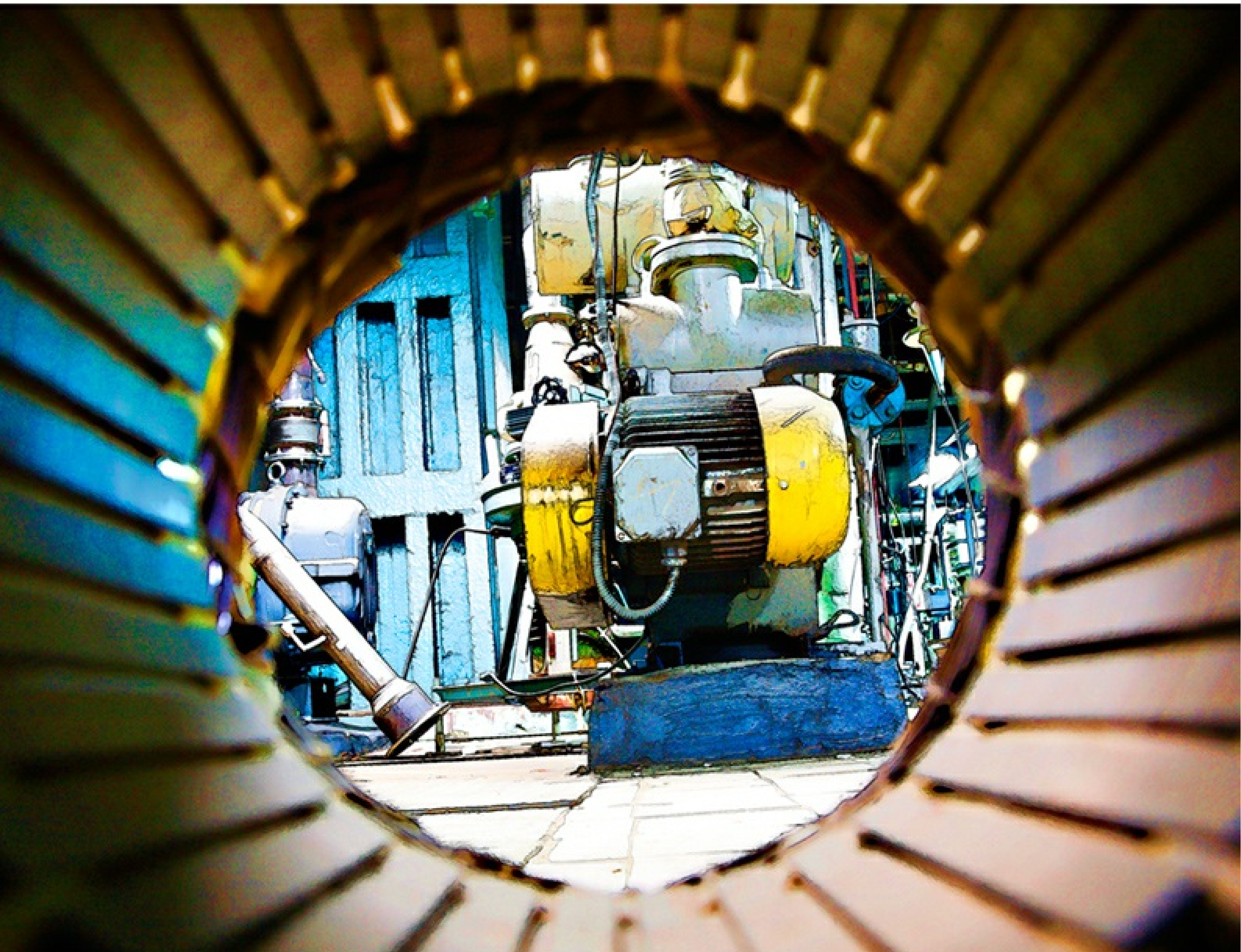
Applied Thermodynamics: Software Solutions

Part-II

Dr. M. Thirumaleshwar



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Applied Thermodynamics: Software Solutions

Part-II (Cycles for Gas turbines and Jet propulsion, Vapor power cycles)

Applied Thermodynamics: Software Solutions: Part-II (Cycles for Gas turbines and Jet propulsion, Vapor power cycles)
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Contents

2 Cycles for Gas Turbines and Jet propulsion

Learning objectives:

1. In this chapter, 'Gas Turbine cycles' are analyzed with 'air standard assumptions'.
2. Brayton cycle is the air standard cycle for Gas Turbines. Ideal Brayton cycle consists of two isentropics and two constant pressure processes.
3. Modifications to the Ideal cycle to increase the thermal efficiency are also studied; these include adding a regenerator and resorting to multistage compression in the compressor and multistage expansion in the turbine.
4. Jet propulsion cycle used for aircraft propulsion is also analysed.
5. Several Functions/ Procedures are written in Mathcad and EES to determine net work, thermal efficiency etc of the Ideal and actual Brayton cycles.
6. Large number of problems from University question papers and standard Text books are solved with Mathcad, EES and TEST.

2.1 Definitions, Statements and Formulas used [1-7]:

2.1.1 Air standard assumptions:

Since the actual Gas power cycles are rather complex, we make following assumptions to simplify the analysis:

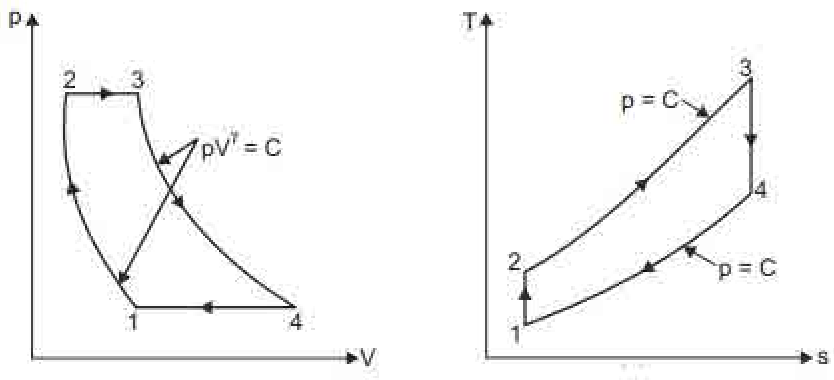
i. Working fluid is air circulating continuously in a closed loop, with air behaving as an Ideal gas
ii. All processes making up the cycle ate internally reversible
iii. The combustion process is replaced by a heat addition process from an external source
iv. The exhaust process is replaced by a heat rejection process that restores the working fluid to its initial state
v. In 'cold air standard assumption', specific heat of air is assumed to be constant at cp = 1.005 kJ/kg.K and ratio of sp. heats as $\gamma = 1.4$

2.1.2 Ideal, simple Brayton cycle:

P-v and T-s diagrams are shown below:

Here, we have:

1-2: isentropic compression in compressor
2-3: external heat addition in heater (combustion chamber)
3-4: isentropic expansion in turbine
4-1: heat rejection in a cooler



Various quantities for the ideal Brayton cycle are calculated as follows:

Air standard efficiency:

$$\eta_{th} = 1 - \left(\frac{1}{r_p}\right)^{\frac{\gamma-1}{\gamma}}$$

Compressor work:

$$W_{comp} = cp \cdot T1 \cdot \left(r_p^{\frac{\gamma-1}{\gamma}} - 1 \right) \qquad \text{kJ/kg}$$

Turbine work:

$$W_{turb} = cp \cdot T3 \cdot \left[1 - \left(\frac{1}{r_p}\right)^{\frac{\gamma-1}{\gamma}} \right] \qquad \text{kJ/kg}$$

Net work:

$$W_{net} = W_{turb} - W_{comp} \qquad \text{kJ/kg}$$

From Theory, **optimum r_p for max. work is:** $r_p = \left(\frac{T3}{T1}\right)^{\frac{\gamma}{2\cdot(\gamma-1)}}$

Back Work ratio:

$$BWRatio = \frac{W_{comp}}{W_{turb}}$$

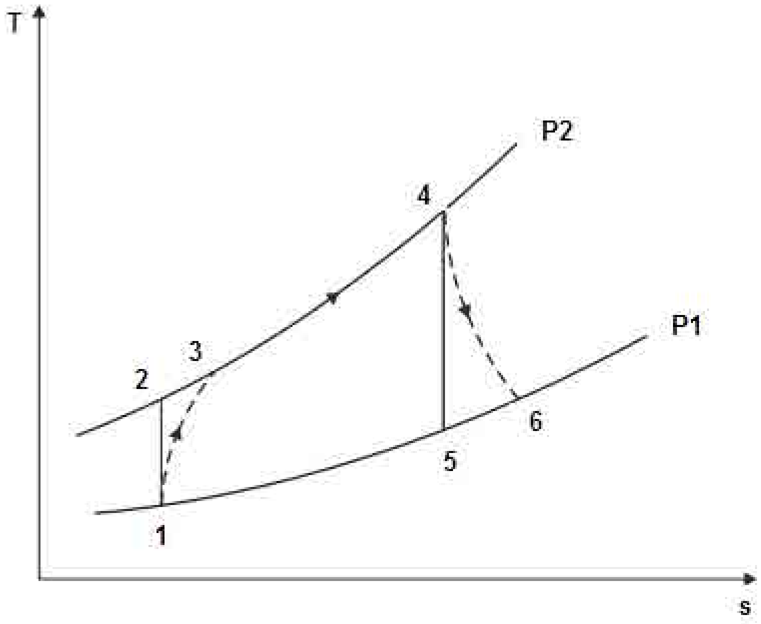
Heat supplied:

$$Q_{in} = cp\cdot(T3 - T2) \qquad \text{kJ/kg}$$

Thermal efficiency:

$$\eta_{th} = \frac{W_{net}}{Q_{in}}$$

2.1.3 Actual, simple Brayton cycle:



Actual, Simple open cycle...Compr. work, Turbine work, Back Work Ratio:

$$W_{comp} = cp \cdot \frac{T1 \cdot \left(r_p^{\frac{\gamma-1}{\gamma}} - 1 \right)}{\eta_{comp}} \quad \text{kJ/kg}$$

$$W_{turb} = cp \cdot \left[T3 \cdot \left(1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}} \right) \cdot \eta_{turb} \right] \quad \text{kJ/kg}$$

$$BWRatio = \frac{W_{comp}}{W_{turb}}$$

Net work:

$$W_{net} = W_{turb} - W_{comp}$$

Heat supplied:

$$Q_{in} = cp \cdot \left[T3 - \left[T1 + \frac{T1 \cdot \left(r_p^{\frac{\gamma-1}{\gamma}} - 1 \right)}{\eta_{comp}} \right] \right] \quad \text{kJ/kg}$$

Thermal efficiency of Actual Simple Open Cycle Gas Turbine :

$$Brayton\_actual\_EFF = \frac{W_{net}}{Q_{in}}$$

==

Efficiency of Ideal Open Cycle Gas Turbine with Ideal Regeneration:.

..Depends on pressure ratio and the cycle max to min temp. ratio

$$Brayton\_IdealRegen\_EFF = 1 - \left(\frac{T1}{T3} \right) \cdot r_p^{\frac{\gamma-1}{\gamma}}$$

Efficiency of Ideal Open Cycle Gas Turbine with Ideal Regeneration:

In terms of temp. ratio, t=T1/T3, re-writing the above eqn, we have:

$$\text{Brayton\_IdealRegen\_EFF} = 1 - (t) \cdot r_p^{\frac{\gamma-1}{\gamma}}$$

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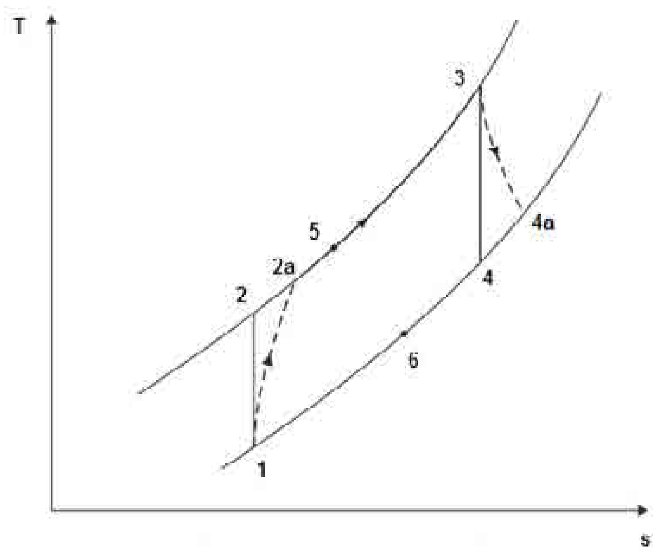
2.1.4 Actual Open Brayton Cycle with Regeneration:

Here ε is the effcy of regenerator, defined as:

$$\varepsilon = \frac{T5 - T2a}{T4a - T2a}$$



Turbine Work:

$$W_{turb} = cp \cdot \left[T3 \cdot \left(1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}} \right) \cdot \eta_{turb} \right] \qquad \text{kJ/kg}$$

Compressor Work:

$$W_{comp} = cp \cdot \frac{T1 \cdot \left(r_p^{\frac{\gamma-1}{\gamma}} - 1 \right)}{\eta_{comp}} \qquad \text{kJ/kg}$$

Net Work:

$$W_{net} = W_{turb} - W_{comp} \quad \text{kJ/kg}$$

Back Work Ratio:

$$BWRatio = \frac{W_{comp}}{W_{turb}}$$

Temp at exit of compressor:

$$T2a = T1 + \frac{T1 \cdot \left(r_p^{\frac{\gamma - 1}{\gamma}} - 1 \right)}{\eta_{comp}} \quad \text{K}$$

Temp at exit of turbine:

$$T4a = T3 - T3 \cdot \left(1 - \frac{1}{r_p^{\frac{\gamma - 1}{\gamma}}} \right) \cdot \eta_{turb} \quad \text{K}$$

Regen. effectiveness, ε:

$$\varepsilon = \frac{T5 - T2a}{T_{4a} - T2a}$$

Therefore, temp at exit of high pressure stream in regenerator, T5 (K):

$$T5 = T2a + \varepsilon \cdot (T4a - T2a) \quad K$$

Heat supplied:

$$Q_{in} = cp \cdot (T3 - T5) \quad kJ/kg$$

Thermal efficiency:

$$Brayton\_actual\_regen\_EFF = \frac{W_{net}}{Q_{in}}$$

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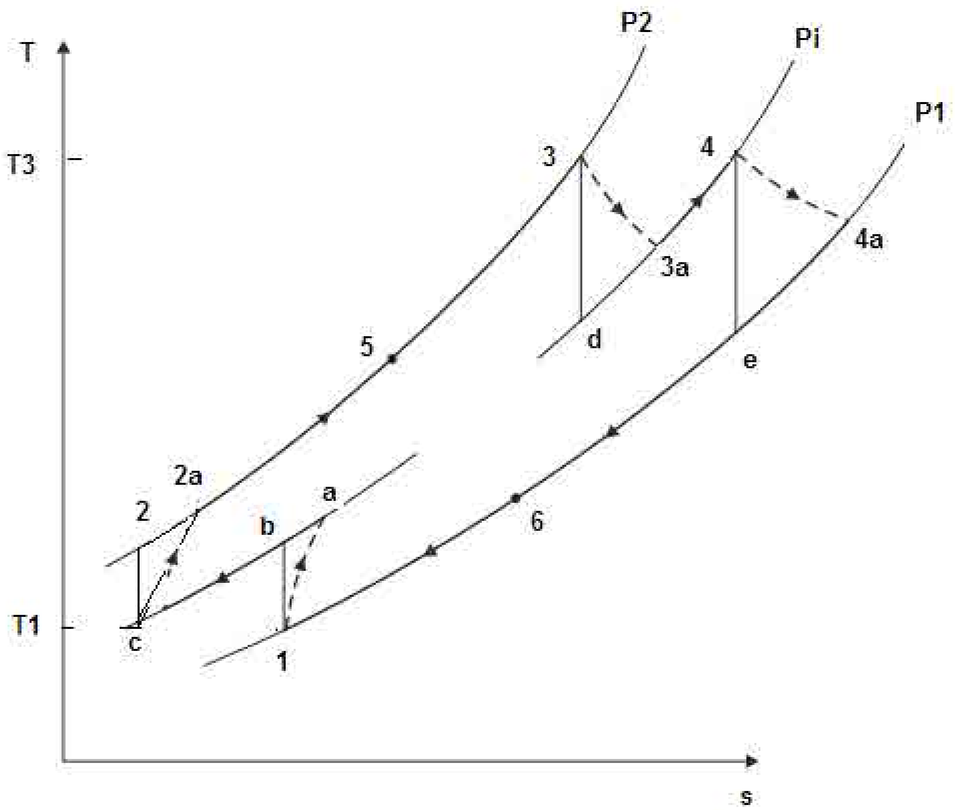
2.1.5 Actual open cycle…with reheating, inter-cooling and regeneration:

Given overall pr. ratio, rp:

Therefore, pressure ratio per stage = $rp^{0.5}$



Total Compressor work input, for two stages:

$$WK_{comp} = cp \cdot \frac{T1 \cdot \left(r_p^{0.5 \cdot \frac{\gamma - 1}{\gamma}} - 1 \right) \cdot 2}{\eta_{comp}} \quad \text{kJ/kg}$$

Total Turbine work output, for 2 stages:

$$WK_{turb} = c_p \cdot \left[T3 \cdot \left(1 - \frac{1}{r_p^{0.5 \cdot \frac{\gamma - 1}{\gamma}}} \right) \cdot \eta_{turb} \right] \cdot 2 \quad \text{kJ/kg}$$

Net Work output:

$$W_{net} = WK_{turb} - WK_{comp} \quad \text{kJ/kg}$$

Back Work Ratio:

$$BWRATIO = \frac{WK_{comp}}{WK_{turb}}$$

Work Ratio:

$$WRATIO = \frac{WK_{turb} - WK_{comp}}{WK_{turb}}$$

Temp. T2a:

$$T2a = \frac{T1 \cdot \left(r_p^{0.5 \cdot \frac{\gamma - 1}{\gamma}} - 1 \right)}{\eta_{comp}} + T1 \quad \text{K}$$

Temp. T4a:

$$T4a = T3 - \left[T3 \cdot \left(1 - \frac{1}{r_p^{0.5 \cdot \frac{\gamma - 1}{\gamma}}} \right) \cdot \eta_{turb} \right] \quad \text{K}$$

T5, temp at exit of high pressure stream in regenerator:

$$\varepsilon = \frac{T5 - T2a}{T4a - T2a} \quad \text{....regen. effcy.}$$

Then:

$T5 = T2a + \varepsilon \cdot (T4a - T2a)$ K

Heat supplied:

$Q1 = cp \cdot (T3 - T5) + cp \cdot (T3 - T4a)$ kJ/kg

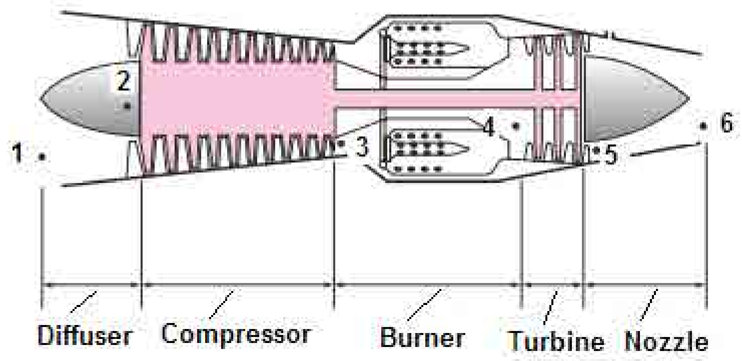
Thermal efficiency:

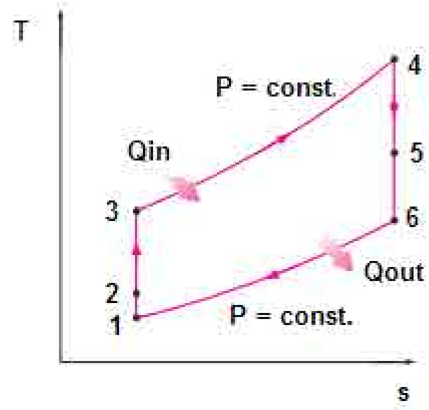
$$EFFCY = \frac{WK_{turb} - WK_{comp}}{Q1}$$

2.1.6 Ideal Jet Propulsion cycle [1]:

Here, the ambient air is first compressed slightly in a diffuser, and then compressed in a compressor. The turbine produces just enough power to run the compressor and auxiliaries. High pressure, high temp exit from the turbine is further expanded in a nozzle to the ambient pressure. High velocity exit from the nozzle provides the thrust to propel the aircraft.

