150.0 kPa; T1= 10.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 0.9 kg/s; }
            State-2: H2O;
            Given: { p2= “p1” kPa; T2= 70.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= “mdot1” kg/s; }
            State-3: H2O;
            Given: { p3= “p1” kPa; T3= 85.0 deg-C; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= 1.5 kg/s; }
            State-4: H2O;
            Given: { p4= “p3” kPa; T4= “T3-(mdot1/mdot3)*(T2-T1)” deg-C; Vel4= 0.0 m/s; z4= 0.0 m;
            mdot4= “mdot3” kg/s; }
            }
```

```
Analysis {
            Device-A: i-State = State-1, State-3; e-State = State-2, State-4; Mixing: false;
            Given: { Qdot= 0.0 kW; Wdot_ext= 0.0 kW; T_B= 298.15 K; }
            }

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

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

# State  p(kPa)      T(K)    x     v(m3/kg)    u(kJ/kg)    h(kJ/kg)    s(kJ/kg)
# 01     150.0       283.2         0.001       42.0        42.15       0.151
# 02     150.0       343.2         0.001       292.95      293.1       0.955
# 03     150.0       358.2         0.001       355.84      356.0       1.134
# 04     150.0       322.2         0.001       205.14      205.29      0.691
```

 # Mass, Energy, and Entropy Analysis Results:

```
#          Device-A: i-State = State-1, State-3; e-State = State-2, State-4; Mixing: false;
#          Given: Qdot= 0.0 kW; Wdot_ext= 0.0 kW; T_B= 298.15 K;

# Calculated: Sdot_gen= 0.058339186 kW/K; Jdot_net= 0.20002486 kW; Sdot_net= -0.058339186 kW/K;

#******CALCULATE VARIABLES: Type in an expression starting with an '=' sign ('= mdot1*(h2-h1)', '= sqrt(4*A1/PI)', etc.) and press the Enter key)*********