Schematic diagram of the turbo-jet and the T-s diagram are shown below:





In the above, we have:

1-2: Isentropic compression in diffuser

2-3: Isentropic compression in compressor

3-4: constant pressure heat addition in burner

4-5: Isentropic expansion in turbine

5-6: Isentropic expansion in nozzle

6-1: Constant pressure heat rejection

Generally, the ambient conditions (at the cruising height of aircraft), P1, T1 are known. Also, the compressor pressure ratio, rp (= P3/P2),and the temp at turbine inlet, T4 are given. The cruising velocity of aircraft, V1 is also known. For ideal jet propulsion cycle, turbine exit temp T5, nozzle exit temp T6, nozzle exit velocity V6, heat supplied, thrust produced, propulsive power and the propulsive efficiency are calculated as follows:

Process 1-2: Isentropic pressure rise in diffuser:

From an energy balance:

$$h2 + \frac{V2^2}{2} = h1 + \frac{V1^2}{2}$$

V2 is nearly equal to zero.

Therefore:

$$(h2 - h1) - \frac{V1^2}{2} = 0$$

i.e. $cp \cdot (T2 - T1) - \frac{V1^2}{2} = 0$

i.e. $T2 = T1 + \frac{V1^2}{2 \cdot cp}$ **K....Ans.**

And: $P2 = P1 \cdot \left(\frac{T2}{T1}\right)^{\frac{\gamma}{\gamma - 1}}$ **kPa...when P1 is in kPa**

Process 2-3: Isentropic compression in compressor:

$P3 = rp \cdot P2$ **kPa...Ans.**

$T3 = T2 \cdot rp^{\frac{\gamma - 1}{\gamma}}$ **K...Ans.**

Process 4-5: Isentropic expansion in turbine:

Remember: $W_{comp} = W_{turb}$

Then: $h3 - h2 = h4 - h5$

i.e. $cp \cdot (T3 - T2) = cp \cdot (T4 - T5)$

i.e. $T5 = T4 - T3 + T2$ **K...Ans.**

And: $P5 = P4 \cdot \left(\frac{T5}{T4}\right)^{\frac{\gamma}{\gamma - 1}}$ **kPa....Ans.**

Process 5-6: Isentropic expansion in nozzle:

$$T6 = T5 \cdot \left(\frac{P6}{P5}\right)^{\frac{\gamma-1}{\gamma}}$$ **K...Ans.**

From an energy balance:

$$h6 + \frac{V6^2}{2} = h5 + \frac{V5^2}{2}$$

But, V5 is almost zero. Therefore:

$$cp \cdot (T6 - T5) + \frac{V6^2}{2} = 0$$

i.e. $V6 = \sqrt{2 \cdot cp \cdot (T5 - T6)}$ **m/s ....Ans.**

Net Thrust:

$F = m \cdot (V6 - V1)$ **N ...where m = air flow rate in kg/s.**

Propulsive power:

$W_P = F \cdot V1 = m \cdot (V6 - V1) \cdot V1$ **kW..Ans.**

Heat supplied:

$$Q_{in} = m\cdot(h4 - h3) = m\cdot cp\cdot(T4 - T3) \quad \text{kW....Ans.}$$

Propulsive efficiency:

$$\eta_P = \frac{W_P}{Q_{in}}$$

K.E. at exit:

$$KE_{exit} = m\cdot\frac{V6^2}{2} \quad \text{kW....Ans.}$$

Heat rejected:

$$Q_{exit} = m\cdot(h6 - h1) \quad \text{kW...Ans.}$$

Check: $Q_{in} = W_P + KE_{exit} + Q_{exit}$

Note: In an actual Jet propulsion cycle, isentropic efficiencies of diffuser, compressor and turbine will have to be considered. Also, combustion efficiency in the burner section and the velocity coefficient of the nozzle will have to be taken in to account.

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2.2 Problems solved with Mathcad:

Prob.2.1. Write Mathcad Functions for Thermal efficiency, compressor work, Turbine work, Net work and Work ratio of an Ideal, Simple Gas Turbine cycle (i.e. Ideal Brayton Cycle):

Mathcad Functions:

Thermal efficiency:

$$\gamma := 1.4$$

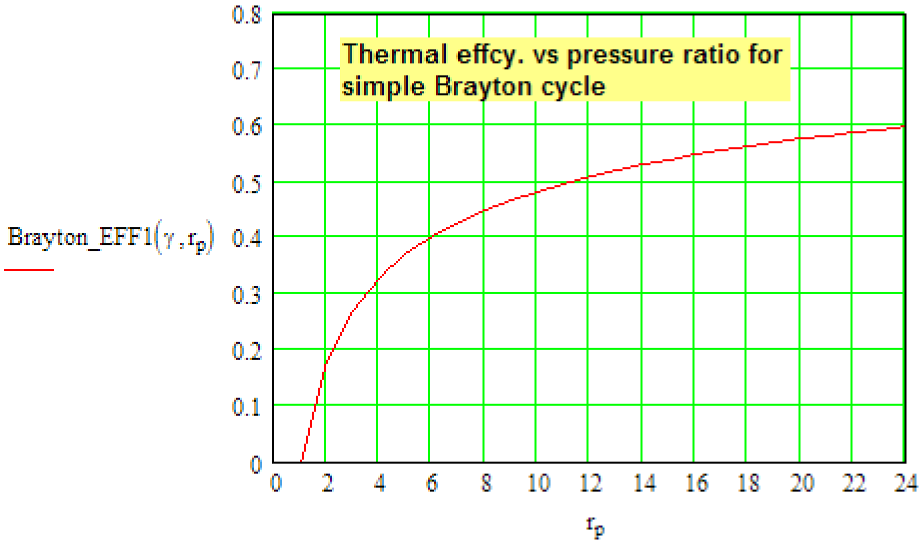
$$Brayton\_EFF1(\gamma, r_p) := 1 - \left(\frac{1}{r_p}\right)^{\frac{\gamma-1}{\gamma}}$$

Ex: $r_p := 4 \quad Brayton\_EFF1(\gamma, r_p) = 0.327$

Plot of effcy. vs pressure ratio, rp:

$r_p := 1, 2 .. 25$ ....define a range variable

$\gamma := 1.4$



Compressor work:

$$W_{comp}(cp, T1, r_p, \gamma) := cp \cdot T1 \cdot \left(r_p^{\frac{\gamma - 1}{\gamma}} - 1 \right) \quad \text{kJ/kg}$$

Ex: $cp := 1.005$ kJ/kg.K $T1 := 300$ K $r_p := 4$ $\gamma := 1.4$

$$W_{comp}(cp, T1, r_p, \gamma) = 146.527 \quad \text{kJ/kg}$$

Turbine work:

$$W_{turb}(cp, T3, r_p, \gamma) := cp \cdot T3 \cdot \left[1 - \left(\frac{1}{r_p} \right)^{\frac{\gamma - 1}{\gamma}} \right] \quad \text{kJ/kg}$$

Ex: $cp := 1.005$ kJ/kg.K $T3 := 1500$ K $r_p := 4$ $\gamma := 1.4$

$$W_{turb}(cp, T3, r_p, \gamma) = 493.028 \quad \text{kJ/kg}$$

Net work:

$W_{net}(cp, T1, T3, r_p, \gamma) := W_{turb}(cp, T3, r_p, \gamma) - W_{comp}(cp, T1, r_p, \gamma)$ kJ/kg

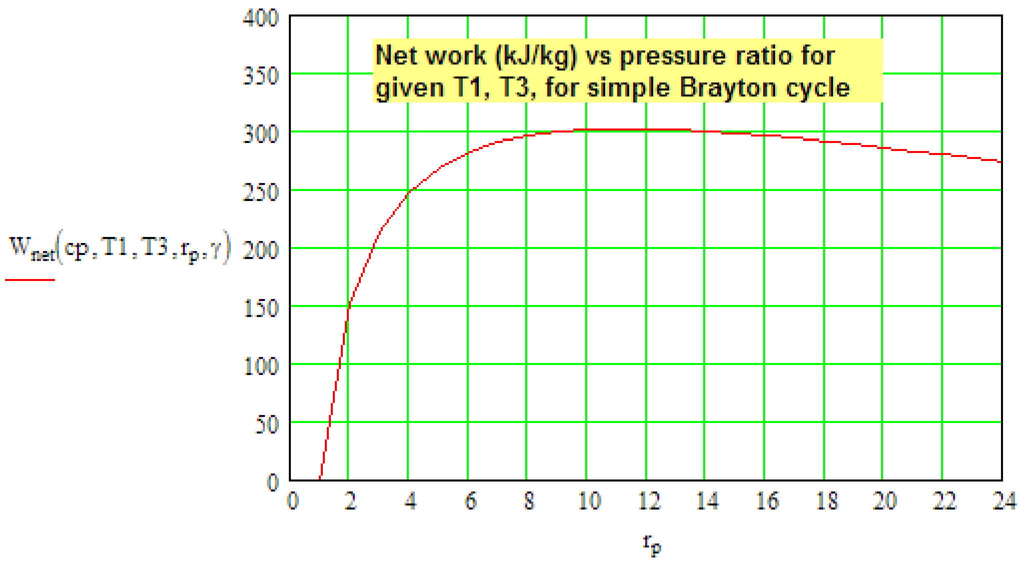
Ex: $cp := 1.005$ kJ/kg.K $T3 := 1500$ K $T1 := 300$ K $r_p := 4$ $\gamma := 1.4$

$W_{net}(cp, T1, T3, r_p, \gamma) = 346.5$ kJ/kg

Plot W_{net} vs r_p for given T1, T3:

$T1 := 300$ K $T3 := 1200$ K

$r_p := 1, 2 .. 24$ ....define a range variable



From Theory, **optimum r_p for max. work is:** $r_p = \left(\frac{T3}{T1}\right)^{\frac{\gamma}{2\cdot(\gamma-1)}}$

Now: $T1 := 300$ K $T3 := 1200$ K

And, $\left(\frac{T3}{T1}\right)^{\frac{\gamma}{2\cdot(\gamma-1)}} = 11.314$

i.e. optimum pressure ratio for max. work = r_p = 11.314.

This is verified from the above graph.

Back Work ratio:

$$BWRatio(cp, T1, T3, r_p, \gamma) := \frac{W_{comp}(cp, T1, r_p, \gamma)}{W_{turb}(cp, T3, r_p, \gamma)}$$

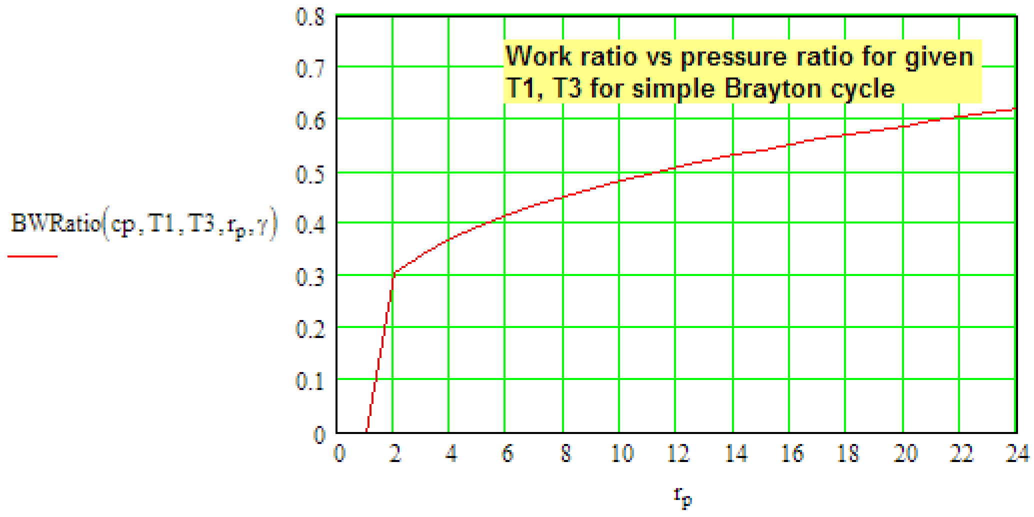
Ex: $cp := 1.005$ kJ/kg.K $T3 := 1200$ K $T1 := 300$ K $r_p := 4$ $\gamma := 1.4$

$BWRatio(cp, T1, T3, r_p, \gamma) = 0.371$

Plot Back Work ratio vs r_p:

$T3 := 1200$ K $\quad T1 := 300$ K

$r_p := 1, 2 .. 24$ ....define a range variable



Single program for Ideal, simple Brayton cycle:

$$\text{Brayton\_cycle\_simple}(cp, T1, T3, r_p, \gamma) := \left| \begin{array}{l} \text{Effcy} \leftarrow \text{Brayton\_EFF1}(\gamma, r_p) \\ W_{comp} \leftarrow W_{comp}(cp, T1, r_p, \gamma) \\ W_{turb} \leftarrow W_{turb}(cp, T3, r_p, \gamma) \\ W_{net} \leftarrow W_{net}(cp, T1, T3, r_p, \gamma) \\ \text{BWRatio} \leftarrow \text{BWRatio}(cp, T1, T3, r_p, \gamma) \\ A \leftarrow \begin{pmatrix} \text{"Th.effcy."} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb(kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Back Work Ratio"} \\ \text{Effcy} & W_{comp} & W_{turb} & W_{net} & \text{BWRatio} \end{pmatrix} \end{array} \right.$$

Ex: $\quad T3 := 1200$ K $\quad T1 := 300$ K $\quad cp := 1.005$ kJ/kg $\quad \gamma := 1.4 \quad r_p := 4$

Let: $\quad B := \text{Brayton\_cycle\_simple}(cp, T1, T3, r_p, \gamma)$

i.e. $\quad B = \begin{pmatrix} \text{"Th.effcy."} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb(kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Back Work Ratio"} \\ 0.327 & 146.527 & 394.422 & 247.895 & 0.371 \end{pmatrix}$

Thus, for given T1, T3, cp, γ, and r_p, Thermal effcy etc are calculated in one step, very conveniently.

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Prob.2.2. In a gas turbine plant, working on a simple Brayton cycle, air at the inlet to the compressor is at 1 bar, 30 C. Pressure ratio is 6. Max. temp is 900 C. Find the thermal efficiency, net work and back work ratio.

Mathcad Solution:

Apply the above written Mathcad program:

Data:

$T1 := 30 + 273$ K $\quad T3 := 900 + 273$ K $\quad cp := 1.005$ kJ/kg.K $\quad r_p := 6 \quad \gamma := 1.4$

Applying the Mathcad Function:

$$B := \text{Brayton\_cycle\_simple}(cp, T1, T3, r_p, \gamma)$$

i.e.
$$B = \begin{pmatrix} \text{"Th.effcy."} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb(kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Back Work Ratio"} \\ 0.401 & 203.571 & 472.328 & 268.756 & 0.431 \end{pmatrix}$$

Thus:

Th. effcy. = 0.401 = 40.1%…Ans.

Compressor work = Wcomp = 203.571 kJ/kg … Ans.

Turbine work = Wturb = 472.328 kJ/kg … Ans.

Net work = Wnet = 268.756 kJ/kg …. Ans.

Back Work Ratio = 0.431 …. Ans.

===

Prob.2.3. Write Mathcad Functions for thermal efficiency etc of an actual, simple Brayton cycle i.e. taking in to account the isentropic efficiencies of compressor and turbine.

Mathcad Functions:

Compressor Work (kJ/kg):

$$W_{comp}(T1, r_p, \gamma, cp, \eta_{comp}) := c_p \cdot \frac{T1 \cdot \left(r_p^{\frac{\gamma-1}{\gamma}} - 1 \right)}{\eta_{comp}}$$

Turbine Work (kJ/kg):

$$W_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) := c_p \cdot \left[T3 \cdot \left(1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}} \right) \cdot \eta_{turb} \right]$$

Net Work (kJ/kg):

$$W_{net}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) := W_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) - W_{comp}(T1, r_p, \gamma, cp, \eta_{comp})$$

Back Work Ratio:

$$BWRatio(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) := \frac{W_{comp}(T1, r_p, \gamma, cp, \eta_{comp})}{W_{turb}(T3, r_p, \gamma, cp, \eta_{turb})}$$

Heat supplied (kJ/kg):

$$Q_{in}(T1, T3, r_p, \gamma, cp, \eta_{comp}) := cp \cdot \left[T3 - \left[T1 + \frac{T1 \cdot \left(r_p^{\frac{\gamma-1}{\gamma}} - 1 \right)}{\eta_{comp}} \right] \right]$$

Efficiency of Actual Simple Open Cycle Gas Turbine:

$$\text{Brayton\_actual\_EFF}(r_p, \gamma, cp, T1, T3, \eta_{comp}, \eta_{turb}) := \frac{W_{net}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb})}{Q_{in}(T1, T3, r_p, \gamma, cp, \eta_{comp})}$$

Single program for actual, simple Bryton cycle:

$$\text{Brayton\_cycle\_actual}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) := \left| \begin{array}{l} \text{Effcy} \leftarrow \text{Brayton\_actual\_EFF}(r_p, \gamma, cp, T1, T3, \eta_{comp}, \eta_{turb}) \\ W_{comp} \leftarrow W_{comp}(T1, r_p, \gamma, cp, \eta_{comp}) \\ W_{turb} \leftarrow W_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) \\ W_{net} \leftarrow W_{net}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) \\ Q_{supp} \leftarrow Q_{in}(T1, T3, r_p, \gamma, cp, \eta_{comp}) \\ \text{BWRatio} \leftarrow \text{BWRatio}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) \\ A \leftarrow \begin{pmatrix} \text{"Effcy"} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb (kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Qsupp (kJ/kg)"} & \text{"Back WRatio"} \\ \text{Effcy} & W_{comp} & W_{turb} & W_{net} & Q_{supp} & \text{BWRatio} \end{pmatrix} \end{array} \right.$$

==

Prob.2.4. In a gas turbine plant, working on a simple Brayton cycle, air at the inlet to the compressor is at 1 bar, 30 C. Pressure ratio is 6. Max. temp is 900 C. Isentropic efficiencies of the compressor and turbine are 0.8 each. Find the thermal efficiency, net work and work ratio.

Mathcad Solution:

Data:

$\gamma := 1.4 \quad c_p := 1.005 \quad \gamma := 1.4 \quad T1 := 303 \text{ K} \quad T3 := 1173 \text{ K} \quad r_p := 6$

$\eta_{comp} := 0.8 \quad \eta_{turb} := 0.8$

Then, we have, using the Mathcad Function written above:

$BB := \text{Brayton\_cycle\_actual}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb})$

i.e.

$$BB = \begin{pmatrix} \text{"Effcy"} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb (kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Qsupp (kJ/kg)"} & \text{"Back WRatio"} \\ 0.199 & 254.464 & 377.862 & 123.398 & 619.886 & 0.673 \end{pmatrix}$$

Thus:

Th. effcy. = 0.199 = 19.9 %…Ans.

Compressor work = Wcomp = 254.464 kJ/kg … Ans.

Turbine work = Wturb = 377.862 kJ/kg … Ans.

Net work = Wnet = 123.398 kJ/kg …. Ans.

Heat supplied = Qsupp = 619.886 kJ/kg … Ans.

Back Work Ratio = 0.673 …. Ans.

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Prob.2.5 Write a Mathcad Function for Thermal efficiency of an Ideal Brayton cycle with ideal regenerator.

Efficiency of Ideal Open Cycle Gas Turbine with Ideal Regeneration:.

Depends on pressure ratio and the cycle max to min temp. ratio:

$$\text{Brayton\_IdealRegen\_EFF}(\gamma, r_p, T1, T3) := 1 - \left(\frac{T1}{T3}\right) \cdot r_p^{\frac{\gamma-1}{\gamma}}$$

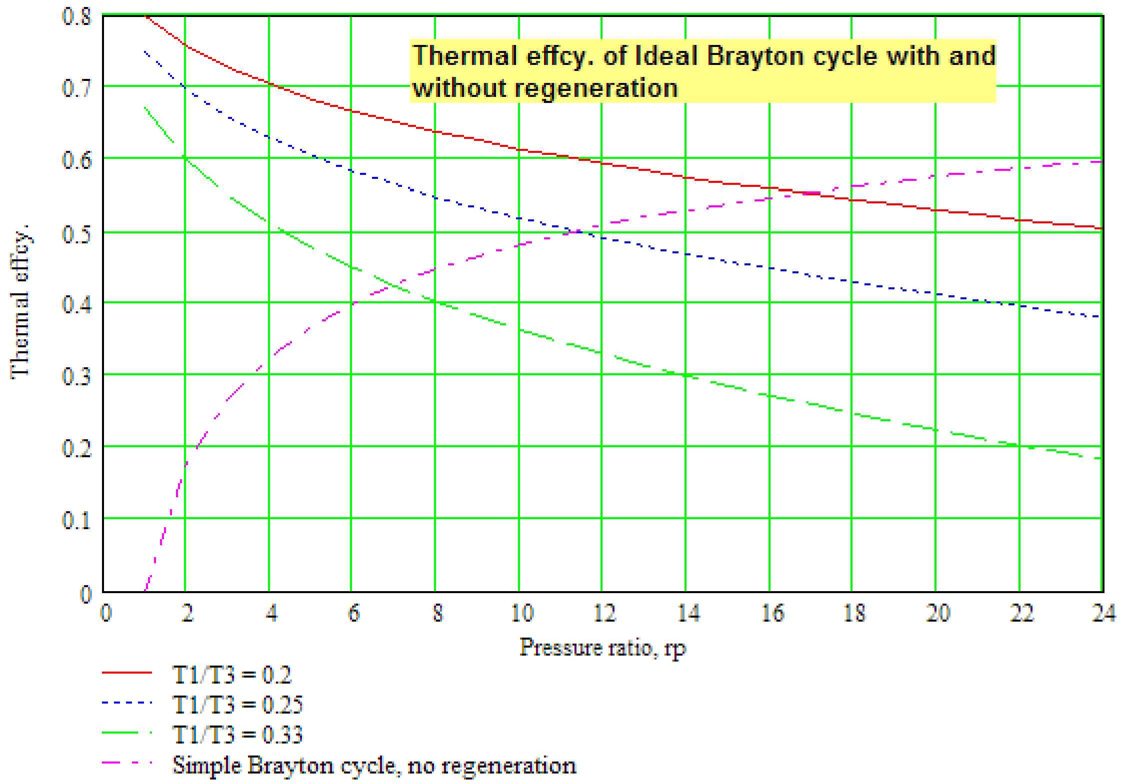
In terms of temp. ratio, t = T1/T3, re-writing the above eqn, we have:

$$\text{Brayton\_IdealRegen\_EFF}(\gamma, t, r_p) := 1 - (t) \cdot r_p^{\frac{\gamma-1}{\gamma}}$$

Plot the Efficiency vs pressure ratio, for different temp ratios:

$\gamma := 1.4$

$r_p := 1, 2 .. 24$ ....define a range variable


Thermal effcy. of Ideal Brayton cycle with and without regeneration
Thermal effcy.
Pressure ratio, rp
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
2
4
6
8
10
12
14
16
18
20
22
24
T1/T3 = 0.2
T1/T3 = 0.25
T1/T3 = 0.33
Simple Brayton cycle, no regeneration

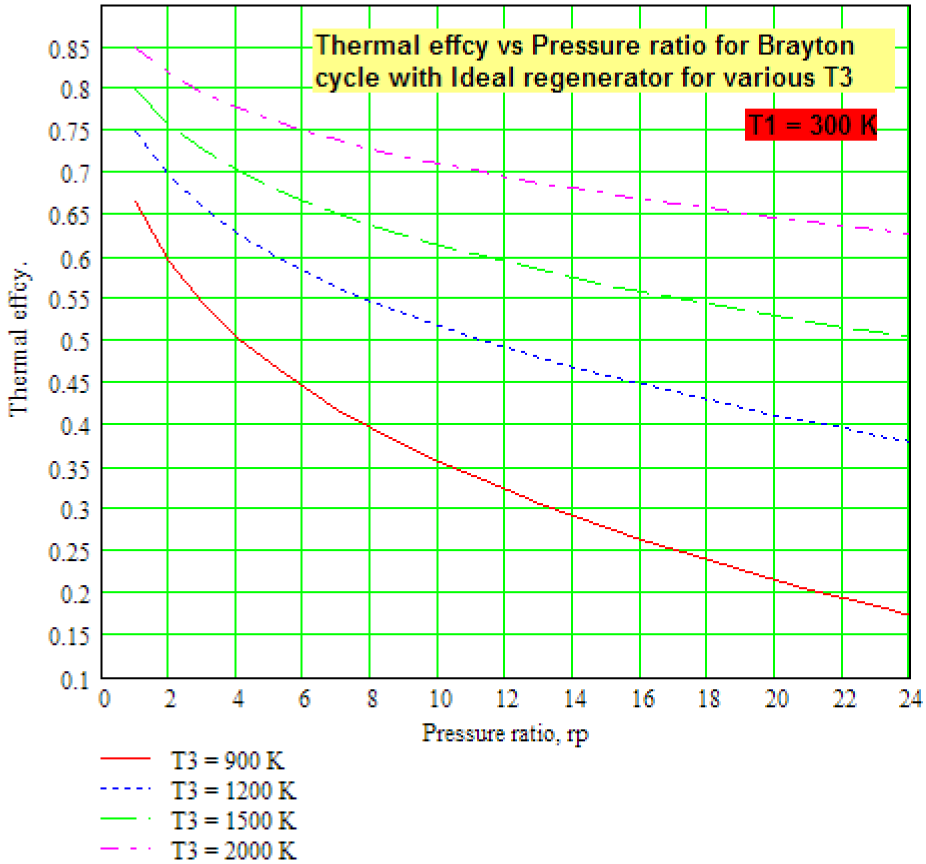
Also, plot thermal effcy vs pressure ratio for T3 = 900, 1200, 1500 and 2000 K, with T1 = 300 K:

We have:

$T1 := 300\,K \quad \gamma := 1.4$

$$\text{Brayton\_IdealRegen\_EFF}(\gamma, r_p, T1, T3) := 1 - \left(\frac{T1}{T3}\right)\cdot r_p^{\frac{\gamma-1}{\gamma}}$$

$r_p := 1, 2 .. 24$ ....define a range variable



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Prob.2.6 Write Mathcad Functions for Thermal efficiency etc of an **ideal Brayton cycle with regenerator of efficiency = ε**

Mathcad Solution:

Let the pressure ratio be 10, and regenerator efficiency = 80%. Also, T1 = 300 K, T3 = 1400 K, cp = 1.005 kJ/kg.K, γ = 1.4.

We shall write Functions for all calculated quantities:

Data:

$r_p := 10 \quad \gamma := 1.4 \quad cp := 1.005$ kJ/kg.K

$T1 := 300$ K $\quad T3 := 1400$ K $\quad \varepsilon := 0.8$ ....regen. effectiveness

We have for Regen. effectiveness: $\varepsilon = \dfrac{T5 - T2}{T4 - T2}$

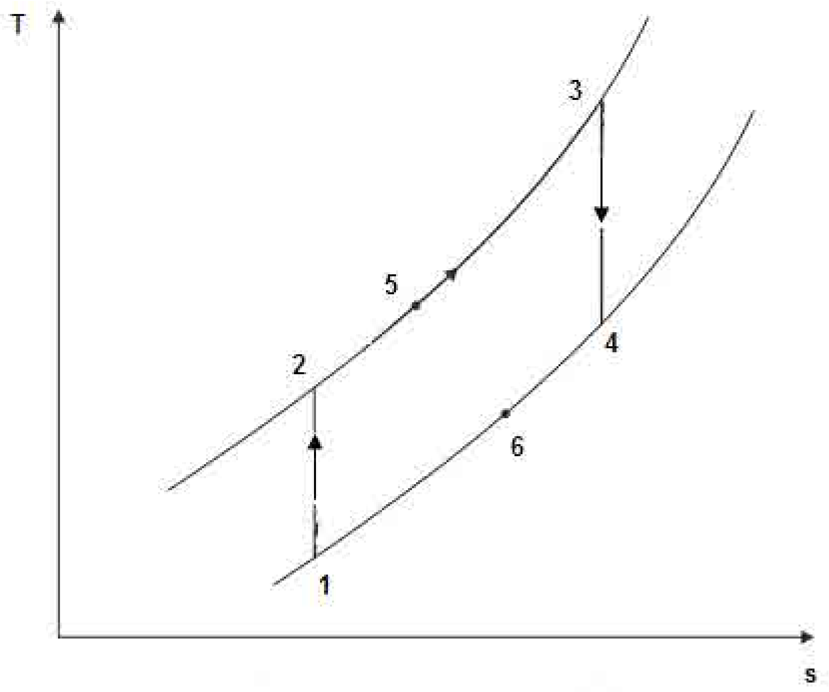


Fig.Prob.2.6

Temp at exit of compressor:

$$T2(r_p, \gamma, T1) := T1 \cdot r_p^{\frac{\gamma-1}{\gamma}}$$ K.

Temp at exit of turbine:

$$T4(r_p, \gamma, T3) := \frac{T3}{r_p^{\frac{\gamma-1}{\gamma}}}$$ K

Temp at exit of high pressure stream in regenerator:

$$T5(r_p,\gamma,\varepsilon,T1,T3) := T2(r_p,\gamma,T1) + \varepsilon\cdot(T4(r_p,\gamma,T3) - T2(r_p,\gamma,T1)) \quad \text{K}$$

Heat supplied:

$$Q_s(cp,r_p,\gamma,\varepsilon,T1,T3) := cp\cdot(T3 - T5(r_p,\gamma,\varepsilon,T1,T3)) \quad \text{kJ/kg}$$

Compressor Work:

$$W_{comp}(cp,r_p,\gamma,T1) := cp\cdot(T2(r_p,\gamma,T1) - T1) \quad \text{kJ/kg}$$

Turbine Work:

$$W_{turb}(cp,r_p,\gamma,T3) := cp\cdot(T3 - T4(r_p,\gamma,T3)) \quad \text{kJ/kg}$$

Net Work:

$W_{net}(cp, r_p, \gamma, T1, T3) := W_{turb}(cp, r_p, \gamma, T3) - W_{comp}(cp, r_p, \gamma, T1)$ kJ/kg

Thermal efficiency:

$$\eta_{th}(cp, r_p, \gamma, \varepsilon, T1, T3) := \frac{W_{net}(cp, r_p, \gamma, T1, T3)}{Q_s(cp, r_p, \gamma, \varepsilon, T1, T3)}$$

i.e. $\eta_{th}(cp, r_p, \gamma, \varepsilon, T1, T3) = 0.562$ **= 56.2 % ... Ans.**

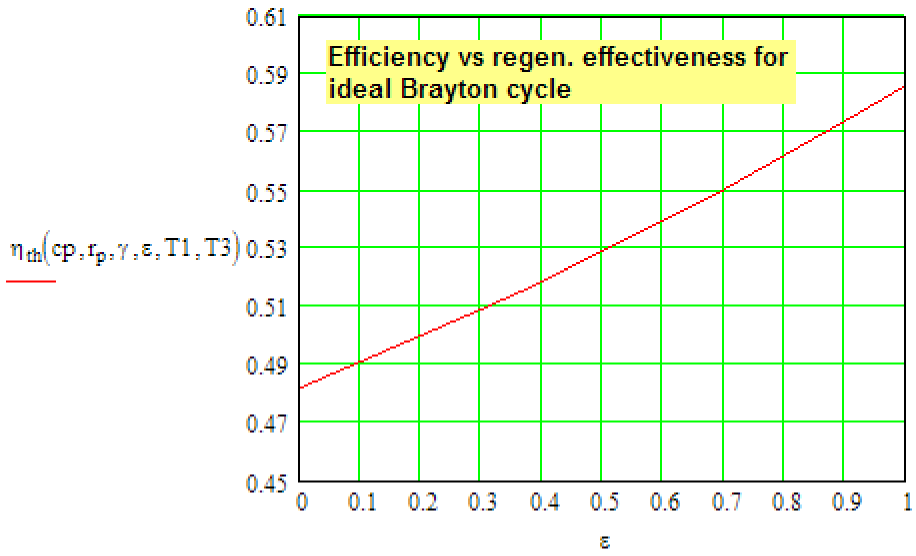
(b) Plot Thermal efficiency of the cycle vs regenerator effectiveness, other conditions remaining the same:

Since efficiency is written as a function of other, involved variables, it is very easy to plot efficiency against any of the other variables.

$r_p := 10$ $\gamma := 1.4$ $cp := 1.005$ kJ/kg.K

$T1 := 300$ K $T3 := 1400$ K

$\varepsilon := 0, 0.1 .. 1$ ....define a range variable

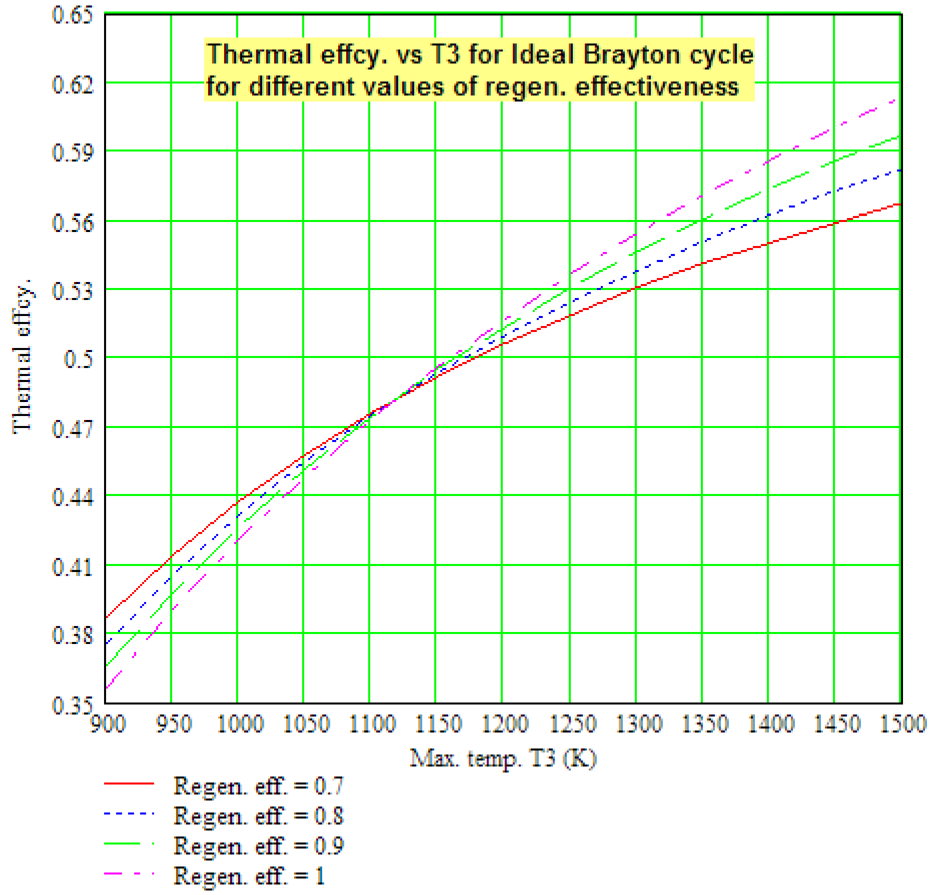


If we need to plot efficiency vs T3:

$r_p := 10$ $\gamma := 1.4$ $cp := 1.005$ kJ/kg.K

$T1 := 300$ K

$T3 := 900, 950 .. 1500$ ....define a range variable



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Prob.2.7 Write a Mathcad Function for Thermal efficiency of an **actual Brayton cycle with regenerator**. i.e. *including* the efficiencies of compressor (η_{comp}), turbine (ηt_{urb}) and the regenerator (ε):