# Heat transfer in HX:
```

=mdot1*(h2-h1) = 225.85292610253674 kW

In addition, plot the variation of T4 and Sdot_gen rate as hot water flow rate, mdot3 varies from 1 kg/s to 2 kg/s:

The procedure is:

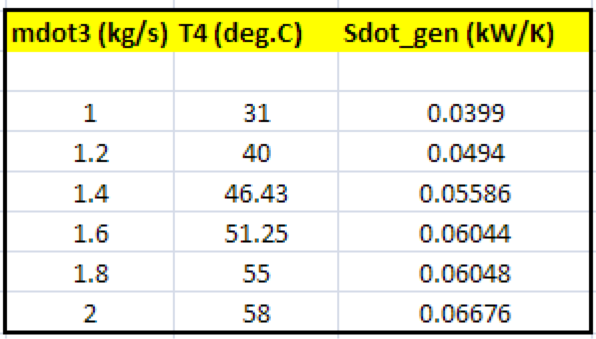
Go to State 3 and change mdot3 = 1 kg/s.

Click on Calculate and then SuperCalculate.

Go to State 4 and read the new value of T4.

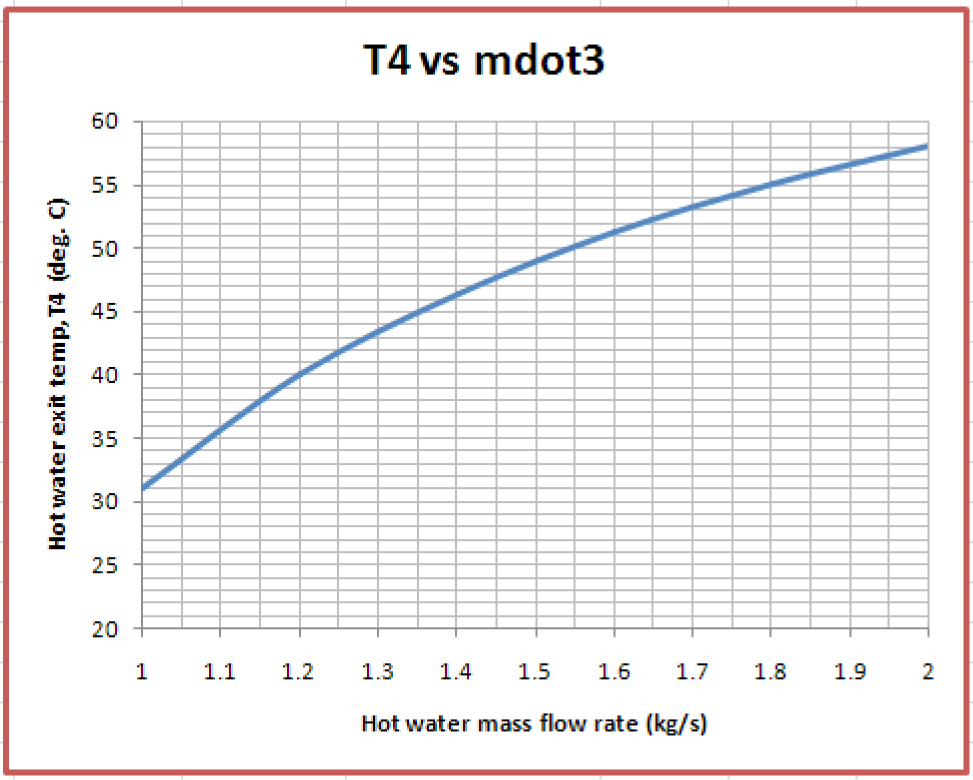
Also, go to Device panel and read the value of Sdot_gen.

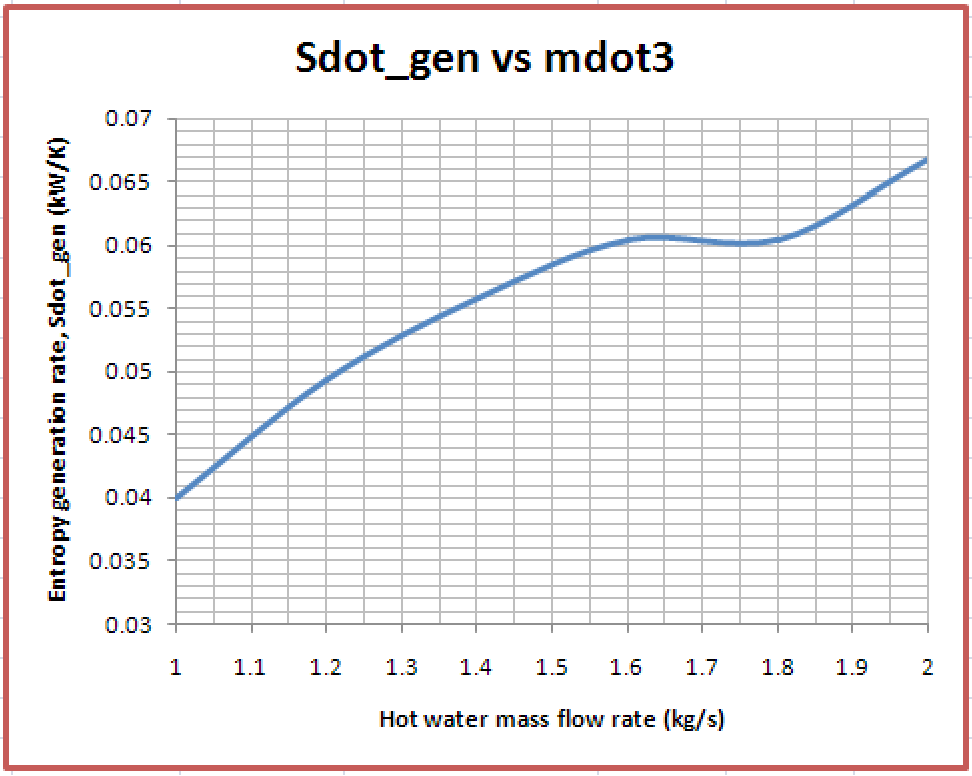
Repeat this procedure for different values of mdot3 and tabulate the corresponding values of T4 and Sdot_gen against mdot3. We get the following:



mdot3 (kg/s)	T4 (deg.C)	Sdot_gen (kW/K)
1	31	0.0399
1.2	40	0.0494
1.4	46.43	0.05586
1.6	51.25	0.06044
1.8	55	0.06048
2	58	0.06676

Now, plot the results in EXCEL:





==

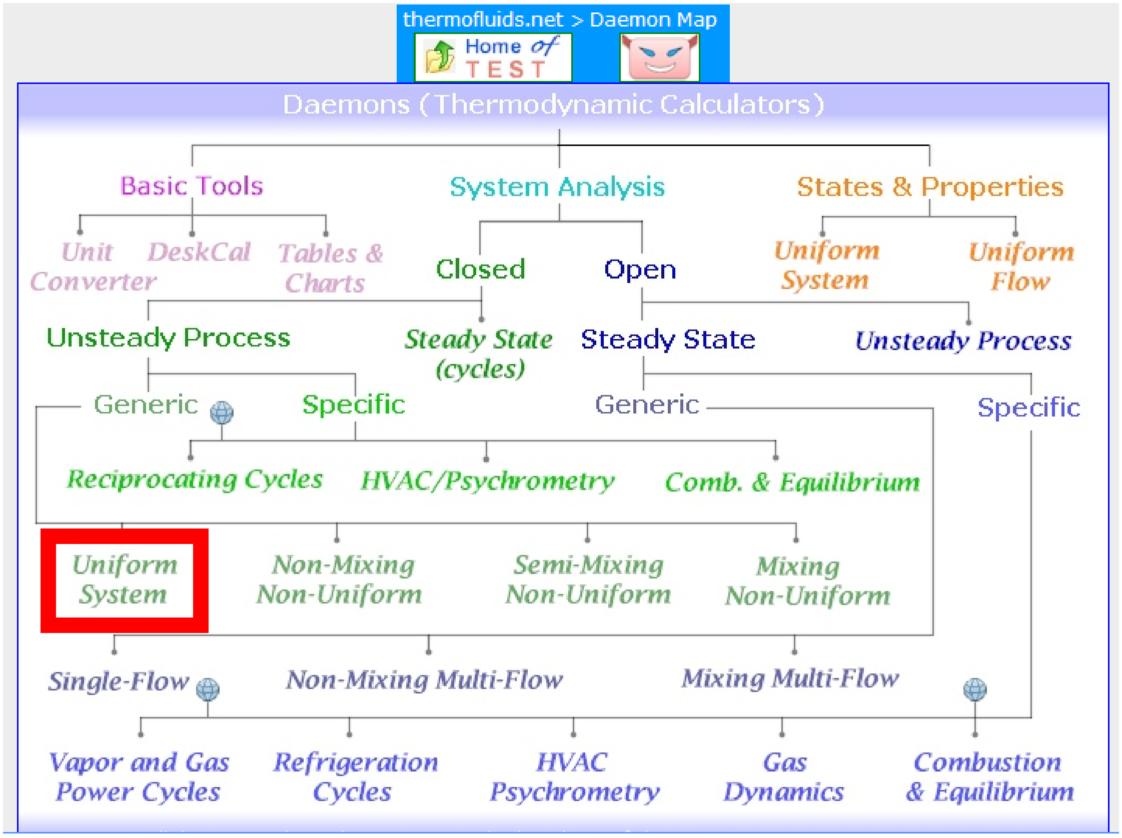
Prob.7.26. A 5 L jug of milk at 25 C is placed in the refrigerator where it is cooled down to the refrigerator's inside constant temp of 5 C. Assume that the milk has properties of liquid water and find the entropy generated in the cooling process. [VTU-BTD-Dec. 2009–Jan. 2010]

TEST Solution:

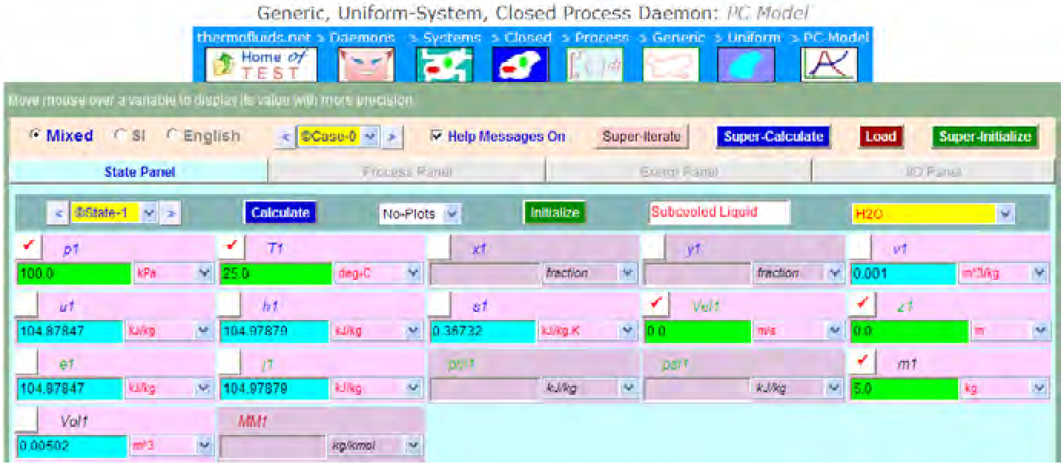
Note that for this case, milk is considered as equivalent to water as far as properties are concerned. Also refrigerator temp is constant at 5 C, and this is the sink (or surroundings) to which heat is rejected.

Following are the steps:

1. From the Daemons tree, select the System Analysis – Closed – Generic – Uniform System as shown below:



2. Click on Uniform System, and for material model, select the Phase Change (PC) model, and choose H2O as the working substance. For State 1, enter values for P1, T1 and m1. Hit Enter. We get:



● Mixed ○ SI ○ English
@Case-0
☑ Help Messages On
@State-1
No-Plots
Subcooled Liquid
H2O

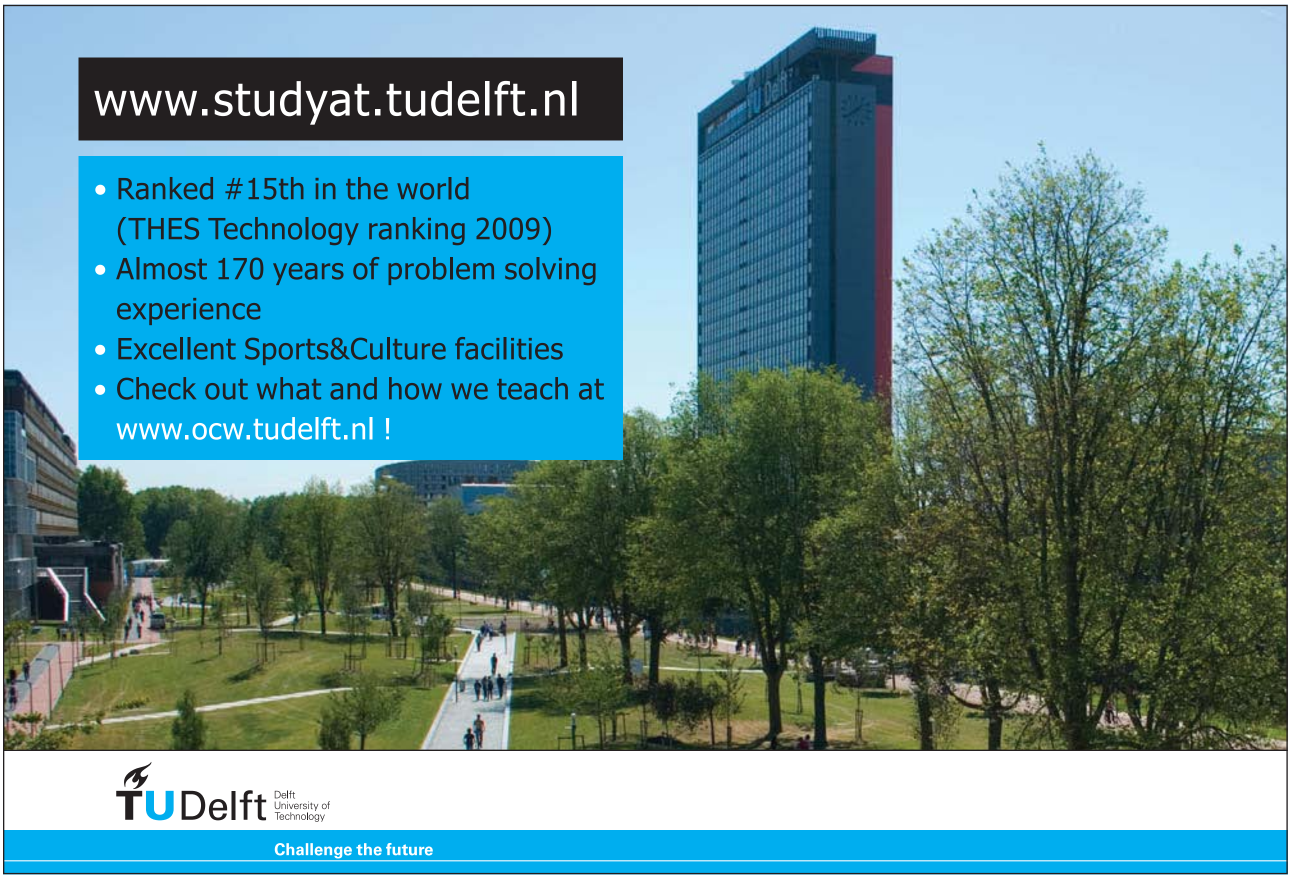
✓ p1: 100.0 kPa	✓ T1: 25.0 deg-C	☐ x1: fraction	☐ y1: fraction	☐ v1: 0.001 m^3/kg
☐ u1: 104.87847 kJ/kg	☐ h1: 104.97879 kJ/kg	☐ s1: 0.36732 kJ/kg.K	✓ Vel1: 0.0 m/s	✓ z1: 0.0 m
☐ e1: 104.87847 kJ/kg	☐ j1: 104.97879 kJ/kg	phi1: kJ/kg	psi1: kJ/kg	✓ m1: 5.0 kg
☐ Vol1: 0.00502 m^3	MM1: kg/kmol			

3. For State 2, enter P2, T2 and m2 = m1, and hit Enter. We get:

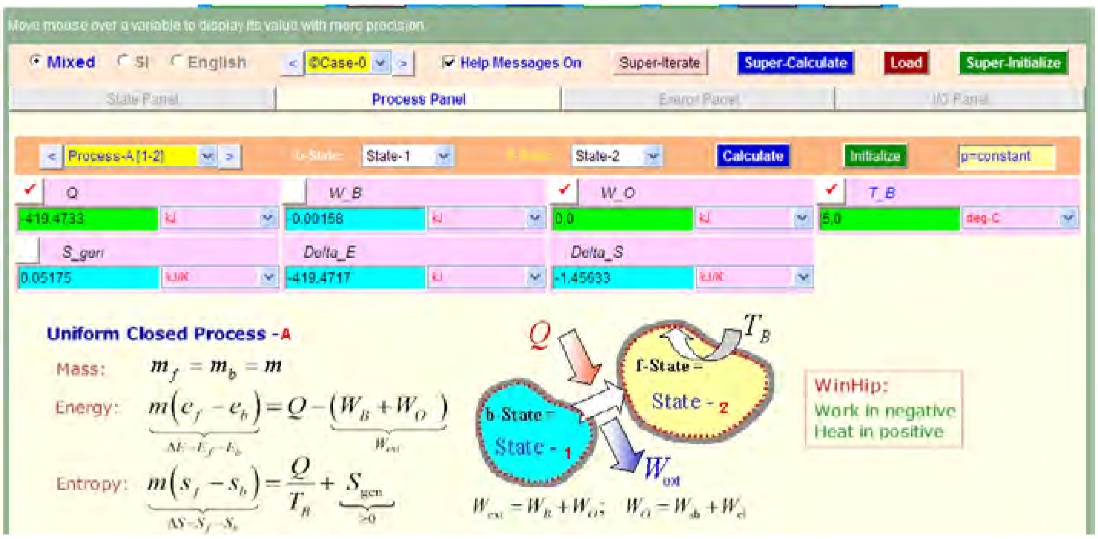
Subcooled Liquid

H2O

✓ p2	✓ T2	☐ x2	☐ y2	☐ v2
100.0 kPa	5.0 deg-C	fraction	fraction	0.001 m^3/kg
☐ u2	☐ h2	☐ s2	✓ Vel2	✓ z2
20.98413 kJ/kg	21.08413 kJ/kg	0.07605 kJ/kg.K	0.0 m/s	0.0 m
☐ e2	☐ j2	phi2	psi2	✓ m2
20.98413 kJ/kg	21.08413 kJ/kg	kJ/kg	kJ/kg	=m1 kg
☐ Vol2	MM2			
0.005 m^3	kg/kmol			



4. Now, go to Process Panel. Enter State 1 and State 2 for b-State and f-State respectively. Enter W_O = 0 (since there are no other works), and Q is –ve, i.e. Q = -m1*4.18*(T1-T2) = heat *leaving* the system (i.e. the water). **Also, it is important to enter the Surrounding (or Boundary) temp T_B as 5 C**. Hit Enter. We get:



Process-A [1-2]; b-State: State-1; f-State: State-2; p=constant

Q: -419.4733 kJ
W_B: 0.00158 kJ
W_O: 0.0 kJ
T_B: 5.0 deg-C
S_gen: 0.05175 kJ/K
Delta_E: -419.4717 kJ
Delta_S: -1.45633 kJ/K

Uniform Closed Process -A

Mass: $m_f = m_b = m$

Energy: $\underbrace{m(e_f - e_b)}_{\Delta E = E_f - E_b} = Q - \underbrace{(W_B + W_O)}_{W_{ext}}$

Entropy: $\underbrace{m(s_f - s_b)}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + \underbrace{S_{gen}}_{\geq 0}$

$W_{ext} = W_B + W_O; \quad W_O = W_{sh} + W_{el}$

WinHip:
Work in negative
Heat in positive

Thus, we get: Entropy generated = S_gen = 0.05175 kJ/K …. Ans.

5. Clicking on **SuperCalculate** gives TEST code etc. in the I/O Panel:

TEST code etc:

```
#          Daemon Path: Systems>Closed>Process>Generic>Uniform>PC-Model; v-10.cb01

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

States    {
             State-1: H2O;
             Given: { p1= 100.0 kPa; T1= 25.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 5.0 kg; }
             State-2: H2O;
             Given: { p2= 100.0 kPa; T2= 5.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; m2= "m1" kg; }
             }

Analysis {
             Process-A: b-State = State-1; f-State = State-2;
             Given: { Q= -419.4733 kJ; W_O= 0.0 kJ; T_B= 5.0 deg-C; }
             }

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

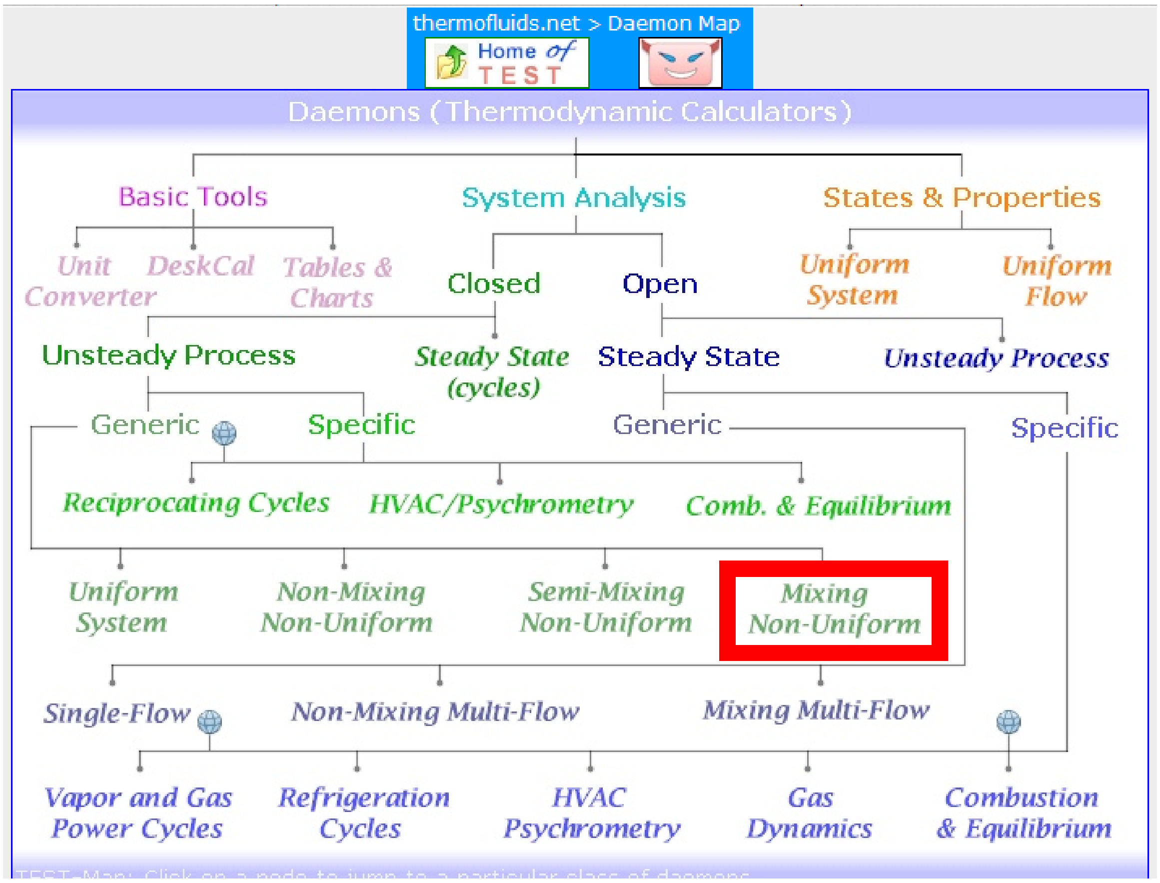
```
#--------Property spreadsheet starts:

# State  p(kPa)      T(K)   x     v(m3/kg)    u(kJ/kg)    h(kJ/kg)    s(kJ/kg)
# 01     100.0       298.2        0.001       104.88      104.98      0.367
# 02     100.0       278.2        0.001       20.98       21.08       0.076

# Mass, Energy, and Entropy Analysis Results:

#        Process-A: b-State = State-1; f-State = State-2;
#                 Given: Q= -419.4733 kJ; W_O= 0.0 kJ; T_B= 5.0 deg-C;
#                 Calculated: W_B= -0.0015783508 kJ; S_gen= 0.051749725 kJ/K; Delta_E= -419.4717
kJ; Delta_S= -1.4563333 kJ/K;

========================================================================
```

Prob.7.27. An open, insulated vessel contains 10 kg of water at 30 C. A mass of 2 kg of ice at a temp of -4 C is added to the water and after a time, the temp of the contents of the vessel becomes uniform. Assuming the heat transfer to the atmosphere to be zero, determine the final temp and the change in entropy of the mixture. [VTU-BTD-July 2007]

TEST Solution:

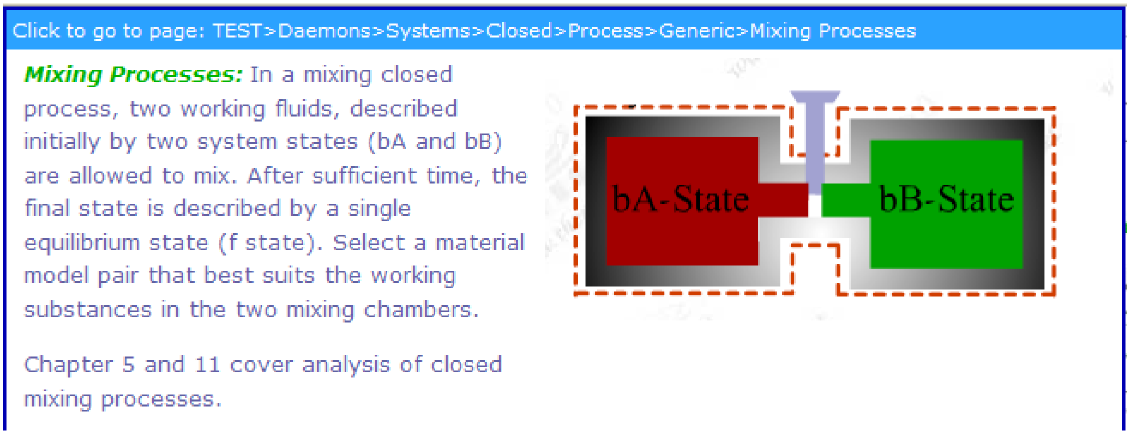
Following are the steps:

1. From the Daemons tree, select the System Analysis – Closed – Generic _ Mixing Non-Uniform as shown below:



TEST-Map: Click on a node to jump to a particular class of daemons

Hovering the mouse pointer over 'Mixing Non-Uniform' brings up the following pop-up explanatory window:

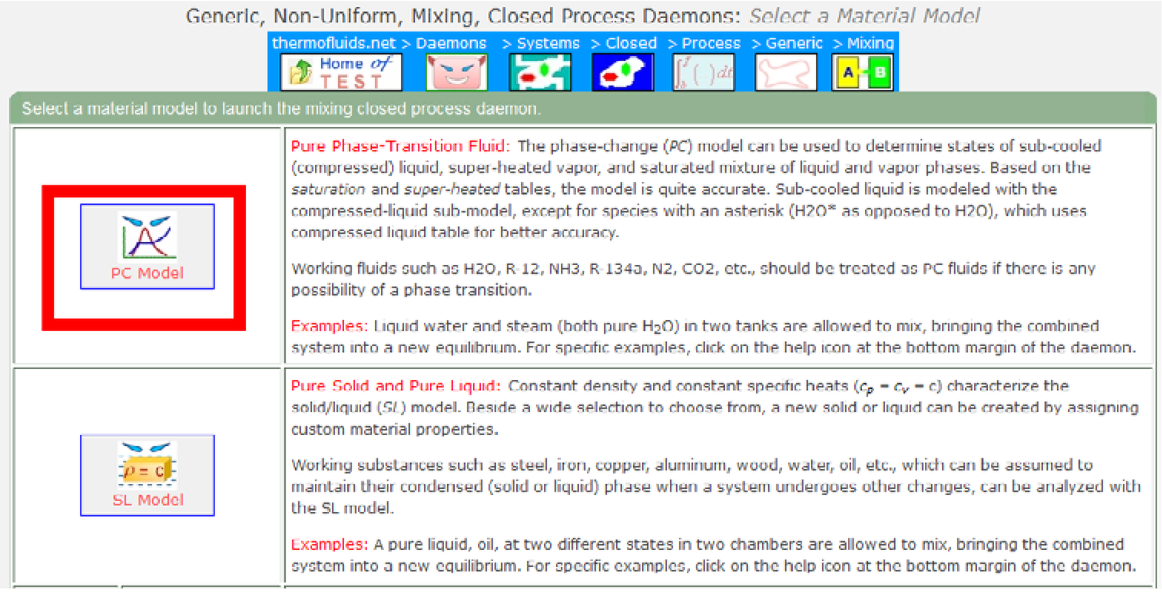


Click to go to page: TEST>Daemons>Systems>Closed>Process>Generic>Mixing Processes

Mixing Processes: In a mixing closed process, two working fluids, described initially by two system states (bA and bB) are allowed to mix. After sufficient time, the final state is described by a single equilibrium state (f state). Select a material model pair that best suits the working substances in the two mixing chambers.

Chapter 5 and 11 cover analysis of closed mixing processes.

2. Select the PC model for Material model:



Select a material model to launch the mixing closed process daemon.

Pure Phase-Transition Fluid: The phase-change (*PC*) model can be used to determine states of sub-cooled (compressed) liquid, super-heated vapor, and saturated mixture of liquid and vapor phases. Based on the *saturation* and *super-heated* tables, the model is quite accurate. Sub-cooled liquid is modeled with the compressed-liquid sub-model, except for species with an asterisk (H2O* as opposed to H2O), which uses compressed liquid table for better accuracy.

Working fluids such as H2O, R-12, NH3, R-134a, N2, CO2, etc., should be treated as PC fluids if there is any possibility of a phase transition.

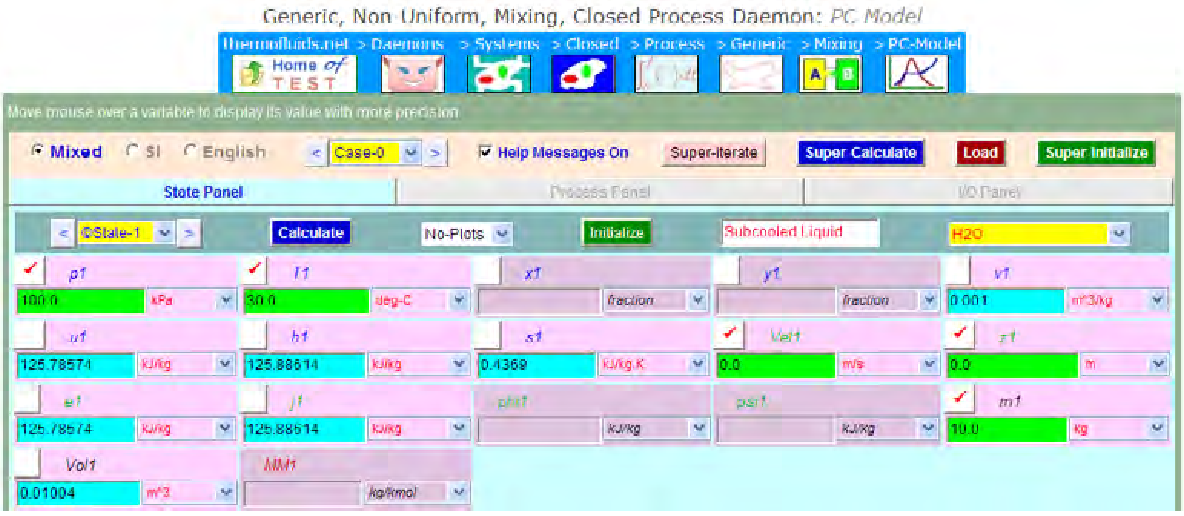
Examples: Liquid water and steam (both pure H_2O) in two tanks are allowed to mix, bringing the combined system into a new equilibrium. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Solid and Pure Liquid: Constant density and constant specific heats ($c_p = c_v = c$) characterize the solid/liquid (*SL*) model. Beside a wide selection to choose from, a new solid or liquid can be created by assigning custom material properties.