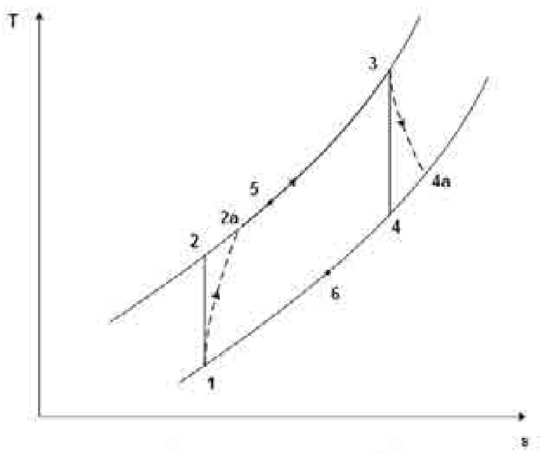


Fig.Prob.2.7

Mathcad Functions:

Turbine Work:

$$W_{turb}(r_p,\gamma,cp,T3,\eta_{turb}) := cp\cdot\left[T3\cdot\left(1-\frac{1}{r_p^{\frac{\gamma-1}{\gamma}}}\right)\cdot\eta_{turb}\right]$$ kJ/kg

Compressor Work:

$$W_{comp}(r_p,\gamma,cp,T1,\eta_{comp}) := cp\cdot\frac{T1\cdot\left(r_p^{\frac{\gamma-1}{\gamma}}-1\right)}{\eta_{comp}}$$ kJ/kg

Net Work:

$$W_{net}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb}) := W_{turb}(r_p,\gamma,cp,T3,\eta_{turb}) - W_{comp}(r_p,\gamma,cp,T1,\eta_{comp})$$ kJ/kg

Back Work Ratio:

$$BWRatio(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb}) := \frac{W_{comp}(r_p,\gamma,cp,T1,\eta_{comp})}{W_{turb}(r_p,\gamma,cp,T3,\eta_{turb})}$$

Temp at exit of compressor:

$$T2a\left(r_p,\gamma,T1,\eta_{comp}\right) := T1 + \frac{T1\cdot\left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right)}{\eta_{comp}} \quad K$$

Temp at exit of turbine:

$$T4a\left(r_p,\gamma,T3,\eta_{turb}\right) := T3 - T3\cdot\left(1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}}\right)\cdot\eta_{turb} \quad K$$

Regen. effectiveness, ε:

$$\varepsilon = \frac{T5 - T2a}{T_{4a} - T2a}$$

Therefore, temp at exit of high pressure stream in regenerator:

$$T5\left(r_p,\gamma,T1,T3,\eta_{comp},\eta_{turb},\varepsilon\right) := T2a\left(r_p,\gamma,T1,\eta_{comp}\right) + \varepsilon\cdot\left(T4a\left(r_p,\gamma,T3,\eta_{turb}\right) - T2a\left(r_p,\gamma,T1,\eta_{comp}\right)\right) \quad K$$

Heat supplied:

$$Q_{in}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb},\varepsilon) := cp\cdot(T3 - T5(r_p,\gamma,T1,T3,\eta_{comp},\eta_{turb},\varepsilon)) \quad \text{kJ/kg}$$

Thermal efficiency:

$$\text{Brayton\_actual\_regen\_EFF}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb},\varepsilon) := \frac{W_{net}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb})}{Q_{in}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb},\varepsilon)}$$

Single program for actual, Brayton cycle with Regenerator:

$$\text{Brayton\_actual\_regen}(T1,T3,r_p,\gamma,cp,\eta_{comp},\eta_{turb},\varepsilon) := \left| \begin{array}{l} \text{Effcy} \leftarrow \text{Brayton\_actual\_regen\_EFF}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb},\varepsilon) \\ W_{comp} \leftarrow W_{comp}(r_p,\gamma,cp,T1,\eta_{comp}) \\ W_{turb} \leftarrow W_{turb}(r_p,\gamma,cp,T3,\eta_{turb}) \\ W_{net} \leftarrow W_{net}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb}) \\ Q_{supp} \leftarrow Q_{in}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb},\varepsilon) \\ \text{BWRatio} \leftarrow \text{BWRatio}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb}) \\ A \leftarrow \begin{pmatrix} \text{"Effcy"} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb (kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Qsupp (kJ/kg)"} & \text{"BWRatio"} \\ \text{Effcy} & W_{comp} & W_{turb} & W_{net} & Q_{supp} & \text{BWRatio} \end{pmatrix} \end{array} \right.$$

Ex:

$\gamma := 1.4$ $c_p := 1.005$ kJ/kg.K $T1 := 303$ K $T3 := 1173$ K $r_p := 6$

$\eta_{comp} := 0.8$ $\eta_{turb} := 0.8$ $\varepsilon := 0.75$ ....effcy of regenerator

Applying the above Mathcad Function, we get:

$$BB := \text{Brayton\_actual\_regen}(T1,T3,r_p,\gamma,cp,\eta_{comp},\eta_{turb},\varepsilon)$$

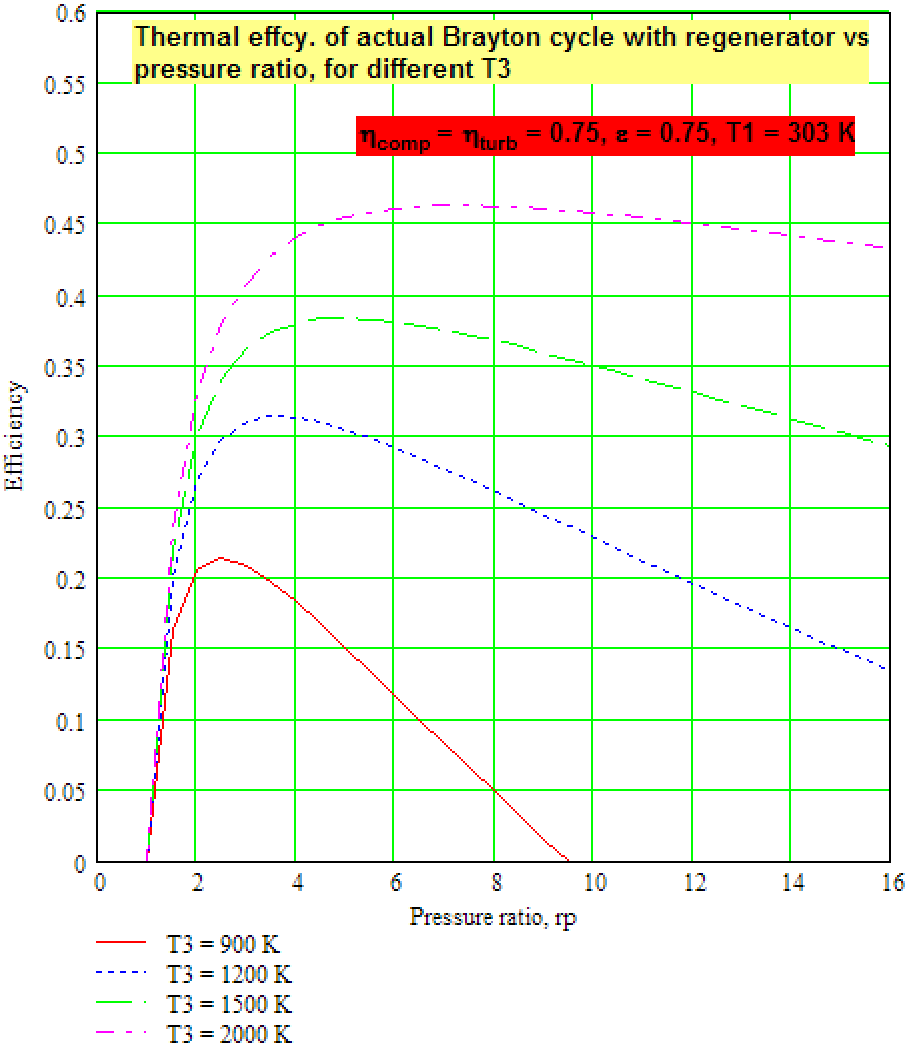
$$BB = \begin{pmatrix} \text{"Effcy"} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb (kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Qsupp (kJ/kg)"} & \text{"BWRatio"} \\ 0.281 & 254.464 & 377.862 & 123.398 & 438.368 & 0.673 \end{pmatrix}$$

Plot Thermal effcy vs rp for various T3:

$\gamma := 1.4$ $c_p := 1.005$ $\gamma := 1.4$ $T1 := 303$ K

$\eta_{comp} := 0.8$ $\eta_{turb} := 0.8$ $\varepsilon := 0.75$ ....effcy of regenerator

$r_p := 1, 1.5 .. 16$ ....define a range variable

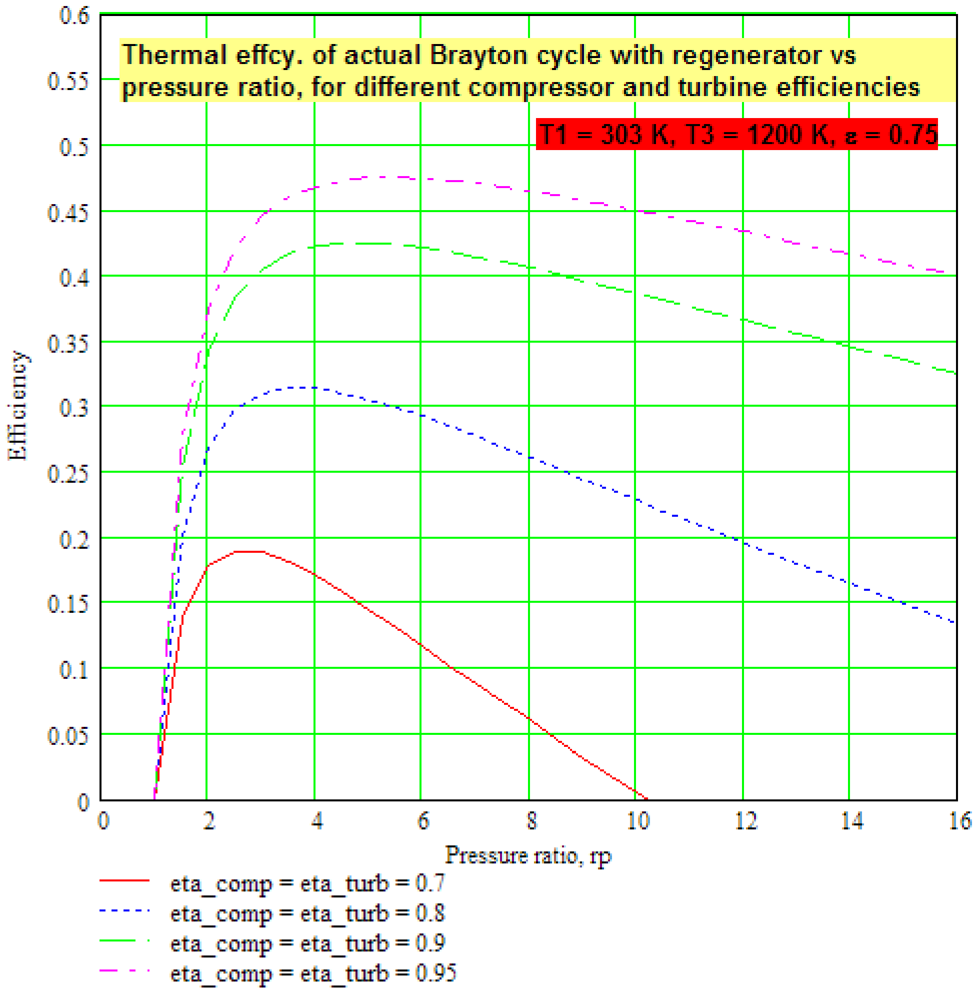


Plot Thermal effcy vs rp for various compressor and turbine efficiencies, for fixed T1,T3:

$\gamma := 1.4$ $c_p := 1.005$ $\gamma := 1.4$ $T1 := 303$ K $T3 := 1200$ K

$\eta_{comp} := 0.8$ $\eta_{turb} := 0.8$ $\varepsilon := 0.75$ ....effcy of regenerator

$r_p := 1, 1.5 .. 16$ ....define a range variable



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Prob.2.8 The extreme pressures and temps in an open cycle gas turbine plant are 1 bar and 5 bar, and 27 C and 550 C respectively. Calculate the efficiency of the cycle when (i) there is no regenerator, (ii) there is a regenerator with 60% effectiveness. Take γ = 1.4 [VTU-Jan. 2003]

Mathcad Solution:

Use the Functions written earlier.

Data:

$P1 := 1$ bar $\quad P3 := 5$ bar $\quad r_p := 5 \quad \gamma := 1.4 \quad \varepsilon := 0.6$ ...effectivenes of regen.

$T1 := 27 + 273$ K $\quad T3 := 550 + 273$ K

Case (i): when there is no regenerator:

$B := \text{Brayton\_cycle\_simple}(cp, T1, T3, r_p, \gamma)$

i.e. $B = \begin{pmatrix} \text{"Th.effcy."} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb(kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Back Work Ratio"} \\ 0.369 & 176.022 & 304.887 & 128.865 & 0.577 \end{pmatrix}$

Thus, Thermal effcy. = 36.9% when there is no regenerator … Ans.

Case (ii): when there is a regenerator with an effectiveness of 60 %:

We use the following program, written earlier:

$$\text{Brayton\_actual\_regen}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}, \varepsilon) := \left| \begin{array}{l} Effcy \leftarrow \text{Brayton\_actual\_regen\_EFF}(r_p, \gamma, cp, T1, T3, \eta_{comp}, \eta_{turb}, \varepsilon) \\ W_{comp} \leftarrow W_{comp}(r_p, \gamma, cp, T1, \eta_{comp}) \\ W_{turb} \leftarrow W_{turb}(r_p, \gamma, cp, T3, \eta_{turb}) \\ W_{net} \leftarrow W_{net}(r_p, \gamma, cp, T1, T3, \eta_{comp}, \eta_{turb}) \\ Q_{supp} \leftarrow Q_{in}(r_p, \gamma, cp, T1, T3, \eta_{comp}, \eta_{turb}, \varepsilon) \\ BWRatio \leftarrow BWRatio(r_p, \gamma, cp, T1, T3, \eta_{comp}, \eta_{turb}) \\ A \leftarrow \begin{pmatrix} \text{"Effcy"} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb (kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Qsupp (kJ/kg)"} & \text{"BWRatio"} \\ Effcy & W_{comp} & W_{turb} & W_{net} & Q_{supp} & BWRatio \end{pmatrix} \end{array} \right.$$

We have:

$\gamma := 1.4$ $cp := 1.005$ kJ/kg.K $r_p := 5$

$T1 := 27 + 273$ K $T3 := 550 + 273$ K $\varepsilon := 0.6$ ....effcy of regenerator

$\eta_{comp} := 1$ $\eta_{turb} := 1$ ....assumed as 100 % since no values are given.

Then:

$BB := \text{Brayton\_actual\_regen}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}, \varepsilon)$

$BB = \begin{pmatrix} \text{"Effcy"} & \text{"Wcomp (kJ/kg)"} & \text{"Wturb (kJ/kg)"} & \text{"Wnet (kJ/kg)"} & \text{"Qsupp (kJ/kg)"} & \text{"BWRatio"} \\ 0.399 & 176.022 & 304.887 & 128.865 & 322.77 & 0.577 \end{pmatrix}$

Thus, Thermal effcy. = 39.9% when there is a regenerator with ε = 0.6 … Ans.

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Prob.2.9 In a Regenerative Brayton cycle, inlet conditions to compressor are: P1 = 100 kPa, T1 = 300 K. Regenerator efficiency = 80%. Max. temp is 1400 K. Compressor and turbine efficiencies are 90, 80 and 70% each. Plot (i) thermal efficiency, (ii) Back work ratio, (iii) net work developed in kJ/kg, when pressure ratio varies from 2 to 20.

Mathcad Solution:

We shall use the Mathcad Functions written above, viz:

$$\text{Brayton\_actual\_regen\_EFF}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb},\varepsilon) := \frac{W_{net}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb})}{Q_{in}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb},\varepsilon)}$$

$$\text{BWRatio}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb}) := \frac{W_{comp}(r_p,\gamma,cp,T1,\eta_{comp})}{W_{turb}(r_p,\gamma,cp,T3,\eta_{turb})}$$

$$W_{net}(r_p,\gamma,cp,T1,T3,\eta_{comp},\eta_{turb}) := W_{turb}(r_p,\gamma,cp,T3,\eta_{turb}) - W_{comp}(r_p,\gamma,cp,T1,\eta_{comp}) \text{ kJ/kg}$$

Data:

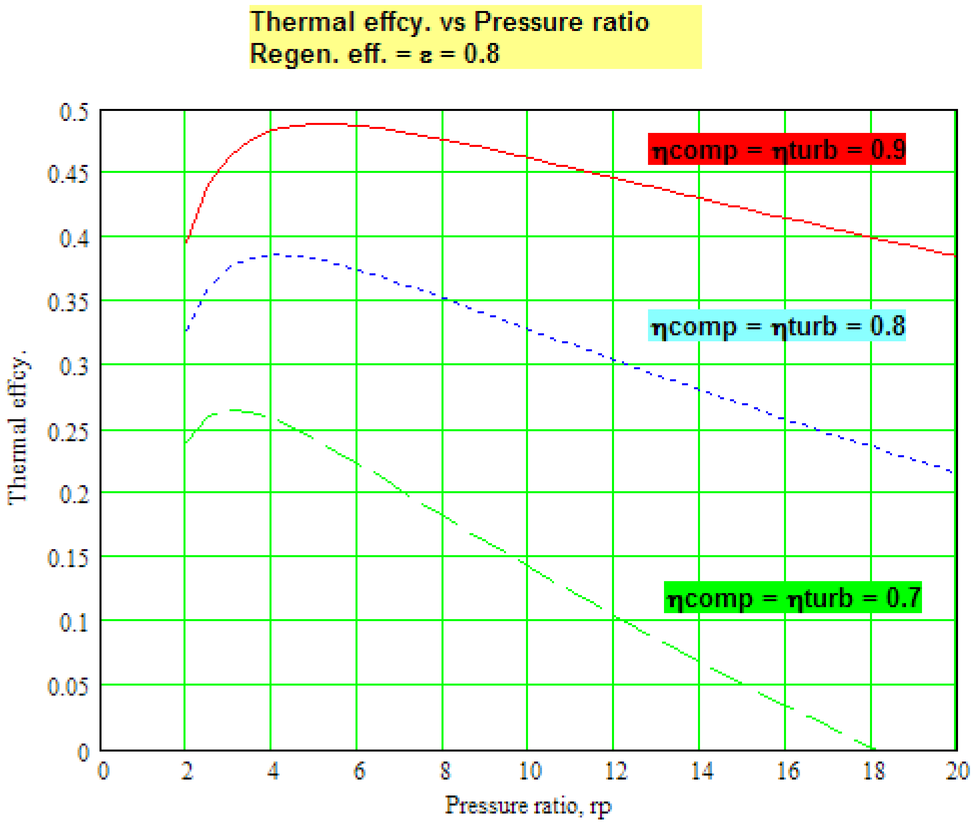
$T1 := 300$ K $\quad T3 := 1400$ K $\quad \varepsilon := 0.8$ ....regen. effcy.