Working substances such as steel, iron, copper, aluminum, wood, water, oil, etc., which can be assumed to maintain their condensed (solid or liquid) phase when a system undergoes other changes, can be analyzed with the SL model.

Examples: A pure liquid, oil, at two different states in two chambers are allowed to mix, bringing the combined system into a new equilibrium. For specific examples, click on the help icon at the bottom margin of the daemon.

3. Then, choose H2O for substance, and for State 1 (for Water), enter P1, T1, m1 and hit Enter. We get:



Subcooled Liquid

H2O

✓ p1: 100.0 kPa

✓ T1: 30.0 deg-C

x1: fraction

y1: fraction

v1: 0.001 m^3/kg

u1: 125.78574 kJ/kg

h1: 125.88614 kJ/kg

s1: 0.4369 kJ/kg.K

✓ Vel1: 0.0 m/s

✓ z1: 0.0 m

e1: 125.78574 kJ/kg

j1: 125.88614 kJ/kg

phi1: kJ/kg

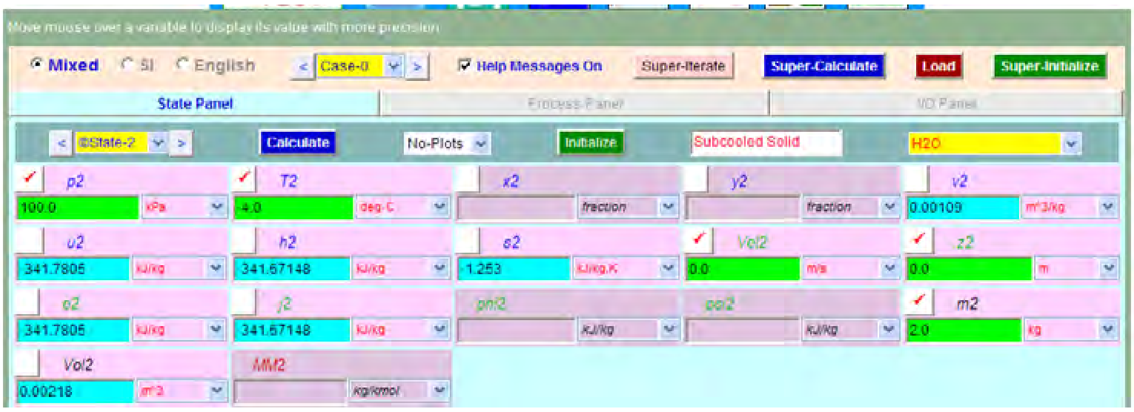
psi1: kJ/kg

✓ m1: 10.0 kg

Vol1: 0.01004 m^3

MM1: kg/kmol

4. Similarly for State 2 (i.e. for Ice), enter P2, T2 and m2. Hit Enter. We get:



Move mouse over a variable to display its value with more precision

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

@State-2

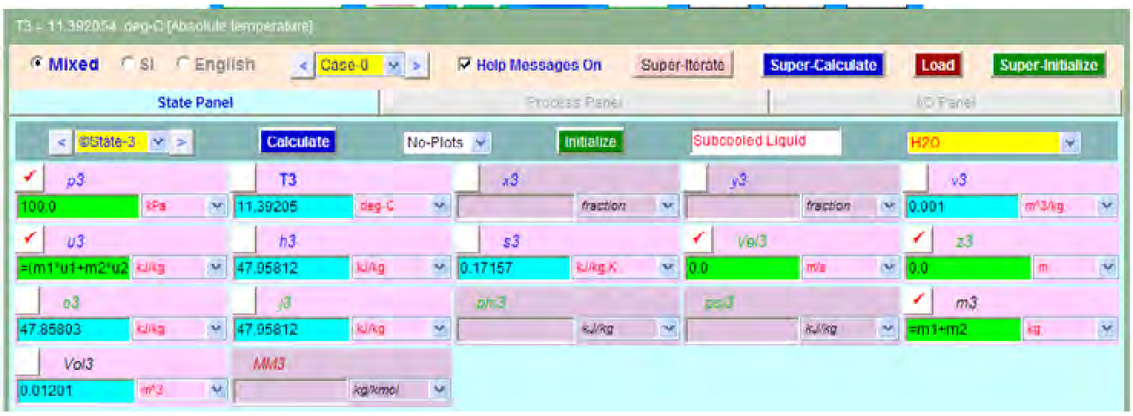
No-Plots

Subcooled Solid

H2O

✓ p2 100.0 kPa
✓ T2 -4.0 deg-C
x2 fraction
y2 fraction
v2 0.00109 m^3/kg
u2 341.7805 kJ/kg
h2 341.67148 kJ/kg
s2 -1.253 kJ/kg.K
✓ Vel2 0.0 m/s
✓ z2 0.0 m
e2 341.7805 kJ/kg
j2 341.67148 kJ/kg
phi2 kJ/kg
psi2 kJ/kg
✓ m2 2.0 kg
Vol2 0.00218 m^3
MM2 kg/kmol

5. Now, for State 3 (i.e. for the mixture), enter P3, u3 = (m1 * u1 + m2 * u2)/m3 .. by heat balance, and, m3 = (m1 + m2). Hit Enter. We get:



T3 = 11.392054 deg-C [Absolute temperature]

● Mixed ○ SI ○ English

Case-0

☑ Help Messages On

@State-3

No-Plots

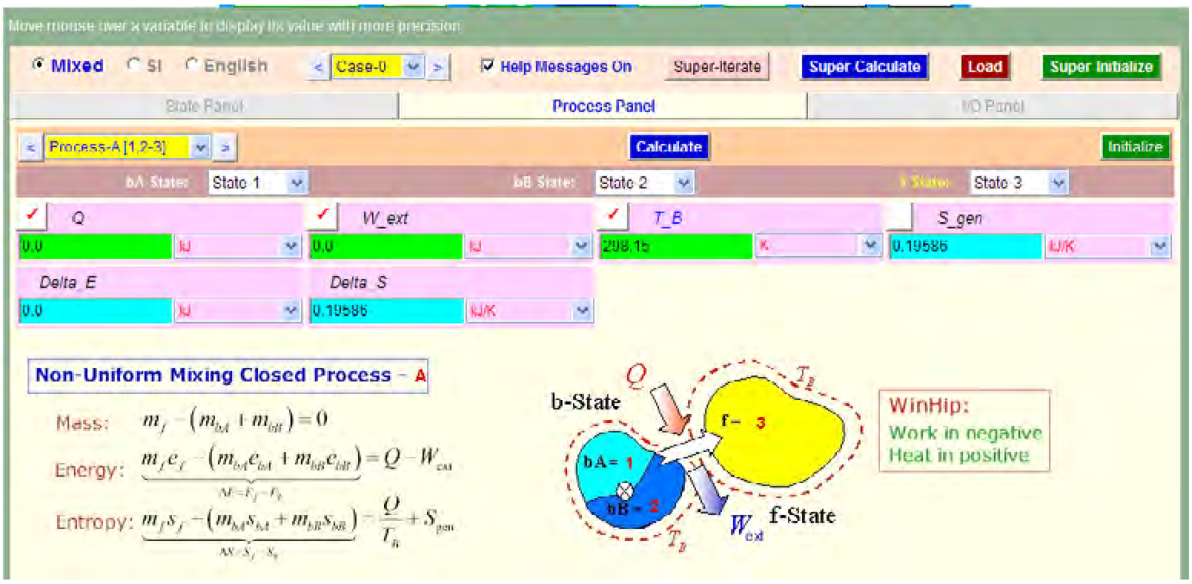
Subcooled Liquid

H2O

✓ p3 100.0 kPa
T3 11.39205 deg-C
x3 fraction
y3 fraction
v3 0.001 m^3/kg
✓ u3 =(m1*u1+m2*u2 kJ/kg
h3 47.95812 kJ/kg
s3 0.17157 kJ/kg.K
✓ Vel3 0.0 m/s
✓ z3 0.0 m
e3 47.85803 kJ/kg
j3 47.95812 kJ/kg
phi3 kJ/kg
psi3 kJ/kg
✓ m3 =m1+m2 kg
Vol3 0.01201 m^3
MM3 kg/kmol

Note immediately that final mixture temp = T3 = 11.39 C …. Ans.

6. Now, go to Process Panel. Enter State 1 for bA-State, State 2 for bB-State, and State 3 for f-State. Also, Q = 0 (since vessel is insulated), W_ext = 0 (since no external work). Hit Enter. We get:



Move mouse over a variable to display its value with more precision

● Mixed ○ SI ○ English Case-0 ☑ Help Messages On

Process Panel

Process-A [1,2-3]

bA State: State 1 bB State: State 2 f State: State 3

✓ Q: 0.0 kJ
✓ W_ext: 0.0 kJ
✓ T_B: 298.15 K
S_gen: 0.19586 kJ/K
Delta_E: 0.0 kJ
Delta_S: 0.19586 kJ/K

Non-Uniform Mixing Closed Process - A

Mass: $m_f - (m_{bA} + m_{bB}) = 0$

Energy: $\underbrace{m_f e_f - (m_{bA} e_{bA} + m_{bB} e_{bB})}_{\Delta E = E_f - E_b} = Q - W_{ext}$

Entropy: $\underbrace{m_f s_f - (m_{bA} s_{bA} + m_{bB} s_{bB})}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + S_{gen}$

WinHip:
Work in negative
Heat in positive

Thus: S_gen = 0.19586 kJ/K …. Ans.

7. Click on **SuperCalculate,** and get TEST code etc from the I/O Panel:

```
#        Daemon Path: Systems>Closed>Process>Generic>NonUniformMixed>PC-Model; v-10.cb01

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

States    {
          State-1: H2O;
          Given: { p1= 100.0 kPa; T1= 30.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 10.0 kg; }
          State-2: H2O;
          Given: { p2= 100.0 kPa; T2= -4.0 deg-C; Vel2= 0.0 m/s; z2= 0.0 m; m2= 2.0 kg; }
          State-3: H2O;
          Given: { p3= 100.0 kPa; u3= “(m1*u1+m2*u2)/m3” kJ/kg; 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; T_B= 298.15 K; }
          }

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

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

# Evaluated States:

#        State-1: H2O > Subcooled Liquid;
#                Given: p1= 100.0 kPa; T1= 30.0 deg-C; Vel1= 0.0 m/s;
#                        z1= 0.0 m; m1= 10.0 kg;
#                Calculated: v1= 0.001 m^3/kg; u1= 125.7857 kJ/kg; h1= 125.8861 kJ/kg;
#                        s1= 0.4369 kJ/kg.K; e1= 125.7857 kJ/kg; j1= 125.8861 kJ/kg;
#                        Vol1= 0.01 m^3;
#        State-2: H2O > Subcooled Solid;
#                Given: p2= 100.0 kPa; T2= -4.0 deg-C; Vel2= 0.0 m/s;
#                        z2= 0.0 m; m2= 2.0 kg;
#                Calculated: v2= 0.0011 m^3/kg; u2= -341.7805 kJ/kg; h2= -341.6715 kJ/kg;
#                        s2= -1.253 kJ/kg.K; e2= -341.7805 kJ/kg; j2= -341.6715 kJ/kg;
#                        Vol2= 0.0022 m^3;
```

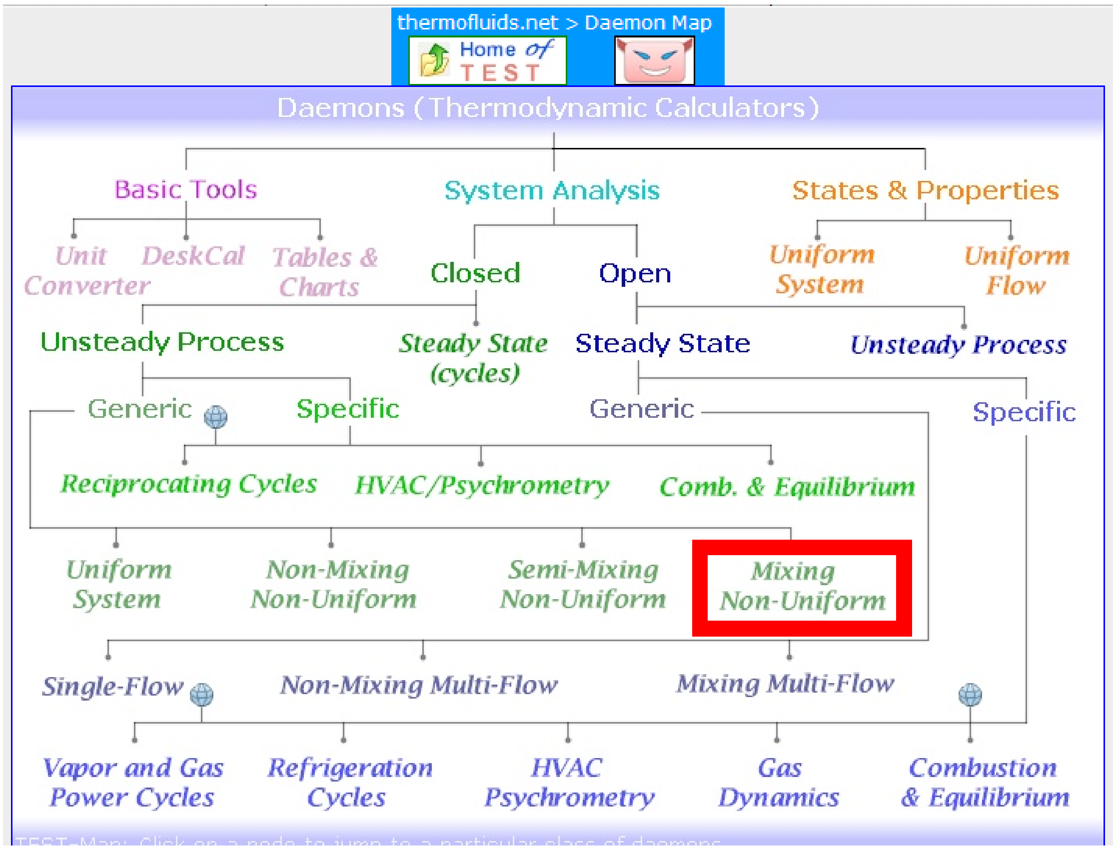
```
#         State-3: H2O > Subcooled Liquid;
#                   Given: p3= 100.0 kPa; u3= "(m1*u1+m2*u2)/m3" kJ/kg; Vel3= 0.0 m/s;
#                          z3= 0.0 m; m3= "m1+m2" kg;
#                   Calculated: T3= 11.392 deg-C; v3= 0.001 m^3/kg; h3= 47.9581 kJ/kg;
#                          s3= 0.1716 kJ/kg.K; e3= 47.858 kJ/kg; j3= 47.9581 kJ/kg;
#                          Vol3= 0.012 m^3;
#--------Property spreadsheet starts:

# State  p(kPa)      T(K)    x    v(m3/kg)    u(kJ/kg)    h(kJ/kg)    s(kJ/kg)
# 01     100.0       303.2        0.001       125.79      125.89      0.437
# 02     100.0       269.2        0.0011      -341.78     -341.67     -1.253
# 03     100.0       284.5        0.001       47.86       47.96       0.172

# Mass, Energy, and Entropy Analysis Results:

#         Process-A: b-State = State-1, State-2; f-State = State-3;
#                   Given: Q= 0.0 kJ; W_ext= 0.0 kJ; T_B= 298.15 K;
#                   Calculated: S_gen= 0.19586486 kJ/K; Delta_E= -0.0 kJ; Delta_S= 0.19586486 kJ/K;

========================================================================
```

Prob.7.28. A well insulated rigid tank contains 5 kg of a sat. liquid-vapor mixture of water at 150 kPa. Initially, three-quarters of the mass is in liquid phase. An electric resistance heater placed in the tank is now turned on and kept on until all the liquid in the tank is vaporized. Determine the entropy change of the steam during this process. [Ref:1]

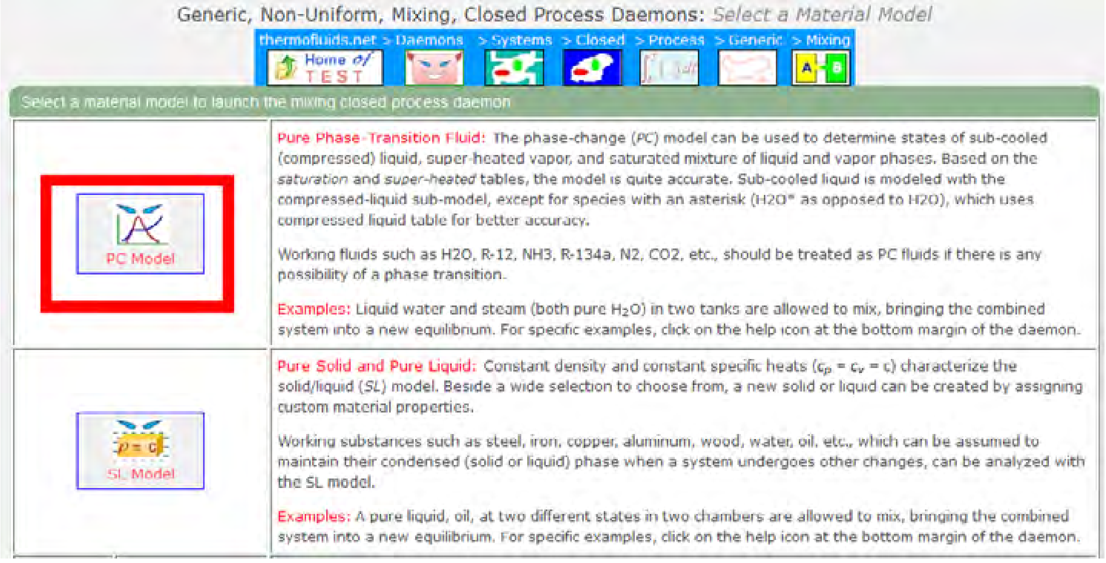
TEST Solution:

Following are the steps:

1. From the Daemons tree, select the System Analysis – Closed – Generic – Mixing Non-Uniform as shown below:



2. Select the PC model for Material model:



Pure Phase-Transition Fluid: The phase-change (*PC*) model can be used to determine states of sub-cooled (compressed) liquid, super-heated vapor, and saturated mixture of liquid and vapor phases. Based on the *saturation* and *super-heated* tables, the model is quite accurate. Sub-cooled liquid is modeled with the compressed-liquid sub-model, except for species with an asterisk (H2O* as opposed to H2O), which uses compressed liquid table for better accuracy.

Working fluids such as H2O, R-12, NH3, R-134a, N2, CO2, etc., should be treated as PC fluids if there is any possibility of a phase transition.

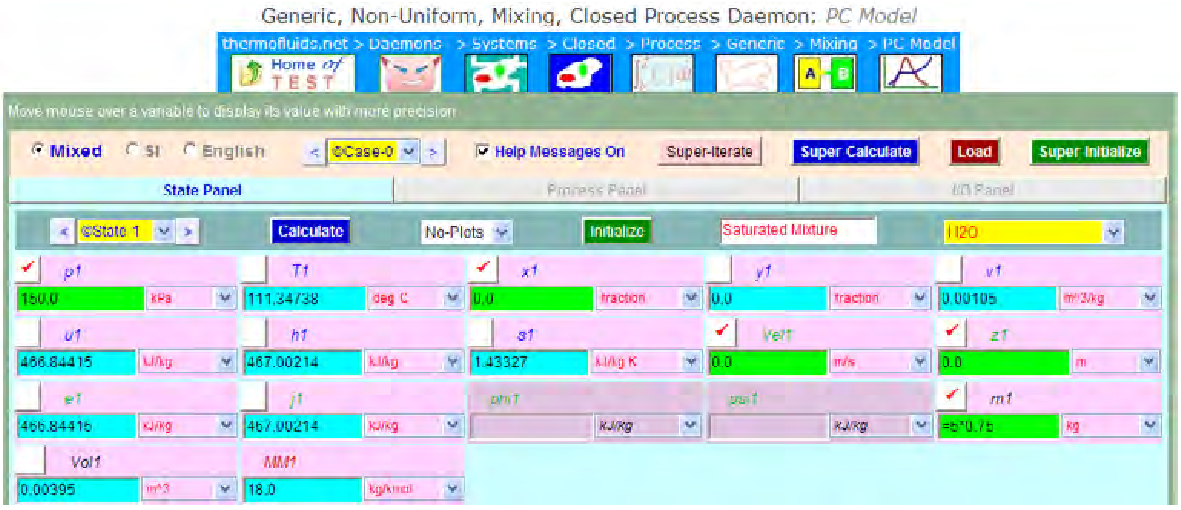
Examples: Liquid water and steam (both pure H_2O) in two tanks are allowed to mix, bringing the combined system into a new equilibrium. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Solid and Pure Liquid: Constant density and constant specific heats ($c_p = c_v = c$) characterize the solid/liquid (*SL*) model. Beside a wide selection to choose from, a new solid or liquid can be created by assigning custom material properties.

Working substances such as steel, iron, copper, aluminum, wood, water, oil, etc., which can be assumed to maintain their condensed (solid or liquid) phase when a system undergoes other changes, can be analyzed with the SL model.

Examples: A pure liquid, oil, at two different states in two chambers are allowed to mix, bringing the combined system into a new equilibrium. For specific examples, click on the help icon at the bottom margin of the daemon.