$\gamma := 1.4 \quad cp := 1.005$ kJ/kg.K

Thermal efficiency.:

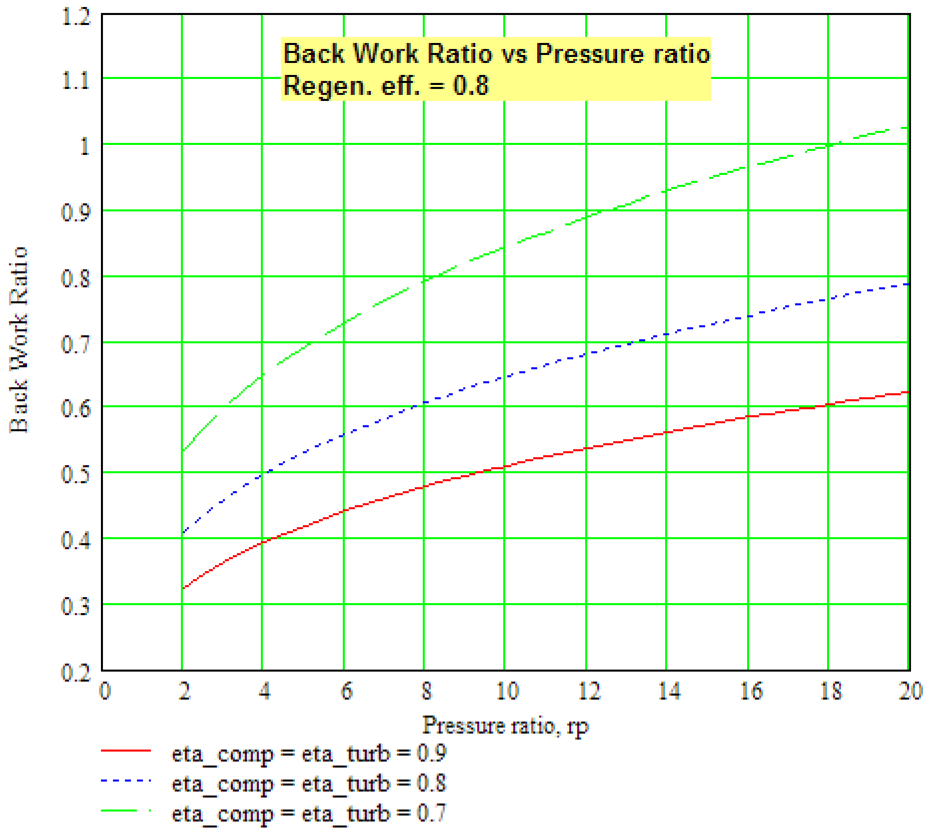
$r_p := 2, 2.5 .. 20$ ...define a range variable

rp	effcy (eta_comp = eta_turb = 0.9)	effcy (eta_comp = eta_turb = 0.8)	effcy (eta_comp = eta_turb = 0.7)
2	0.397	0.327	0.24
4	0.483	0.386	0.265
6	0.487	0.374	0.258
8	0.476	0.352	0.242
10	0.462	0.328	0.223
12	0.446	0.304	0.202
14	0.43	0.28	0.182
16	0.415	0.258	0.162
18	0.4	0.236	0.142
20	0.385	0.215	0.123



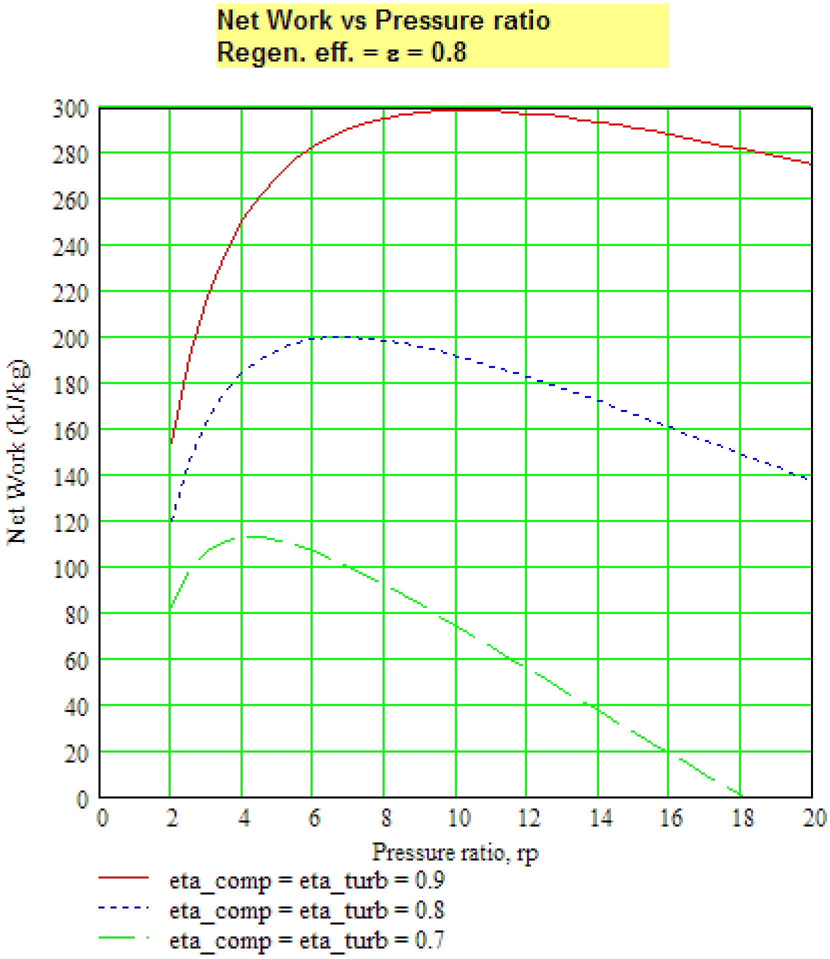
Back Work Ratio (BWR):

rp	BWR (eta_comp = eta_turb = 0.9)	BWR (eta_comp = eta_turb = 0.8)	BWR (eta_comp = eta_turb = 0.7)
2	0.322	0.408	0.533
4	0.393	0.498	0.65
6	0.441	0.559	0.73
8	0.479	0.607	0.792
10	0.511	0.646	0.844
12	0.538	0.681	0.889
14	0.562	0.712	0.93
16	0.584	0.739	0.966
18	0.604	0.765	0.999
20	0.623	0.788	1.029



Net Work:

rp	Wnet (eta_comp = eta_turb = 0.9)	Wnet (eta_comp = eta_turb = 0.8)	Wnet (eta_comp = eta_turb = 0.7)
2	154.14	119.69	82.619
4	251.335	184.968	112.787
6	283.409	199.041	106.676
8	295.411	198.404	91.689
10	298.639	191.842	73.909
12	297.345	182.526	55.335
14	293.491	171.855	36.754
16	288.101	160.526	18.496
18	281.761	148.913	0.705
20	274.823	137.225	-16.567



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Prob.2.10. Write Mathcad Functions for efficiency etc of a Brayton cycle with intercooling, reheating and regenerator.

Mathcad Solution:

Assumed that:

The compressor has two stages, with equal pressure ratio in each stage.

Overall pressure ratio = rp, preassure ratio in each stage = rp^0.5

'Perfect inter-cooling' between compressor stages, i.e. after compression in first stage, air is cooled back to initial temp before entry to second stage.

Similarly, turbine has two stages, pressure ratios in LP and HP turbines being equal, and re-heating back to HP turbine inlet temp after expansion, before entering LP turbine.

Regenerator effectiveness = ε.

$$\varepsilon = \frac{T5 - T2a}{T4a - T2a} \quad \text{....regen. effcy.}$$

See the diagram below:

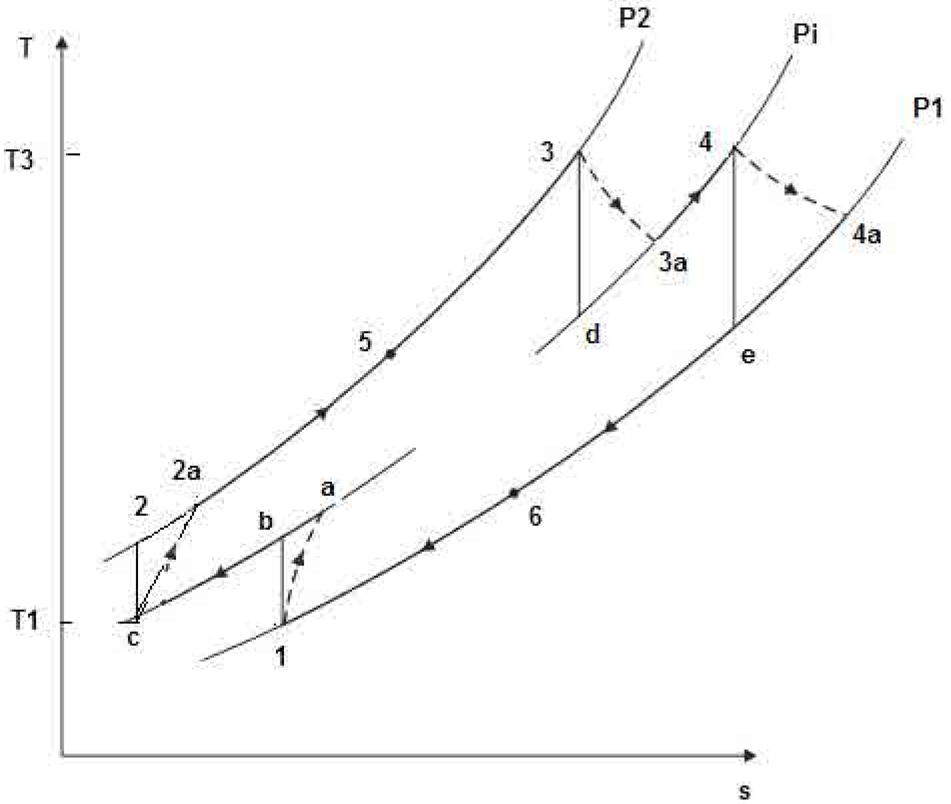


Fig.Prob.2.10

We have the following Mathcad Functions:

Total Compressor work input:

$$WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp}) := c_p \cdot \frac{T1 \cdot \left(r_p^{0.5 \cdot \frac{\gamma - 1}{\gamma}} - 1 \right) \cdot 2}{\eta_{comp}} \quad \text{kJ/kg}$$

Total Turbine work output:

$$WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) := c_p \cdot \left[T3 \cdot \left(1 - \frac{1}{r_p^{0.5 \cdot \frac{\gamma-1}{\gamma}}} \right) \cdot \eta_{turb} \right] \cdot 2 \qquad \text{kJ/kg}$$

Net Work output:

$$W_{net}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) := WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) - WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp})$$

Back Work Ratio:

$$BWRATIO(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) := \frac{WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp})}{WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb})}$$

Work Ratio:

$$WRATIO(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) := \frac{WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) - WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp})}{WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb})}$$

Temp. T2a:

$$T2a(T1, r_p, \gamma, \eta_{comp}) := \frac{T1 \cdot \left(r_p^{0.5 \cdot \frac{\gamma-1}{\gamma}} - 1 \right)}{\eta_{comp}} + T1 \quad K$$

Temp. T4a:

$$T4a(T3, r_p, \gamma, \eta_{turb}) := T3 - \left[T3 \cdot \left(1 - \frac{1}{r_p^{0.5 \cdot \frac{\gamma-1}{\gamma}}} \right) \cdot \eta_{turb} \right] \quad K$$

T5, temp at exit of high pressure stream in regenerator:

$$\varepsilon = \frac{T5 - T2a}{T4a - T2a} \quad \text{....regen. effcy.}$$

Then:

$$T5(T1, T3, r_p, \gamma, \eta_{comp}, \eta_{turb}, \varepsilon) := T2a(T1, r_p, \gamma, \eta_{comp}) + \varepsilon \cdot (T4a(T3, r_p, \gamma, \eta_{turb}) - T2a(T1, r_p, \gamma, \eta_{comp})) \quad K$$

Heat supplied:

$$Q1(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}, \varepsilon) := cp \cdot (T3 - T5(T1, T3, r_p, \gamma, \eta_{comp}, \eta_{turb}, \varepsilon)) \ldots + cp \cdot (T3 - T4a(T3, r_p, \gamma, \eta_{turb})) \quad kJ/kg$$

Thermal efficiency:

$$EFFCY(T1, T3, r_p, \gamma, \eta_{comp}, \eta_{turb}, \varepsilon) := \frac{WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) - WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp})}{Q1(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}, \varepsilon)}$$

==

Prob.2.11. In a Regenerative Brayton cycle, with intercooling and reheating, overall pressure ratio is 9, inlet conditions to compressor are: T1 = 293 K. Regenerator efficiency = 80%. Max. temp is 898 K. Compressor and turbine have 2 stages and for each stage, efficiencies are 80% and 85% respectively. Find Thermal effcy and Back Work ratio etc.

(b) Plot (i) thermal efficiency, (ii) Back work ratio, (iii) net work developed in kJ/kg, when pressure ratio varies from 2 to 20.

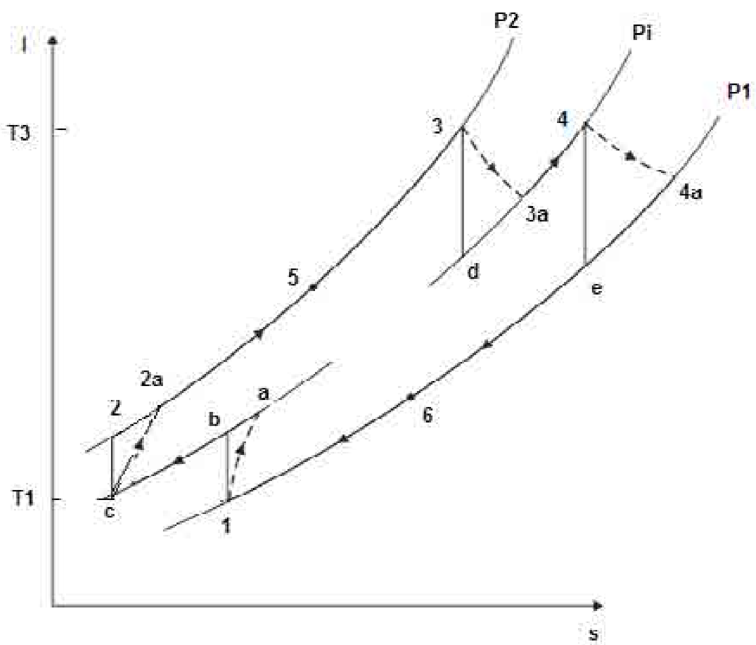


Fig.Prob.2.11

Mathcad Solution:

We shall use the Functions written above.

Data:

$T1 := 293$ K $T3 := 898$ K $\varepsilon := 0.8$ ....regen. effcy.

$\gamma := 1.4$ $cp := 1.005$ kJ/kg.K $r_p := 9$ ...overall pressure ratio

$\eta_{comp} := 0.8$ $\eta_{turb} := 0.85$

Solution:

Total Compressor work input:

$$WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp}) := c_p \cdot \frac{T1 \cdot \left(r_p^{0.5 \cdot \frac{\gamma - 1}{\gamma}} - 1 \right) \cdot 2}{\eta_{comp}}$$

i.e. $WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp}) = 271.451$ **kJ/kg .... Ans.**

Total Turbine work output:

$$WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) := c_p \cdot \left[T3 \cdot \left(1 - \frac{1}{r_p^{0.5 \cdot \frac{\gamma - 1}{\gamma}}} \right) \cdot \eta_{turb} \right] \cdot 2$$

i.e. $WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) = 413.322$ **kJ/kg .... Ans.**

Net Work output:

$$W_{net}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) := WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) - WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp})$$

i.e. $W_{net}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) = 141.871$ **kJ/kg .... Ans.**

Back Work Ratio:

$$BWRATIO(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) := \frac{WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp})}{WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb})}$$

i.e. $BWRATIO(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) = 0.657$ **.... Ans.**

Work Ratio:

$$\mathrm{WRATIO}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) := \frac{WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb}) - WK_{comp}(T1, r_p, \gamma, cp, \eta_{comp})}{WK_{turb}(T3, r_p, \gamma, cp, \eta_{turb})}$$

i.e. $\mathrm{WRATIO}(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}) = 0.343$ **.... Ans.**

Temp. T2a:

$$T2a(T1, r_p, \gamma, \eta_{comp}) := \frac{T1 \cdot \left(r_p^{0.5 \cdot \frac{\gamma - 1}{\gamma}} - 1 \right)}{\eta_{comp}} + T1$$

i.e. $T2a(T1, r_p, \gamma, \eta_{comp}) = 428.05$ **K....Ans.**

Temp. T4a:

$$T4a(T3, r_p, \gamma, \eta_{turb}) := T3 - \left[T3 \cdot \left(1 - \frac{1}{r_p^{0.5 \cdot \frac{\gamma - 1}{\gamma}}} \right) \cdot \eta_{turb} \right]$$

i.e. $T4a(T3, r_p, \gamma, \eta_{turb}) = 692.367$ **K....Ans.**

T5, temp at exit of high pressure stream in regenerator:

$$\varepsilon = \frac{T5 - T2a}{T4a - T2a}$$ ....regen. effcy.

$$T5(T1, T3, r_p, \gamma, \eta_{comp}, \eta_{turb}, \varepsilon) := T2a(T1, r_p, \gamma, \eta_{comp}) + \varepsilon \cdot (T4a(T3, r_p, \gamma, \eta_{turb}) - T2a(T1, r_p, \gamma, \eta_{comp}))$$

i.e. $T5(T1, T3, r_p, \gamma, \eta_{comp}, \eta_{turb}, \varepsilon) = 639.504$ **K....Ans.**

Heat supplied:

$$Q1(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}, \varepsilon) := cp \cdot (T3 - T5(T1, T3, r_p, \gamma, \eta_{comp}, \eta_{turb}, \varepsilon)) \ldots + cp \cdot (T3 - T4a(T3, r_p, \gamma, \eta_{turb}))$$

i.e. $Q1(T1, T3, r_p, \gamma, cp, \eta_{comp}, \eta_{turb}, \varepsilon) = 466.45$ **kJ/kg ... Ans.**

Thermal efficiency:

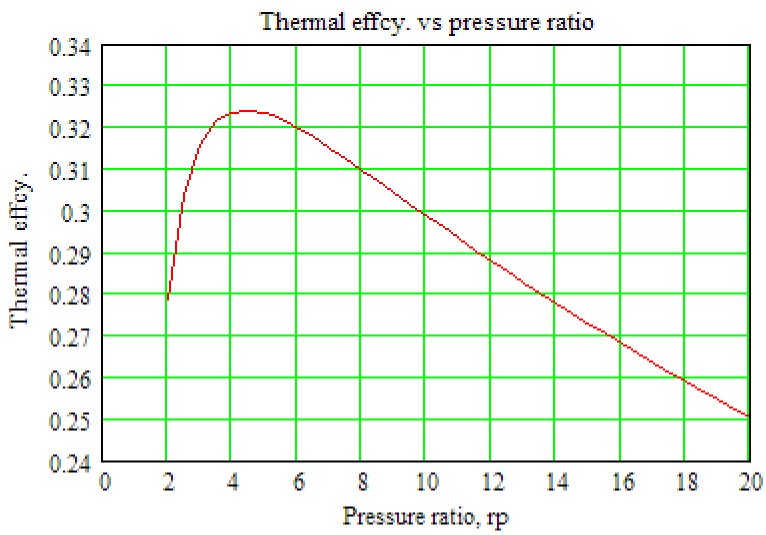
$$EFFCY(T1,T3,r_p,\gamma,\eta_{comp},\eta_{turb},\varepsilon) := \frac{WK_{turb}(T3,r_p,\gamma,cp,\eta_{turb}) - WK_{comp}(T1,r_p,\gamma,cp,\eta_{comp})}{Q1(T1,T3,r_p,\gamma,cp,\eta_{comp},\eta_{turb},\varepsilon)}$$

i.e. $EFFCY(T1,T3,r_p,\gamma,\eta_{comp},\eta_{turb},\varepsilon) = 0.304$ **..Ans.**

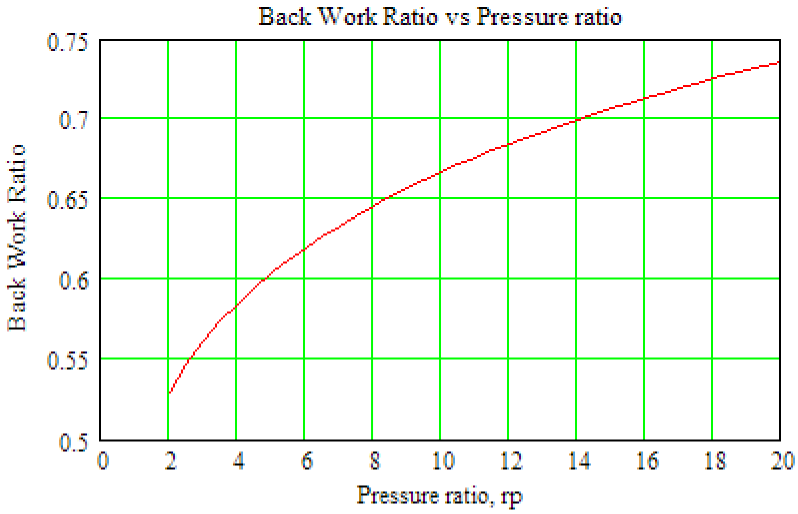
(b) Plot (i) thermal efficiency, (ii) Back work ratio, and (iii) net work developed in kJ/kg, when pressure ratio varies from 2 to 20, other conditions remaining the same:

$r_p := 2, 2.5 .. 20$ ...define a range variable

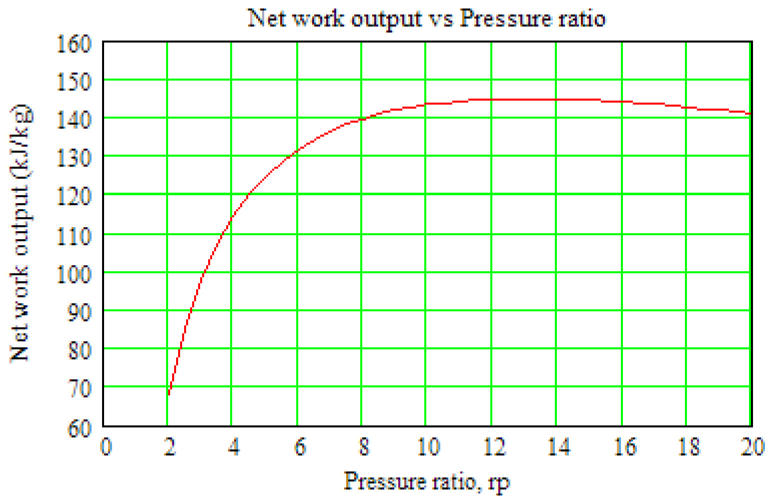
Thermal efficiency:



Back Work Ratio:



Net work output:



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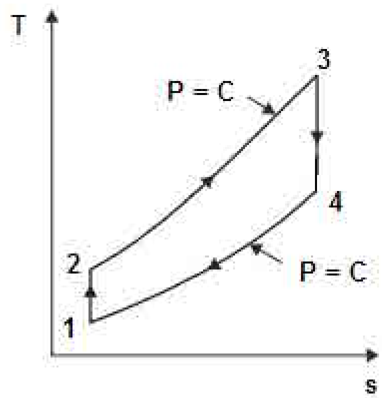
2.3 Problems solved with EES:

Prob.2.12 Write EES Procedures for efficiency etc. of :

i. Simple, Ideal, air standard Brayton cycle
ii. Simple, actual Brayton cycle, i.e. including the isentropic efficiencies of compressor and turbine,
iii. Actual Brayton cycle with regenerator, and
iv. Regenerative Brayton cycle with 'perfect intercooling' and preheating (two stages in compressor and turbine)

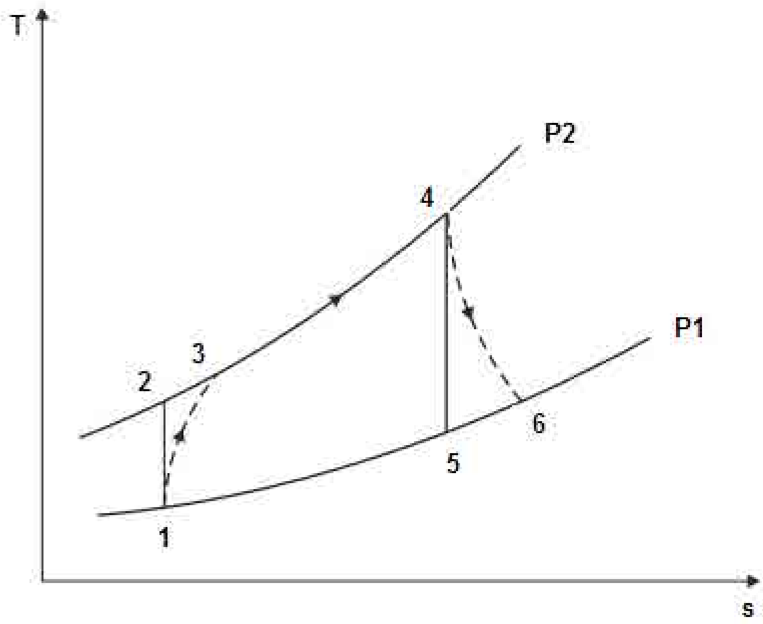
EES Procedures:

1. **Simple, Ideal, air standard Brayton cycle:**



```
$UnitSysyem SI Pa, K, kJ

PROCEDURE Simple_Brayton_ideal(cp, gamma,P1, T1, rp,T3 :T2, T4, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

"Thermal effcy. etc of Air standard, ideal, Brayton cycle"

"Inputs:cp, gamma, P1(kPa), T1 (K), rp,T3 (K)"

"P1, T1 .. at compressor inlet; T2 …compressor exit temp after isentropic comprn;

T3 … temp at turbine inlet; T4 …at turbine exit after isentropic expn. "

"Outputs: T2 (K), T4 (K), Q_in (kJ/kg),W_comp (kJ/kg), W_turb (kJ/kg), W_net (kJ/kg), eta_th, BackWorkRatio"

T2:= T1 * (rp)^((gamma-1)/gamma) "…finds T2"

P2:= P1 * rp

P3:=P2

P4:=P1

T4 := T3 * (1/rp)^((gamma-1)/gamma) "….finds T4"

Q_in := cp * (T3 – T2) "kJ/kg … heat supplied"

W_comp :=cp*(T2-T1) "kJ/kg … compressor work input"

W_turb := cp*(T3-T4) "kJ/kg …. turbine work output"

W_net :=W_turb-W_comp "kJ/kg …. net work output"

eta_th=W_net/Q_in "….thermal effcy."

BackWorkRatio :=W_comp/W_turb "… Back Work Ratio"

END

"==================================================================="
```

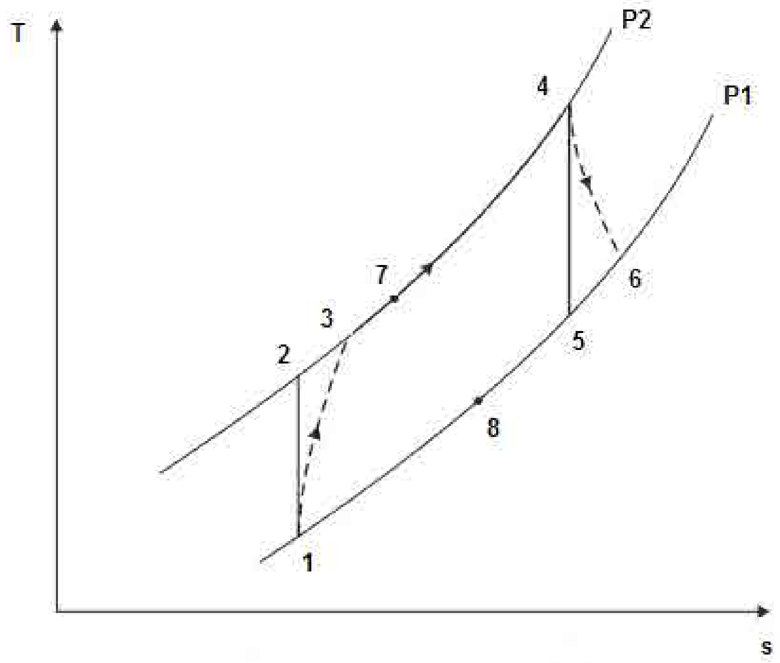
ii. **Simple, actual Brayton cycle, i.e. including the isentropic efficiencies of compressor and turbine:**



PROCEDURE Simple_Brayton_actual(cp, gamma,P1, T1, rp,T4,eta_comp, eta_turb: T3, T6, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

```
"Thermal effcy. etc of Air standard, actual, Brayton cycle"

"Inputs: P1(kPa), T1 (K), rp,T4 (K),eta_comp, eta_turb

P1, T1 … at compressor inlet; T2 …compressor exit temp if comprn. were isentropic; T3 … compr. exit for actual compression

T4 … temp at turbine inlet; T5 …at turbine exit if expn. were isentropic; T6 …at turbine exit for actual expn. "

"Outputs: T3 (K), T6 (K), Q_in (kJ/kg),W_comp (kJ/kg), W_turb (kJ/kg), W_net (kJ/kg), eta_th"

T2:= T1 * (rp)^((gamma-1)/gamma) "…finds T2"

T3:= (T2 – T1) / eta_comp + T1"finds T3"

P2:= P1 * rp

P3:=P2

P4:=P3

P5:=P1

P6:=P1

T5 := T4 * (1/rp)^((gamma-1)/gamma) "….finds T5"

T6 := T4 – (T4 – T5) * eta_turb "…finds T6"

Q_in := cp * (T4 – T3) "kJ/kg … heat supplied"

W_comp :=cp*(T3-T1) "kJ/kg … compressor work input"

W_turb := cp*(T4-T6) "kJ/kg …. turbine work output"

W_net :=W_turb-W_comp "kJ/kg …. net work output"

eta_th=W_net/Q_in "….thermal effcy."

BackWorkRatio :=W_comp/W_turb "… Back Work Ratio"

END

"==========================================================================="
```

iii. **Actual Brayton cycle with regenerator:**



PROCEDURE Regen_Brayton_actual(cp, gamma,P1, T1, rp,T4,eta_comp, eta_turb, epsilon: T3, T6, T7, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

"Thermal effcy. etc of Air standard, regenerative, actual, Brayton cycle"

"Inputs: P1(kPa), T1 (K), rp,T4 (K),eta_comp, eta_turb, epsilon

P1, T1 .. at compressor inlet; T2 …compressor exit temp if comprn. were isentropic; T3 … compr. exit for actual compression

T4 … temp at turbine inlet; T5 …at turbine exit if expn. were isentropic; T6 …at turbine exit for actual expn.

T7 … temp at exit of high pressure stream of regenerator

epsilon = effectiveness of regenerator"

"Outputs: T2 (K), T6 (K), T7 (K), Q_in (kJ/kg),W_comp (kJ/kg), W_turb (kJ/kg), W_net (kJ/kg), eta_th,BackWorkRatio"

T2:= T1 * (rp)^((gamma-1)/gamma) "…finds T2"

```
T3:= (T2 – T1) / eta_comp + T1"finds T3"

P2:= P1 * rp

P3:=P2

P4:=P3

P5:=P1

P6:=P1

P7 := P2

T5 := T4 * (1/rp)^((gamma-1)/gamma) "....finds T5"

T6 := T4 – (T4 – T5) * eta_turb "...finds T6"

T7 := T3 + epsilon * (T6 – T3) "K..finds T7..temp at exit of high pressure stream of regenerator"

Q_in := cp * (T4 – T7) "kJ/kg ... heat supplied"
```

W_comp :=cp*(T3-T1) "kJ/kg … compressor work input"

W_turb := cp*(T4-T6) "kJ/kg …. turbine work output"

W_net :=W_turb-W_comp "kJ/kg …. net work output"

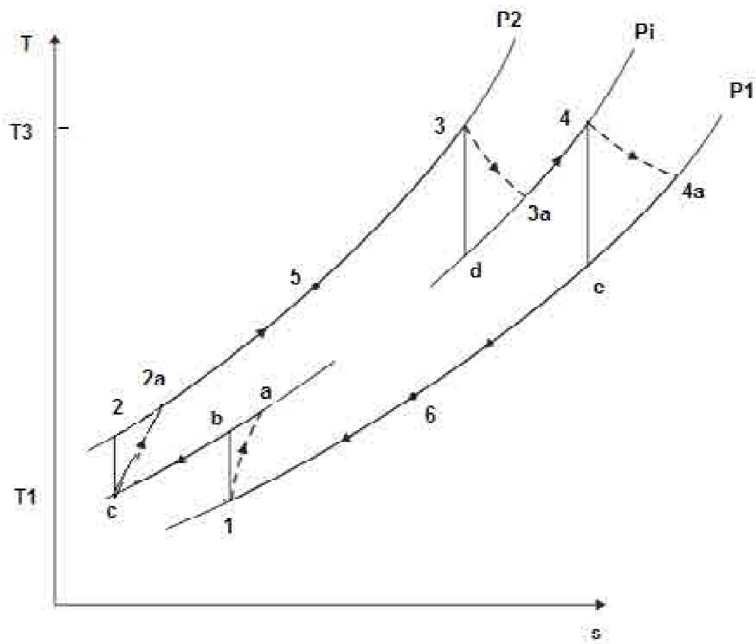
eta_th=W_net/Q_in "….thermal effcy."

BackWorkRatio :=W_comp/W_turb "… Back Work Ratio"

END

"=="

iv. **Regenerative Brayton cycle with 'perfect inter-cooling' and preheating (two stages in compressor and turbine):**



PROCEDURE Brayton_intercool_reheat_regen (cp, gamma, P1, T1, rp_tot, T3, eta_comp, eta_turb, epsilon: T2a, T4a, T5, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

"Thermal effcy. etc of Air standard, regenerative, actual, Brayton cycle, with intercooling and reheating – 2 stages for compr. and turbine"

"Inputs: cp, gamma,P1(kPa), T1(K), rp_tot,T3(K),eta_comp, eta_turb, epsilon

P1, T1 .. at compressor inlet; T2a … … compr. exit for actual compression

rp_tot = overall pressure ratio

T4a … …at turbine exit for actual expn.

T5 … temp at exit of high pressure stream of regenerator

epsilon = effectiveness of regenerator"

"Outputs: T2a (K), T4a (K), T5(K), Q_in(kJ/kg),W_comp(kJ/kg), W_turb(kJ/kg), W_net(kJ/kg), eta_th, BackWorkRatio"

rp = sqrt(rp_tot) "…pressure ratio per stage"

T2:= T1 * (rp)^((gamma-1)/gamma) "…finds T2"

T2a:= (T2 – T1) / eta_comp + T1"finds T2a"

P2:= P1 * rp_tot

P3:=P2

P4a:=P1

P5:=P2

P6:=P1

T4 := T3 * (1/rp)^((gamma-1)/gamma) "….finds T4"

T4a := T3 – (T3 – T4) * eta_turb "…finds T4a"

T5 := T2a + epsilon * (T4a – T2a) "K..finds T5..temp at exit of high pressure stream of regenerator"

Q_in := cp * (T3 – T5) + cp * (T3 – T4a) "kJ/kg … heat supplied"

W_comp :=2* cp * (T2a-T1) "kJ/kg … total compressor work input"

```
W_turb := 2* cp * (T3-T4a) "kJ/kg …. total turbine work output"

W_net :=W_turb-W_comp "kJ/kg …. net work output"

eta_th=W_net/Q_in "….thermal effcy."

BackWorkRatio :=W_comp/W_turb "… Back Work Ratio"

END

"==================================================================="
```

Prob.2.13. Consider a simple Brayton cycle with P1 = 100 kPa, T1 = 300 K, T3 = 1300 K, with pressure ratio = 8.

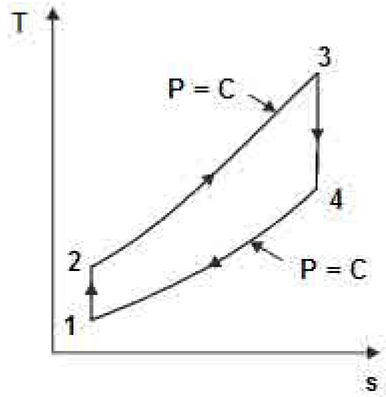


Fig.Prob.2.13

EES Solution: We shall use the EES Procedure written above.

"Data:"

P1=100 "kPa"

T1=300 "K"

T3 = 1300 "K"

cp=1.005 "kJ/kg.K"

gamma=1.4

rp = 8

CALL Simple_Brayton_ideal(cp, gamma,P1, T1, rp,T3 :T2, T4, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

Results:

Main | Simple_Brayton_ideal

Unit Settings: SI K Pa kJ mass deg

BackWorkRatio = 0.418	cp = 1.005 [kJ/kg-K]	η_{th} = 0.448	γ = 1.4
P1 = 100 [kPa]	Q_{in} = 760.3 [kJ/kg]	rp = 8	T1 = 300 [K]
T2 = 543.4 [K]	T3 = 1300 [K]	T4 = 717.7 [K]	W_{comp} = 244.7 [kJ/kg]
W_{net} = 340.6 [kJ/kg]	W_{turb} = 585.3 [kJ/kg]		

Thus:

Net work output = W_net = 340.6 kJ/kg … Ans.