3. Then, choose H2O for substance, and for State 1 (for Water), enter P1 = 150 kPa, x1 = 0 for sat.liq., m1 = 0.75*5 kg and hit Enter. We get:

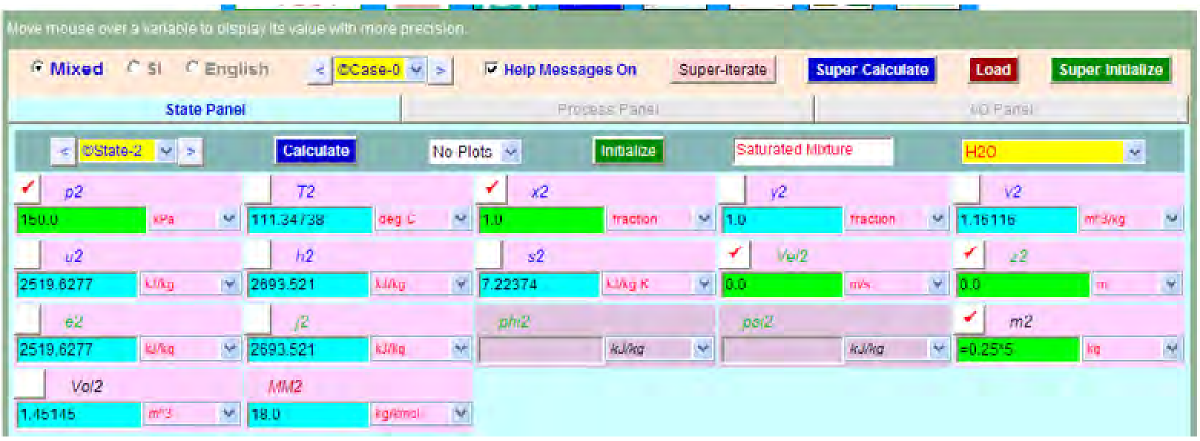


Saturated Mixture

H2O

☑ p1	☐ T1	☑ x1	☐ y1	☐ v1
150.0 kPa	111.34738 deg C	0.0 fraction	0.0 fraction	0.00105 m^3/kg
☐ u1	☐ h1	☐ s1	☑ Vel1	☑ z1
466.84415 kJ/kg	467.00214 kJ/kg	1.43327 kJ/kg.K	0.0 m/s	0.0 m
☐ e1	☐ j1	phi1	psi1	☑ m1
466.84415 kJ/kg	467.00214 kJ/kg	kJ/kg	kJ/kg	=5*0.75 kg
☐ Vol1	MM1			
0.00395 m^3	18.0 kg/kmol			

4. Next, for State 2, enter P2=150 kPa, x2 = 1 for sat. vap, m2 = 0.25 * 5 kg. Hit Enter. We get:



● Mixed ○ SI ○ English

©Case-0

☑ Help Messages On

©State-2

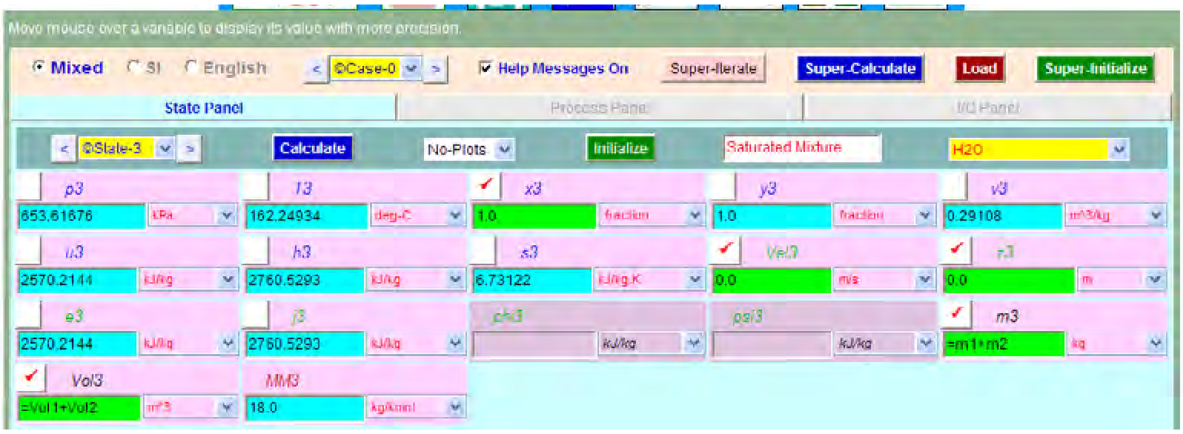
No Plots

Saturated Mixture

H2O

✓	p2	150.0	kPa
☐	T2	111.34738	deg C
✓	x2	1.0	fraction
☐	y2	1.0	fraction
☐	v2	1.16116	m^3/kg
☐	u2	2519.6277	kJ/kg
☐	h2	2693.521	kJ/kg
☐	s2	7.22374	kJ/kg K
✓	Vel2	0.0	m/s
✓	z2	0.0	m
☐	e2	2519.6277	kJ/kg
☐	j2	2693.521	kJ/kg
	phi2		kJ/kg
	psi2		kJ/kg
✓	m2	=0.25*5	kg
☐	Vol2	1.45145	m^3
	MM2	18.0	kg/kmol

5. For State 3: enter x3 = 1 since all volume is filled with sat.vap., m3 = m1+m2, and Vol3 = (Vol1+Vol2), since total volume has remained same. Hit Enter, and we get:



● Mixed ○ SI ○ English

©Case-0

☑ Help Messages On

©State-3

No-Plots

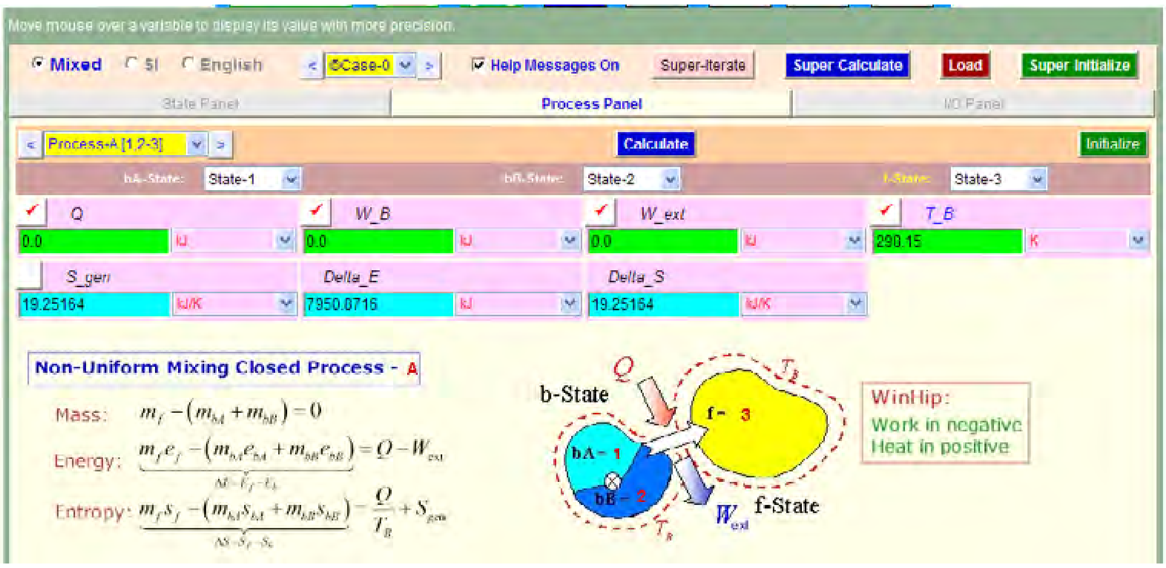
Saturated Mixture

H2O

☐	p3	653.61676	kPa
☐	T3	162.24934	deg-C
✓	x3	1.0	fraction
☐	y3	1.0	fraction
☐	v3	0.29108	m^3/kg
☐	u3	2570.2144	kJ/kg
☐	h3	2760.5293	kJ/kg
☐	s3	6.73122	kJ/kg.K
✓	Vel3	0.0	m/s
✓	z3	0.0	m
☐	e3	2570.2144	kJ/kg
☐	j3	2760.5293	kJ/kg
	phi3		kJ/kg
	psi3		kJ/kg
✓	m3	=m1+m2	kg
✓	Vol3	=Vol1+Vol2	m^3
	MM3	18.0	kg/kmol

Note that final temp. = T3 = 162.25 C, final pressure = P3 = 653.62 kPa … Ans.

6. Now, go to Process Panel. Enter State 1, State 2 and State 3 for bA-State, bB-State and f-State respectively. Also, enter Q = 0 (since the vessel is insulated), W_B = 0 and W_ext = 0. Hit Enter. We get:



Move mouse over a variable to display its value with more precision.

● Mixed ○ SI ○ English | Case-0 | ☑ Help Messages On

Process-A [1,2-3]

bA-State: State-1 | bB-State: State-2 | f-State: State-3

☑ Q	☑ W_B	☑ W_ext	☑ T_B
0.0 kJ	0.0 kJ	0.0 kJ	290.15 K
☐ S_gen	Delta_E	Delta_S	
19.25164 kJ/K	7950.0716 kJ	19.25164 kJ/K	

Non-Uniform Mixing Closed Process - A

Mass: $m_f - (m_{bA} + m_{bB}) = 0$

Energy: $\underbrace{m_f e_f - (m_{bA} e_{bA} + m_{bB} e_{bB})}_{\Delta E = E_f - E_b} = Q - W_{ext}$

Entropy: $\underbrace{m_f s_f - (m_{bA} s_{bA} + m_{bB} s_{bB})}_{\Delta S = S_f - S_b} = \frac{Q}{T_B} + S_{gen}$

WinHip: Work in negative Heat in positive

Thus:

Entropy change of water = Delta_S = 19.25164 kJ/K …. Ans.

Entropy change of universe = S_gen =Delta_S = 19.25164 kJ/K …. Ans. since entropy chane of surr. = 0 since Q = 0.

Also, Delta_E = 7950.87 kJ … change in stored energy of the system….Ans.

7. Click on **SuperCalculate** and get the TEST code etc from the I/O panel:

```
#	Daemon Path: Systems>Closed>Process>Generic>NonUniformMixed>PC-Model; v-10.cb01

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

States	{
	State-1: H2O;
	Given: { p1= 150.0 kPa; x1= 0.0 fraction; Vel1= 0.0 m/s; z1= 0.0 m; m1= "5*0.75" kg; }
	State-2: H2O;
	Given: { p2= 150.0 kPa; x2= 1.0 fraction; Vel2= 0.0 m/s; z2= 0.0 m; m2= "0.25*5" kg; }
	State-3: H2O;
	Given: { x3= 1.0 fraction; Vel3= 0.0 m/s; z3= 0.0 m; m3= "m1+m2" kg; Vol3= "Vol1+Vol2" m^3; }
	}
```

```
Analysis {
        Process-A: b-State = State-1, State-2; f-State = State-3;
        Given: { Q= 0.0 kJ; W_B= 0.0 kJ; W_ext= 0.0 kJ; T_B= 298.15 K; }
        }

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

 # Evaluated States:

```
#       State-1: H2O > Saturated Mixture;
#               Given: p1= 150.0 kPa; x1= 0.0 fraction; Vel1= 0.0 m/s;
#                       z1= 0.0 m; m1= "5*0.75" kg;
#               Calculated: T1= 111.3474 deg-C; y1= 0.0 fraction; v1= 0.001 m^3/kg;
#                       u1= 466.8442 kJ/kg; h1= 467.0021 kJ/kg; s1= 1.4333 kJ/kg.K;
#                       e1= 466.8442 kJ/kg; j1= 467.0021 kJ/kg; Vol1= 0.004 m^3;
#                       MM1= 18.0 kg/kmol;
#       State-2: H2O > Saturated Mixture;
#               Given: p2= 150.0 kPa; x2= 1.0 fraction; Vel2= 0.0 m/s;
#                       z2= 0.0 m; m2= "0.25*5" kg;
```

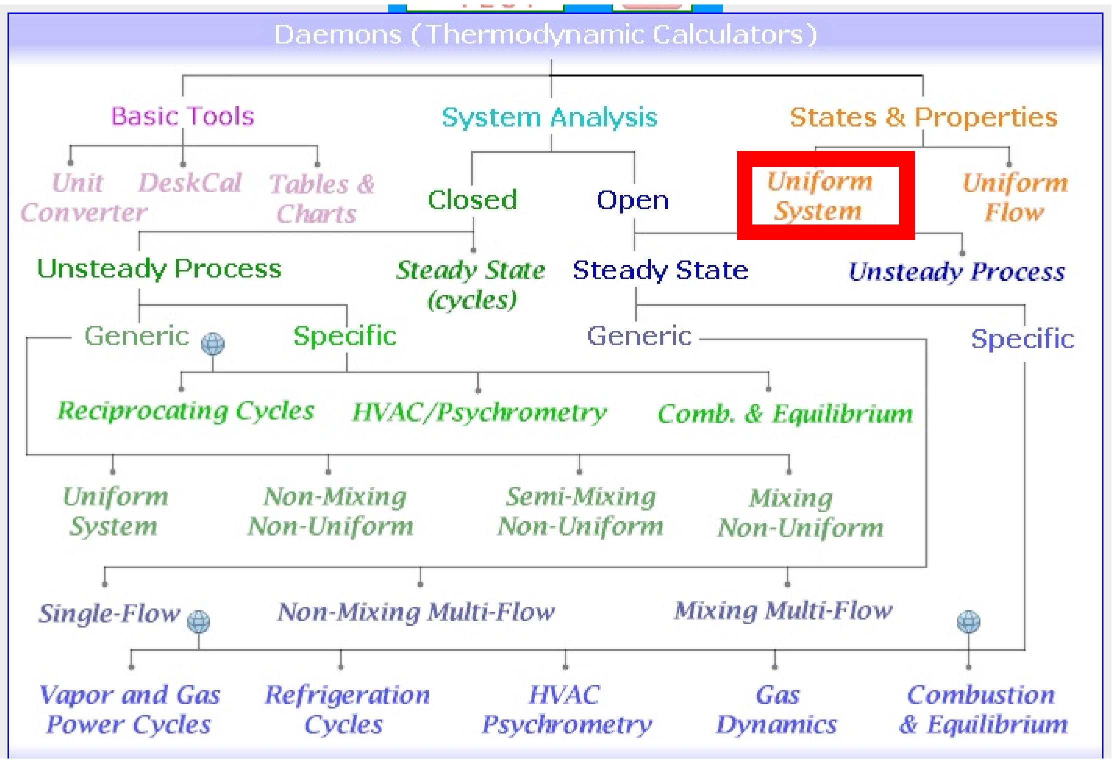
```
#                  Calculated: T2= 111.3474 deg-C; y2= 1.0 fraction; v2= 1.1612 m^3/kg;
#                          u2= 2519.6277 kJ/kg; h2= 2693.521 kJ/kg; s2= 7.2237 kJ/kg.K;
#                          e2= 2519.6277 kJ/kg; j2= 2693.521 kJ/kg; Vol2= 1.4514 m^3;
#                          MM2= 18.0 kg/kmol;
#         State-3: H2O > Saturated Mixture;
#                  Given: x3= 1.0 fraction; Vel3= 0.0 m/s; z3= 0.0 m;
#                          m3= "m1+m2" kg; Vol3= "Vol1+Vol2" m^3;
#                  Calculated: p3= 653.6168 kPa; T3= 162.2494 deg-C; y3= 1.0 fraction;
#                          v3= 0.2911 m^3/kg; u3= 2570.2144 kJ/kg; h3= 2760.5293 kJ/kg;
#                          s3= 6.7312 kJ/kg.K; e3= 2570.2144 kJ/kg; j3= 2760.5293 kJ/kg;
#                          MM3= 18.0 kg/kmol;
#
#--------Property spreadsheet starts:

# State  p(kPa)      T(K)    x    v(m3/kg)   u(kJ/kg)   h(kJ/kg)   s(kJ/kg)
# 01     150.0       384.5   0.0  0.0011     466.84     467.0       1.433
# 02     150.0       384.5   1.0  1.1612     2519.63    2693.52     7.224
# 03     653.62      435.4   1.0  0.2911     2570.21    2760.53     6.731
#