Thermal effcy. = eta_th = 0.448 = 44.8% …. Ans.

Back Work Ratio = 0.418 …. Ans.

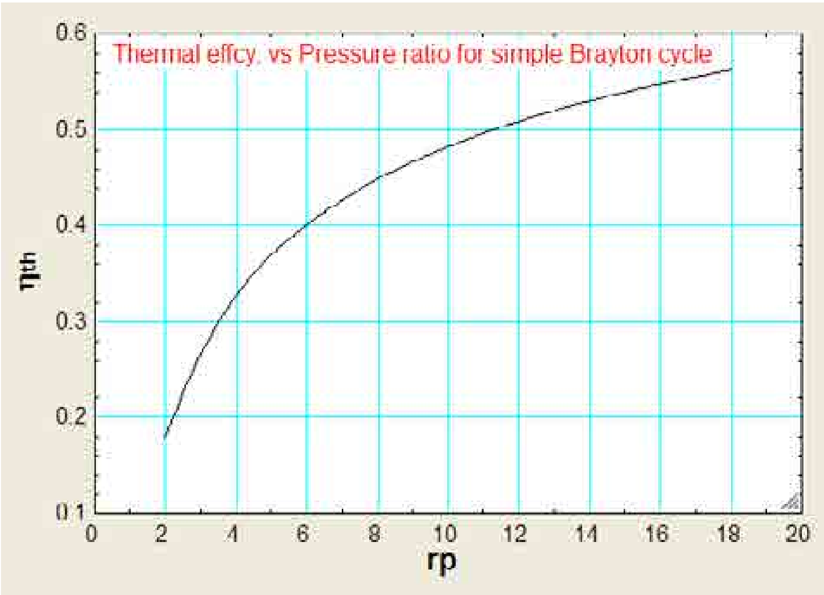
(b) Plot eta_th vs rp, for rp = 2 to 18:

First, compute the Parametric Table:

T3 = 1300 K:

1..9	rp	η_{th}
Run 1	2	0.1797
Run 2	4	0.327
Run 3	6	0.4007
Run 4	8	0.448
Run 5	10	0.4821
Run 6	12	0.5083
Run 7	14	0.5295
Run 8	16	0.5471
Run 9	18	0.5621

Now, plot the result:



(c) Plot W_net vs rp, for T3 = 900, 1200 and 1500 K:

T3 = 900 K:

1..9	rp	W_{net} [kJ/kg]
Run 1	2	96.47
Run 2	4	149.3
Run 3	6	160.8
Run 4	8	160.5
Run 5	10	155.4
Run 6	12	148.1
Run 7	14	139.6
Run 8	16	130.6
Run 9	18	121.4

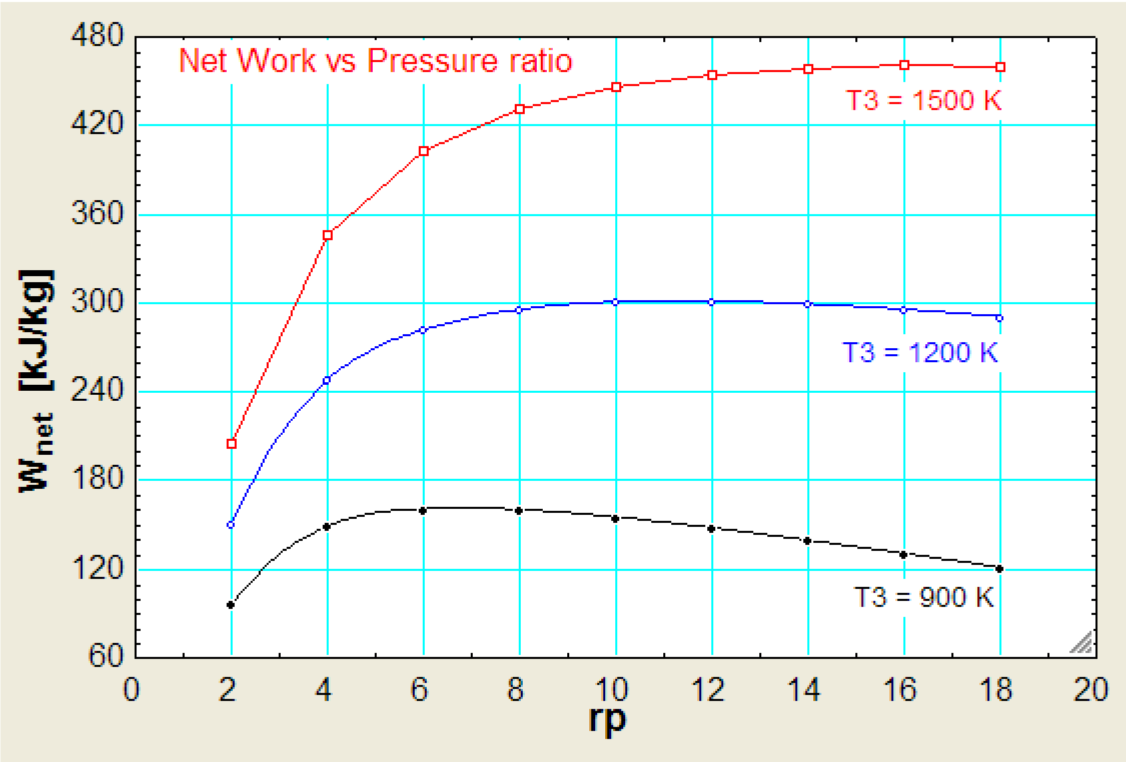
T3 = 1200 K:

1..9	rp	W_{net} [kJ/kg]
Run 1	2	150.6
Run 2	4	247.9
Run 3	6	281.6
Run 4	8	295.6
Run 5	10	300.7
Run 6	12	301.3
Run 7	14	299.3
Run 8	16	295.6
Run 9	18	290.9

T3 = 1500 K:

1..9	rp	W_{net} [kJ/kg]
Run 1	2	204.8
Run 2	4	346.5
Run 3	6	402.4
Run 4	8	430.6
Run 5	10	446.1
Run 6	12	454.6
Run 7	14	458.9
Run 8	16	460.5
Run 9	18	460.4

Now, plot the results:



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"**Prob.2.14**. A gas turbine operates on a pressure ratio of 6. Inlet temp to the compressor is 300 K and to the turbine is 577 C. If the volume of air entering the compressor is 240 m^3/s, calculate the net power output of the cycle in MW. Also, compute its efficiency. Assume that the cycle operates under ideal conditions. [VTU-ATD-Jan.–Feb. 2005]"

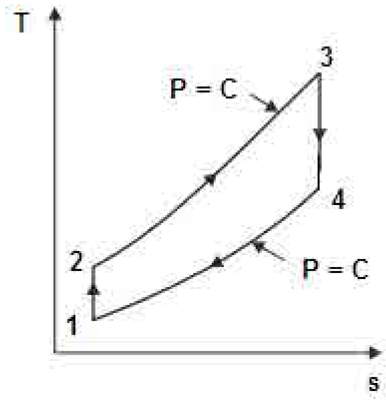

Fig.Prob.2.14

EES Solution: We shall use the EES Function written above.

"Data:"

P1=100 "kPa"

V1 = 240 "m^3/s"

T1=300 "K"

T3 = 577+273 "K"

cp=1.005 "kJ/kg.K"

gamma=1.4

rp = 6

R_air = 0.287 "kJ/kg.K"

"Calculations:"

m_air = P1 * V1 / (R_air * T1) "kg/s …. mass rate of air entering the compressor"

"Using the EES Function written above:"

CALL Simple_Brayton_ideal(cp, gamma,P1, T1, rp,T3 :T2, T4, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

NetPower = m_air * W_net / 1000"MW …. Net power developed in MW"

Results:

Unit Settings: SI K Pa kJ mass deg

BackWorkRatio = 0.5889	cp = 1.005 [kJ/kg-K]	η_{th} = 0.4007
γ = 1.4	m_{air} = 278.7 [kg/s]	NetPower = 39.22 [MW]
P1 = 100 [kPa]	Q_{in} = 351.2 [kJ/kg]	rp = 6
R_{air} = 0.287 [kJ/kg-K]	T1 = 300 [K]	T2 = 500.6 [K]
T3 = 850 [K]	T4 = 509.4 [K]	V1 = 240
W_{comp} = 201.6 [kJ/kg]	W_{net} = 140.7 [kJ/kg]	W_{turb} = 342.3 [kJ/kg]

Thus:

Net power developed = 39.22 MW … Ans.

Efficiency = eta_th = 0.4007 = 40.07% ….Ans.

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"**Prob.2.15**. In an open cycle constant pressure gas turbine, air enters the compressor at 1 bar, 300 K. Pressure of air after compression is 8 bar. Isentropic efficiencies of compressor and turbine are 80% and 85% respectively. Temp of air at entry to turbine is 1300 K. Calculate the net work and the thermal efficiency of the cycle. Take cp = 1.005 kJ/kg.K"

Note: This is the same problem as in Prob.2.13, but with compressor and turbine efficiencies considered.

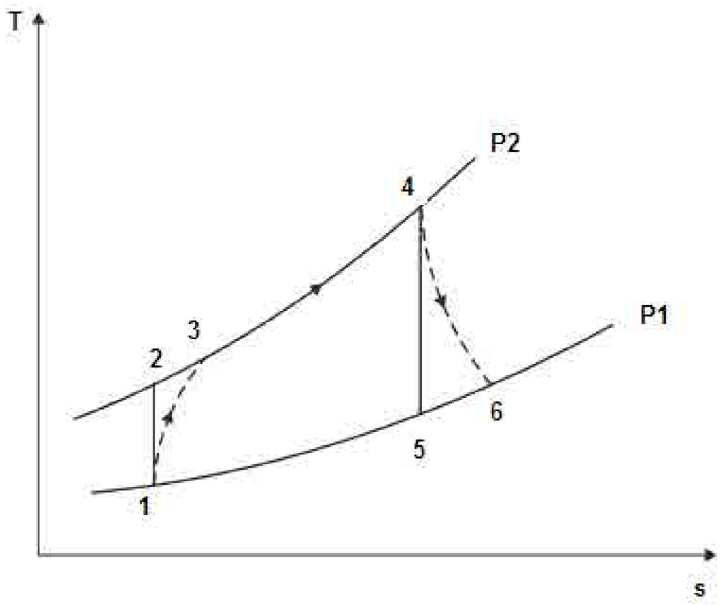


Fig.Prob.2.15

EES Solution: We shall use the EES Function written above.

"Data:"

P1=100 "kPa"
T1=300 "K"
T4 = 1300 "K"
cp=1.005 "kJ/kg.K"
gamma=1.4
rp = 8
eta_comp = 0.8"…compressor isentropic effcy."
eta_turb = 0.85 "turbine isentropic effcy."

"Calculations:"

CALL Simple_Brayton_actual(cp, gamma,P1, T1, rp,T4,eta_comp, eta_turb:T3, T6, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

Results:

Unit Settings: SI K Pa kJ mass deg

BackWorkRatio = 0.6147	cp = 1.005 [kJ/kg-K]	η_{comp} = 0.8
η_{th} = 0.2741	η_{turb} = 0.85	γ = 1.4
P1 = 100 [kPa]	Q_{in} = 699.2 [kJ/kg]	rp = 8
T1 = 300 [K]	T3 = 604.3 [K]	T4 = 1300 [K]
T6 = 805 [K]	W_{comp} = 305.8 [kJ/kg]	W_{net} = 191.7 [kJ/kg]
W_{turb} = 497.5 [kJ/kg]		

Thus:

Net work = W_net = 191.7 kJ/kg …. Ans.

Thermal effcy. = eta_th = 0.2741 = 27.41% ….Ans.

Comparing with Prob.2.13, there, we had:

Net work output = W_net = 340.6 kJ/kg

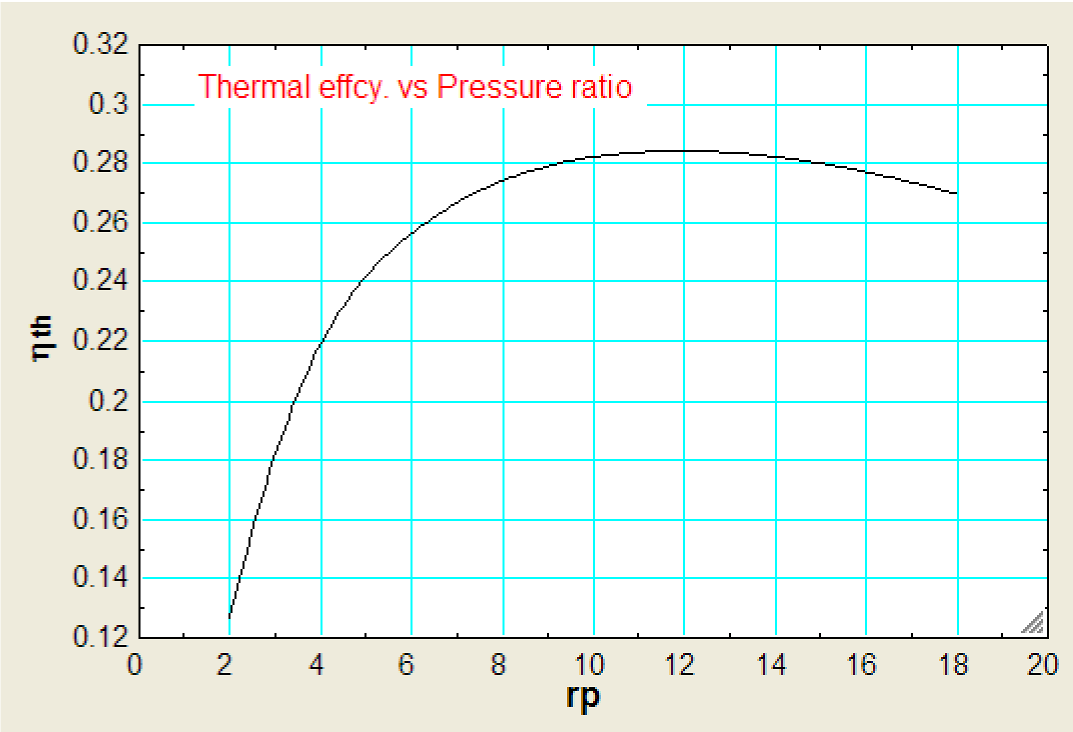
Thermal effcy. = eta_th = 0.448 = 44.8%

(b) Plot eta_th against pressure ratio, other conditions remaining the same:

First, compute the Parametric Table:

1..9	rp	η_{th}
Run 1	2	0.1268
Run 2	4	0.2191
Run 3	6	0.2563
Run 4	8	0.2741
Run 5	10	0.2821
Run 6	12	0.2842
Run 7	14	0.2821
Run 8	16	0.277
Run 9	18	0.2695

Now, plot the results:



(c) Plot W_net vs rp, for T4 = 900, 1200 and 1500 K:

T4 = 900 K:

1..9	rp	W_{net} [kJ/kg]
Run 1	2	55.59
Run 2	4	68.29
Run 3	6	56.09
Run 4	8	38.58
Run 5	10	19.86
Run 6	12	1.162
Run 7	14	-17.07
Run 8	16	-34.68
Run 9	18	-51.64

Note that beyond rp = 12, W_net is –ve, i.e. cycle is not feasible.

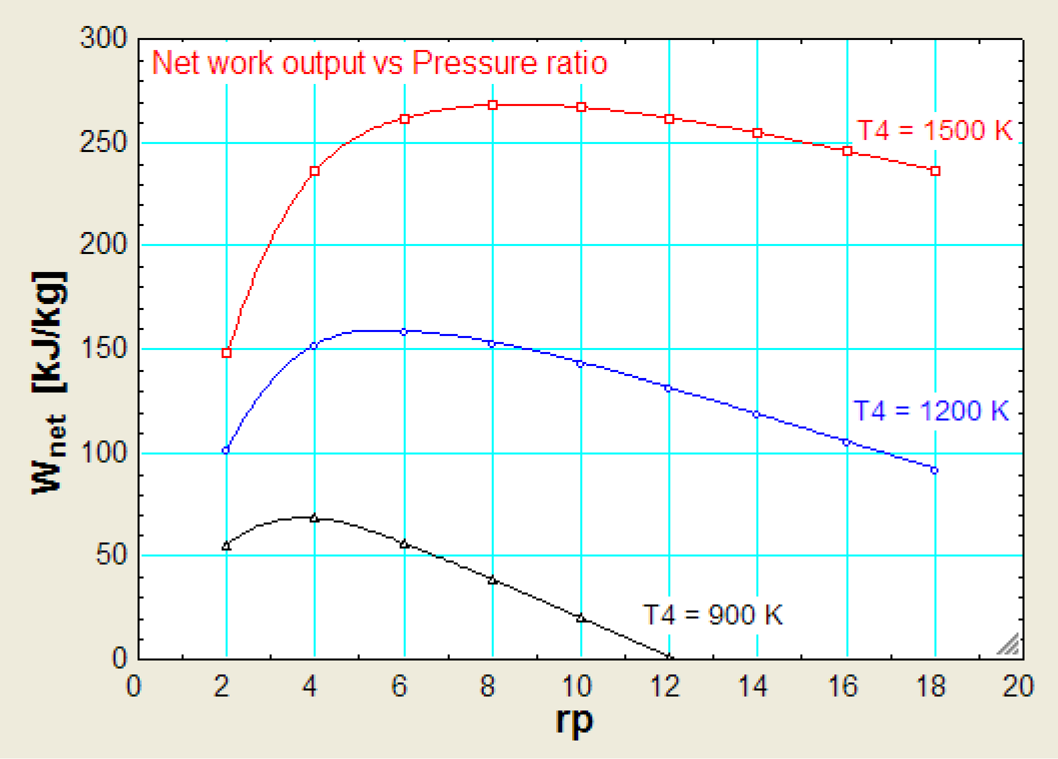
T4 = 1200 K:

1..9	rp	W_{net} [kJ/kg]
Run 1	2	101.6
Run 2	4	152.1
Run 3	6	158.8
Run 4	8	153.4
Run 5	10	143.4
Run 6	12	131.4
Run 7	14	118.6
Run 8	16	105.5
Run 9	18	92.42

T4 = 1500 K:

1..9	rp	W_{net} [kJ/kg]
Run 1	2	147.7
Run 2	4	235.9
Run 3	6	261.5
Run 4	8	268.2
Run 5	10	266.9
Run 6	12	261.7
Run 7	14	254.3
Run 8	16	245.8
Run 9	18	236.5

Now, plot the results:



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"**Prob.2.16**. In a regenerative gas turbine, air enters the compressor at 1 bar, 300 K. Pressure of air after compression is 8 bar. Isentropic efficiencies of compressor and turbine are 80% and 85% respectively. Temp of air at entry to turbine is 1300 K. Regenerator efficiency = 78%. Calculate the net work and the thermal efficiency of the cycle. Take cp = 1.005 kJ/kg.K"

Note: This is the same problem as in Prob.2.15, but with regenerator efficiency considered.