# Mass, Energy, and Entropy Analysis Results:
#         Process-A: b-State = State-1, State-2; f-State = State-3;
#                  Given: Q= 0.0 kJ; W_B= 0.0 kJ; W_ext= 0.0 kJ; T_B= 298.15 K;
#         Calculated: S_gen= 19.251644 kJ/K; Delta_E= 7950.8716 kJ; Delta_S= 19.251644 kJ/K;
================================================================================
```

Prob.7.29. A rigid tank is divided in to two equal parts by a partition. One part of the tank contains 2.5 kg of compressed liquid water at 400 kPa and 60 C while the other part is evacuated. The partition is now removed, and the water expands to fill the entire tank. Determine the entropy change of water during this process, if the final pressure in the tank is 40 kPa. [Ref:1]

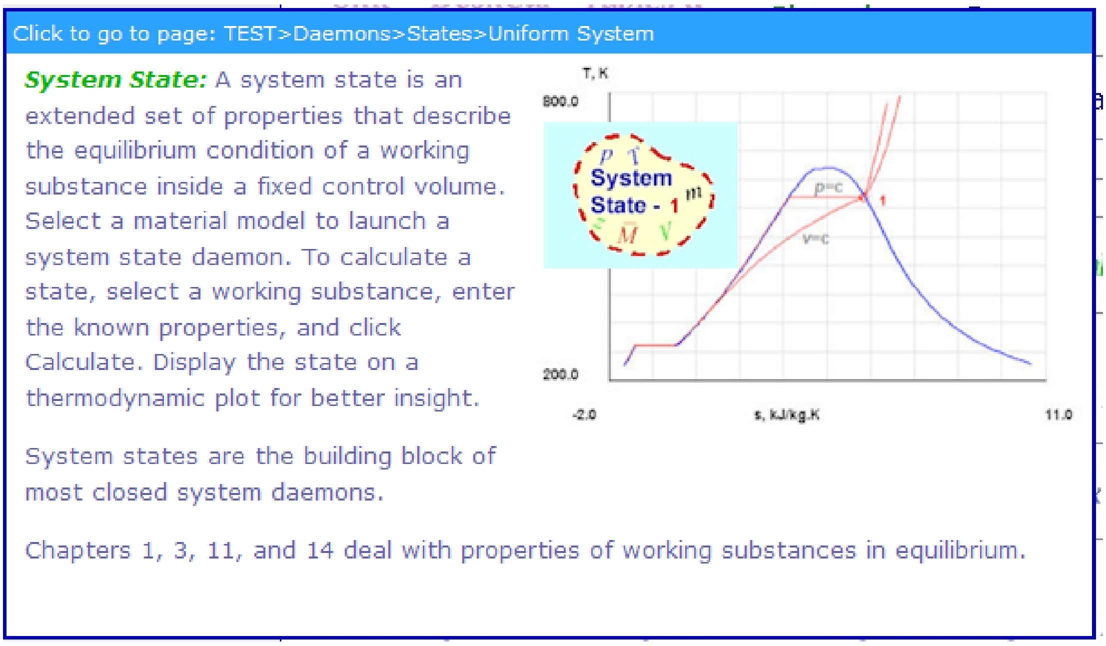
TEST Solution:

Following are the steps:

1. From the Daemon tree, select States and Properties – Uniform System, as shown below:



Hovering the mouse pointer on Uniform System brings up the following pop up:

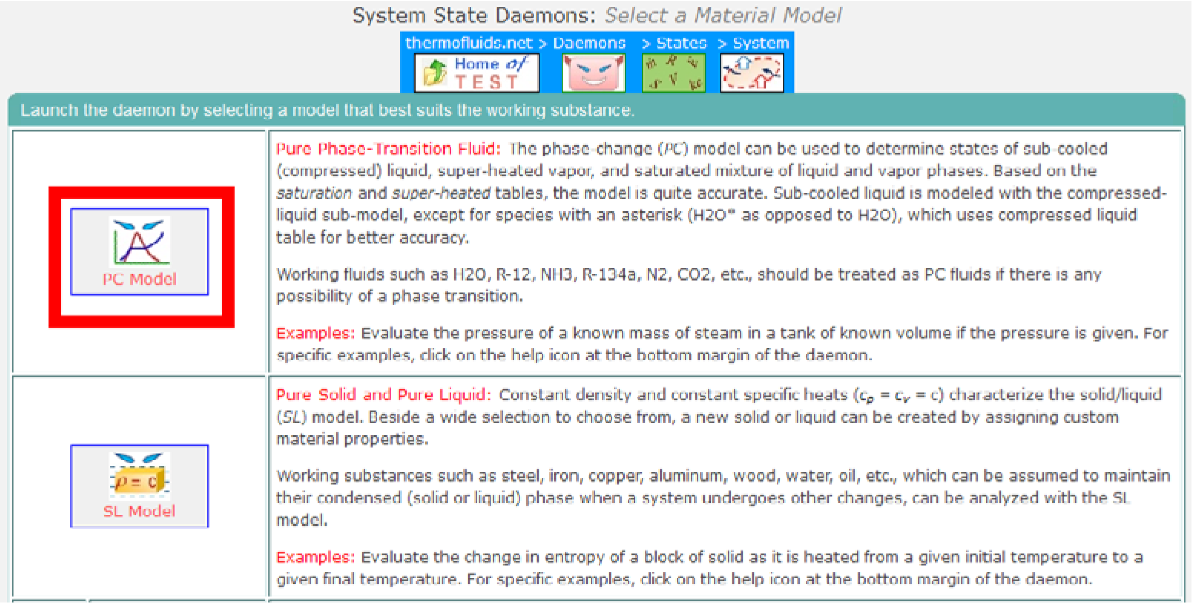


System State: A system state is an extended set of properties that describe the equilibrium condition of a working substance inside a fixed control volume. Select a material model to launch a system state daemon. To calculate a state, select a working substance, enter the known properties, and click Calculate. Display the state on a thermodynamic plot for better insight.

System states are the building block of most closed system daemons.

Chapters 1, 3, 11, and 14 deal with properties of working substances in equilibrium.

2. For Material model, choose PC model:



System State Daemons: *Select a Material Model*

Launch the daemon by selecting a model that best suits the working substance.

Pure Phase-Transition Fluid: The phase change (*PC*) model can be used to determine states of sub-cooled (compressed) liquid, super-heated vapor, and saturated mixture of liquid and vapor phases. Based on the *saturation* and *super-heated* tables, the model is quite accurate. Sub-cooled liquid is modeled with the compressed-liquid sub-model, except for species with an asterisk (H2O* as opposed to H2O), which uses compressed liquid table for better accuracy.

Working fluids such as H2O, R-12, NH3, R-134a, N2, CO2, etc., should be treated as PC fluids if there is any possibility of a phase transition.

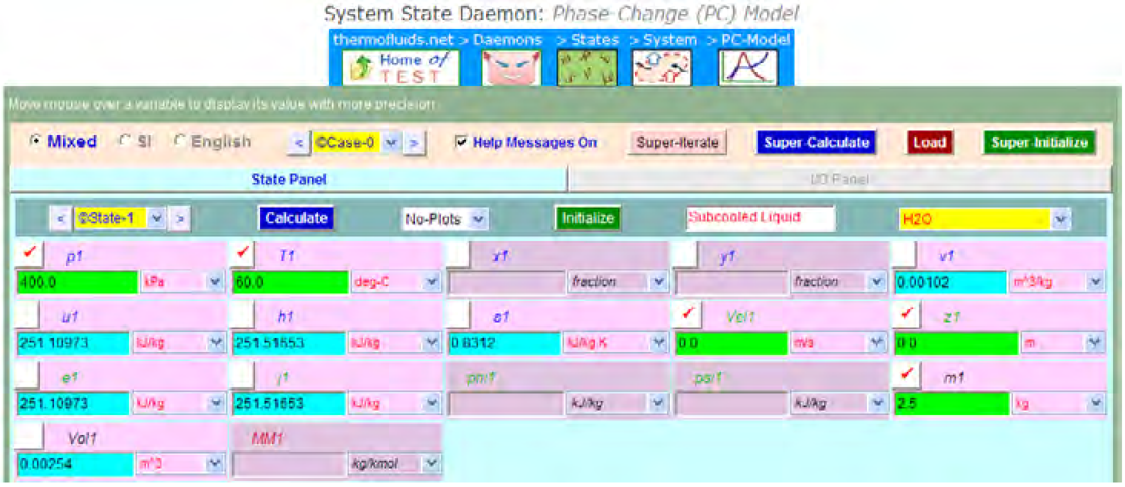
Examples: Evaluate the pressure of a known mass of steam in a tank of known volume if the pressure is given. For specific examples, click on the help icon at the bottom margin of the daemon.

Pure Solid and Pure Liquid: Constant density and constant specific heats ($c_p = c_v = c$) characterize the solid/liquid (*SL*) model. Beside a wide selection to choose from, a new solid or liquid can be created by assigning custom material properties.

Working substances such as steel, iron, copper, aluminum, wood, water, oil, etc., which can be assumed to maintain their condensed (solid or liquid) phase when a system undergoes other changes, can be analyzed with the SL model.

Examples: Evaluate the change in entropy of a block of solid as it is heated from a given initial temperature to a given final temperature. For specific examples, click on the help icon at the bottom margin of the daemon.

3. Choose H2O as the working substance and enter for State 1: P1= 400 kPa, T1 = 60 C, m1= 2.5 kg, and hit Enter. We get:



● Mixed ○ SI ○ English
@Case-0
☑ Help Messages On
@State-1
No-Plots
Subcooled Liquid
H2O

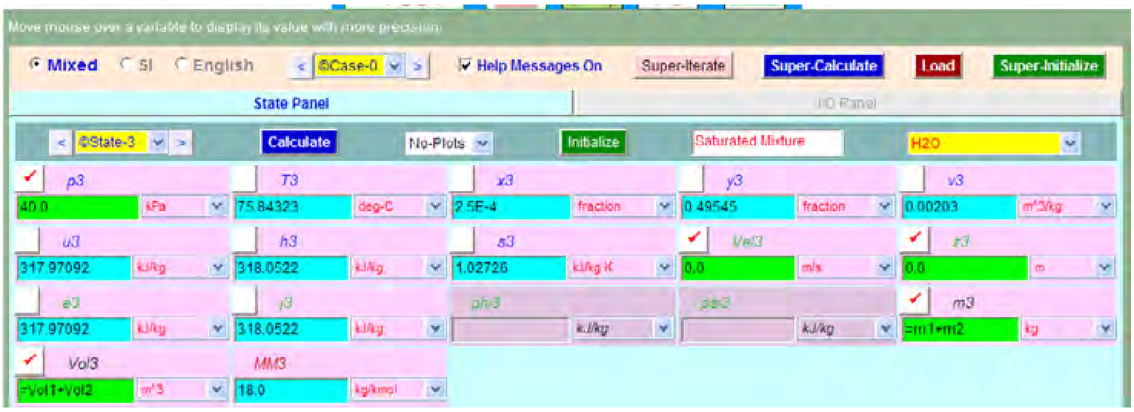
☑ p1 400.0 kPa	☑ T1 60.0 deg-C	☐ x1 fraction	☐ y1 fraction	☐ v1 0.00102 m^3/kg
☐ u1 251.10973 kJ/kg	☐ h1 251.51653 kJ/kg	☐ s1 0.8312 kJ/kg.K	☑ Vel1 0.0 m/s	☑ z1 0.0 m
☐ e1 251.10973 kJ/kg	☐ j1 251.51653 kJ/kg	phi1 kJ/kg	psi1 kJ/kg	☑ m1 2.5 kg
☐ Vol1 0.00254 m^3	MM1 kg/kmol			

4. Now, for State 2: enter P2 = 0 and m2 = 0 (since chamber is evacuated), and Vol2 = Vol1 (since two chambers are equal, by data). Hit Enter:

● Mixed ○ SI ○ English
@Case-0
☑ Help Messages On
@State-2
No-Plots
Saturated Mixture
H2O

☑ p2 0.0 kPa	☐ T2 -273.15 deg-C	☐ x2 0.0 fraction	☐ y2 0.0 fraction	☐ v2 Infinity m^3/kg
☐ u2 0.0 kJ/kg	☐ h2 0.0 kJ/kg	☐ s2 0.0 kJ/kg.K	☑ Vel2 0.0 m/s	☑ z2 0.0 m
☐ e2 0.0 kJ/kg	☐ j2 0.0 kJ/kg	phi2 0.0 kJ/kg	psi2 0.0 kJ/kg	☑ m2 0.0 kg
☑ Vol2 =Vol1 m^3	MM2 18.0 kg/kmol			

5. For State 3, enter: P1 = 40 kPa, m3 = (m1 + m2), and Vol3 = (Vol1 + Vol2), since that partition is now removed. Hit Enter. We get:



● Mixed ○ SI ○ English
@Case-0
☑ Help Messages On
@State-3
No-Plots
Saturated Mixture
H2O

☑ p3 40.0 kPa	☐ T3 75.84323 deg-C	☐ x3 2.5E-4 fraction	☐ y3 0.49545 fraction	☐ v3 0.00203 m^3/kg
☐ u3 317.97092 kJ/kg	☐ h3 318.0522 kJ/kg	☐ s3 1.02726 kJ/kg.K	☑ Vel3 0.0 m/s	☑ z3 0.0 m
☐ e3 317.97092 kJ/kg	☐ j3 318.0522 kJ/kg	phi3 kJ/kg	psi3 kJ/kg	☑ m3 =m1+m2 kg
☑ Vol3 =Vol1+Vol2 m^3	MM3 18.0 kg/kmol			

Note that temp in the final state is T3 = 75.84 C …. Ans.

6. Click on **SuperCalculate** and get TEST code etc from the I/O Panel:

```
#
#         Daemon Path: States>System>PC-Model; v-10.cb01

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

States    {
            State-1: H2O;
            Given: { p1= 400.0 kPa; T1= 60.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; m1= 2.5 kg; }
            State-2: H2O;
            Given: { p2= 0.0 kPa; Vel2= 0.0 m/s; z2= 0.0 m; m2= 0.0 kg; Vol2= "Vol1" m^3; }
            State-3: H2O;
            Given: { p3= 40.0 kPa; Vel3= 0.0 m/s; z3= 0.0 m; m3= "m1+m2" kg; Vol3= "Vol1+Vol2" m^3; }
            }

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

# Evaluated States:

#
#          State-1: H2O > Subcooled Liquid;
#                   Given: p1= 400.0 kPa; T1= 60.0 deg-C; Vel1= 0.0 m/s;
#                          z1= 0.0 m; m1= 2.5 kg;
#                   Calculated: v1= 0.001 m^3/kg; u1= 251.1097 kJ/kg; h1= 251.5165 kJ/kg;
#                          s1= 0.8312 kJ/kg.K; e1= 251.1097 kJ/kg; j1= 251.5165 kJ/kg;
#                          Vol1= 0.0025 m^3;
#          State-2: H2O > Saturated Mixture;
#                   Given: p2= 0.0 kPa; Vel2= 0.0 m/s; z2= 0.0 m;
#                          m2= 0.0 kg; Vol2= "Vol1" m^3;
#                   Calculated: T2= -273.15 deg-C; x2= 0.0 fraction; y2= 0.0 fraction;
#                          v2= Infinity m^3/kg; u2= 0.0 kJ/kg; h2= 0.0 kJ/kg;
#                          s2= 0.0 kJ/kg.K; e2= 0.0 kJ/kg; j2= 0.0 kJ/kg;
#                          phi2= 0.0 kJ/kg; psi2= 0.0 kJ/kg; MM2= 18.0 kg/kmol;
```

```
#         State-3: H2O > Saturated Mixture;
#                  Given: p3= 40.0 kPa; Vel3= 0.0 m/s; z3= 0.0 m;
#                         m3= „m1+m2“ kg; Vol3= „Vol1+Vol2“ m^3;
#                  Calculated: T3= 75.8432 deg-C; x3= 2.0E-4 fraction; y3= 0.4954 fraction;
#                         v3= 0.002 m^3/kg; u3= 317.9709 kJ/kg; h3= 318.0522 kJ/kg;
#                         s3= 1.0273 kJ/kg.K; e3= 317.9709 kJ/kg; j3= 318.0522 kJ/kg;
#                         MM3= 18.0 kg/kmol;
#
#--------Property spreadsheet starts: #

# State  p(kPa)      T(K)    x     v(m3/kg)    u(kJ/kg)    h(kJ/kg)    s(kJ/kg)
# 01     400.0       333.2          0.001       251.11      251.52      0.831
# 02     0.0         0.0     0.0    Infinity    0.0         0.0         0.0
# 03     40.0        349.0   0.0    0.002       317.97      318.05      1.027

#******CALCULATE VARIABLES: Type in an expression starting with an '=' sign ('= mdot1*(h2-h1)',
'= sqrt(4*A1/PI)', etc.) and press the Enter key)*********
```

 # Use the I/O panel as a Calculator to find out the entropy change of system (i.e. water):

Entropy change of system: = m3*s3 – (m1 * s1 + m2 *s2)
And,
m3*s3 – (m1 * s1 + m2 *s2) = **0.4901456832885742 kJ/K**
i.e. ΔS_sys = 0.49 kJ/K … Ans.

==

7.5 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.
4. *P.K. Nag*, Engineering Thermodynamics, 2nd Ed. Tata McGraw Hill Publishing Co., 1995.
5. *R.K. Rajput,* A Text Book of Engineering Thermodynamics, Laxmi Publications, New Delhi, 1998.

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