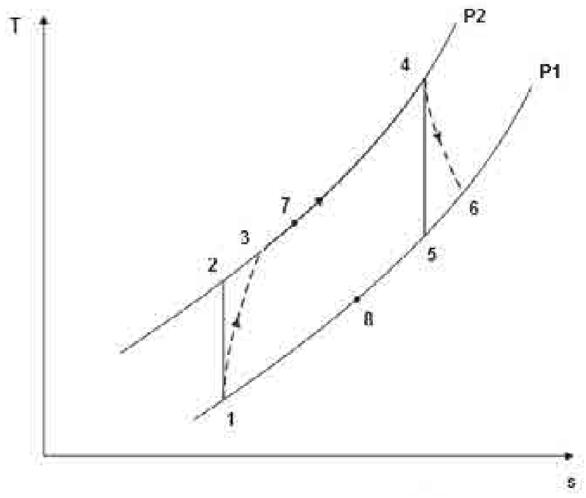


Fig.Prob.2.16

EES Solution: We shall use the EES Function written above.

"Data:"

P1=100 "kPa"

T1=300 "K"

T4 = 1300 "K"

cp=1.005 "kJ/kg.K"

gamma=1.4

rp = 8

eta_comp = 0.8"…compressor isentropic effcy."

eta_turb = 0.85 "turbine isentropic effcy."

epsilon = 0.78 "….regenerator effcy."

"Calculations:"

CALL Regen_Brayton_actual(cp, gamma,P1, T1, rp,T4,eta_comp, eta_turb, epsilon:T3, T6, T7, Q_in, W_comp, W_turb, W_net, eta_th, BackWorkRatio)

Results:

Unit Settings: SI K Pa kJ mass deg

BackWorkRatio = 0.6147	cp = 1.005 [kJ/kg-K]	ε = 0.78
η_{comp} = 0.8	η_{th} = 0.3537	η_{turb} = 0.85
γ = 1.4	P1 = 100 [kPa]	Q_{in} = 541.8 [kJ/kg]
rp = 8	T1 = 300 [K]	T3 = 604.3 [K]
T4 = 1300 [K]	T6 = 805 [K]	T7 = 760.9 [K]
W_{comp} = 305.8 [kJ/kg]	W_{net} = 191.7 [kJ/kg]	W_{turb} = 497.5 [kJ/kg]

Thus:

Net work = W_net = 191.7 kJ/kg … (same as in Prob.2.15, without regen.)

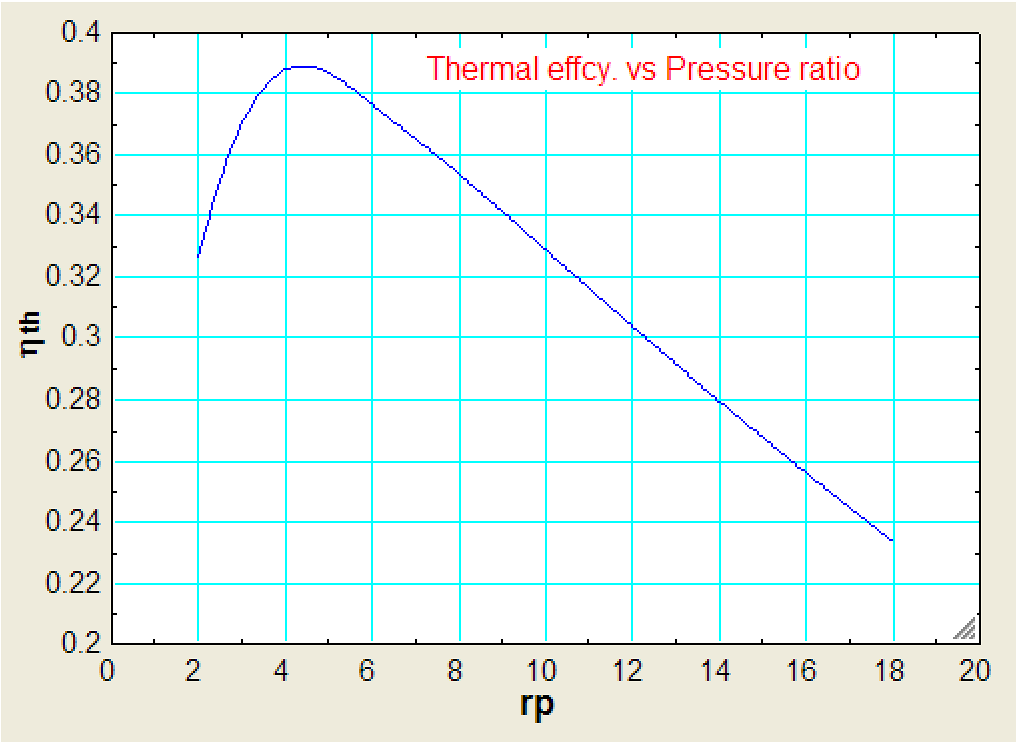
Thermal effcy. = eta_th = 0.3537 = 35.37% …. Ans. (compare this with 27.41% obtained in Prob.2.15, without regen.)

(b) Plot eta_th vs Pressure ratio, rp, other conditions remaining the same:

First, compute the Parametric Table:

1..9	rp	η_{th}
Run 1	2	0.3262
Run 2	4	0.3879
Run 3	6	0.3764
Run 4	8	0.3537
Run 5	10	0.3287
Run 6	12	0.3037
Run 7	14	0.2794
Run 8	16	0.256
Run 9	18	0.2335

Now, plot the results:



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"**Prob.2.17**. In an open cycle constant pressure gas turbine, air enters the compressor at 1 bar, 300 K. Pressure of air after compression is 4 bar. Isentropic efficiencies of compressor and turbine are 80% and 85% respectively. The air fuel ratio is 90 : 1. Calculate the power developed and the thermal efficiency of the cycle if the flow rate of air is 3 kg/s. Take cp = 1.005 kJ/kg.K and gamma = 1.4 for air and gases. Calorific Value of fuel = 42000 kJ/kg. [VTU- ATD-March 2001]"

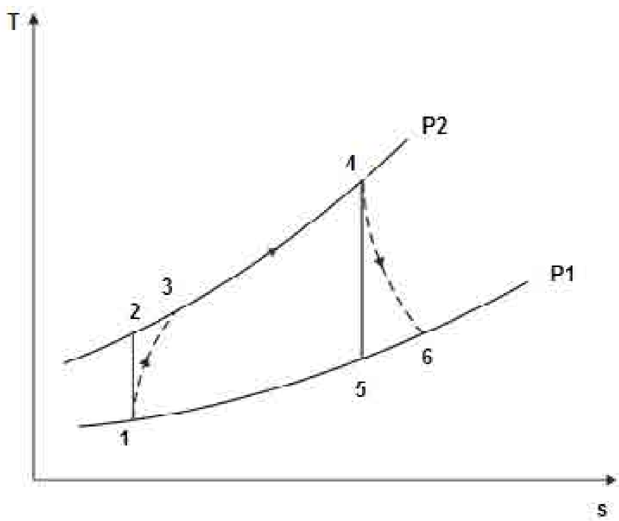


Fig.Prob.2.17

"EES Solution:"

"Data:"

P1=100 "kPa"

T1=300 "K"

P2=400 "kPa"

eta_comp=0.8 "compressor effcy."

eta_turb=0.85 "turbine effcy."

AFratio=90 "air/fuel ratio"

m_a=3.0 "kg/s … air flow rate"

cp=1.005 "kJ/kg.K"

gamma=1.4

CV=42000 "kJ/kg … calorific value of fuel"

"Calculations:"

r_p = P2/P1 "…pressure ratio"

T2/T1=(P2/P1)^((gamma-1)/gamma) "…finds T2"

(T2-T1)/(T3-T1)=eta_comp "finds T3"

m_f * CV=(m_a+m_f) * cp * (T4-T3)"…finds T4"

m_a/m_f = AFratio "…finds mass flow rate of fuel, m_f"

P3=P2

P4=P3

P5=P1

P6=P1

T5/T4=(P5/P4)^((gamma-1)/gamma) "….finds T5"

(T4-T6)/(T4-T5) = eta_turb "…finds T6"

Q_in=m_f*CV "kJ/s … heat supplied"

W_comp=m_a*cp*(T3-T1) "kJ/s … compressor work input"

W_turb=(m_a+m_f)*cp*(T4-T6) "kJ/s …. turbine work output"

W_net=W_turb-W_comp "kJ/s …. net work output"

eta_th=W_net/Q_in "….thermal effcy."

BackWorkRatio=W_comp/W_turb "… Back Work Ratio"

Results:

Unit Settings: SI K kPa kJ mass deg

AFratio = 90	BackWorkRatio = 0.6887	cp = 1.005 [kJ/kg-K]
CV = 42000 [kJ/kg]	η_{comp} = 0.8	η_{th} = 0.1774
η_{turb} = 0.85	γ = 1.4	m_a = 3 [kg/s]
m_f = 0.03333 [kg/s]	P1 = 100 [kPa]	P2 = 400 [kPa]
P3 = 400 [kPa]	P4 = 400 [kPa]	P5 = 100 [kPa]
P6 = 100 [kPa]	Q_{in} = 1400 [kJ/s]	r_p = 4
T1 = 300 [K]	T2 = 445.8 [K]	T3 = 482.2 [K]
T4 = 941.5 [K]	T5 = 633.6 [K]	T6 = 679.8 [K]
W_{comp} = 549.5 [kJ/s]	W_{net} = 248.4 [kJ/s]	W_{turb} = 797.9 [kJ/s]

Thus:

Net power developed = 248.4 kW …. Ans.

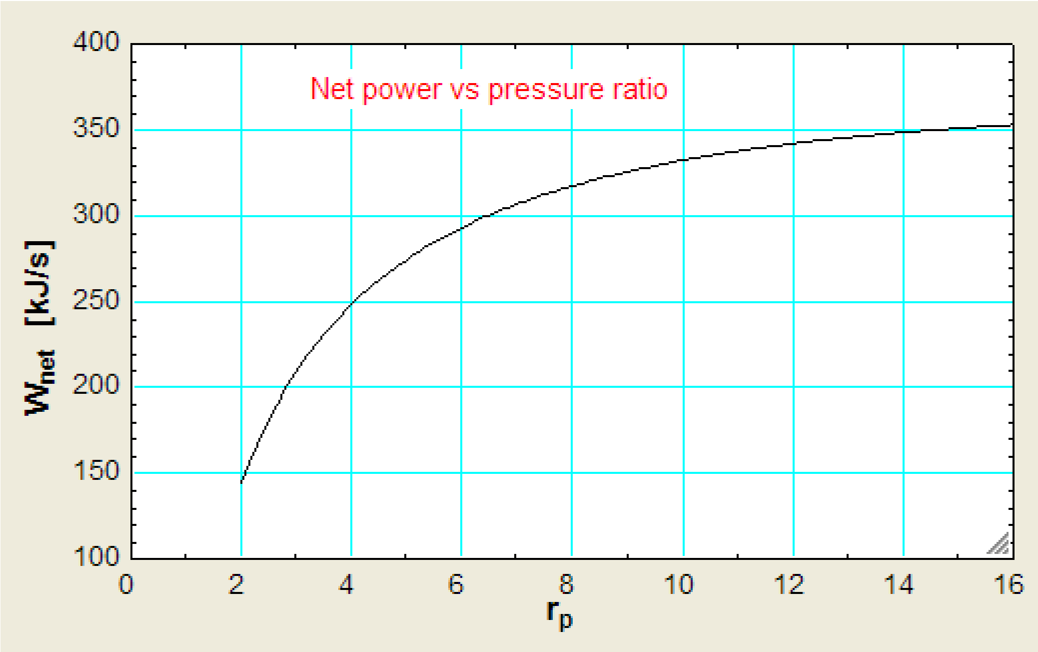
Thermal efficiency = eta_th = 0.1774 = 17.74% …. Ans.

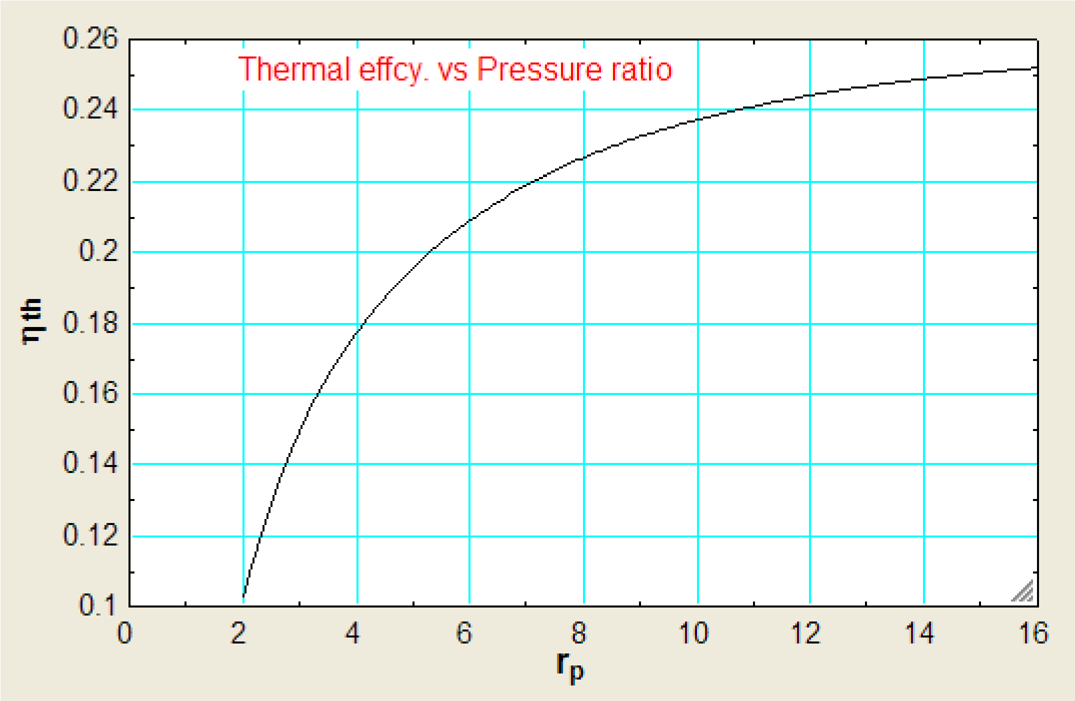
(b) Plot eta_th and W_net vs pressure ratio, r_p:

First, produce the Parametric Table:

1..15	P2 [kPa]	r_p	W_{net} [kJ/s]	η_{th}
Run 1	200	2	144.1	0.1029
Run 2	300	3	209.6	0.1497
Run 3	400	4	248.4	0.1774
Run 4	500	5	274.2	0.1959
Run 5	600	6	292.7	0.2091
Run 6	700	7	306.5	0.2189
Run 7	800	8	317.1	0.2265
Run 8	900	9	325.4	0.2324
Run 9	1000	10	332.1	0.2372
Run 10	1100	11	337.4	0.241
Run 11	1200	12	341.8	0.2442
Run 12	1300	13	345.4	0.2467
Run 13	1400	14	348.4	0.2488
Run 14	1500	15	350.8	0.2506
Run 15	1600	16	352.8	0.252

Now, plot the graphs:





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Prob.2.18. In a Regenerative Brayton cycle, with intercooling and reheating, overall pressure ratio is 9, inlet conditions to compressor are: T1 = 293 K. Regenerator efficiency = 80%. Max. temp is 898 K. Compressor and turbine have 2 stages and for each stage, efficiencies are 80% and 85% respectively. Find Thermal effcy and Back Work ratio etc. Also:

b) Plot eta_th vs regenerator efficiency, ε, and,
c) Plot (i) thermal efficiency, (ii) Back work ratio, (iii) net work developed in kJ/kg, when pressure ratio varies from 2 to 20.

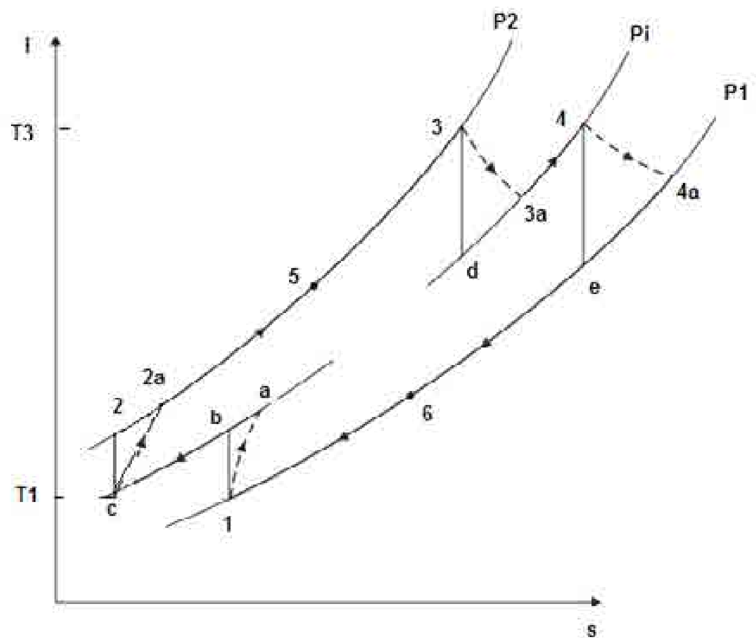


Fig.Prob.2.18

Note: This is the same as Prob.2.11, solved earlier with Mathcad.

Now, we shall solve it with EES, using the EES Procedure written above. (See Prob.2.12)

EES Solution:

"Data:"

P1=100 "kPa"

T1=293 "K"

T3 = 898 "K"

cp=1.005 "kJ/kg.K"

gamma=1.4

rp_tot = 9

eta_comp = 0.8"…compressor isentropic effcy."

eta_turb = 0.85 "turbine isentropic effcy."

epsilon = 0.8 "….regenerator effcy."

"Calculations:"

CALL Brayton_intercool_reheat_regen(cp, gamma,P1, T1, rp_tot,T3,eta_comp, eta_turb, epsilon:T2a, T4a, T5, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

Results:

Unit Settings: SI K Pa kJ mass deg

BackWorkRatio = 0.6568	cp = 1.005 [kJ/kg-K]	ε = 0.8
η_{comp} = 0.8	η_{th} = 0.3042	η_{turb} = 0.85
γ = 1.4	P1 = 100 [kPa]	Q_{in} = 466.5 [kJ/kg]
rp_{tot} = 9	T1 = 293 [K]	T2a = 428.1
T3 = 898 [K]	T4a = 692.4	T5 = 639.5 [K]
W_{comp} = 271.5 [kJ/kg]	W_{net} = 141.9 [kJ/kg]	W_{turb} = 413.3 [kJ/kg]

Thus:

Net work output = W_net = 141.9 kJ/kg …. Ans.

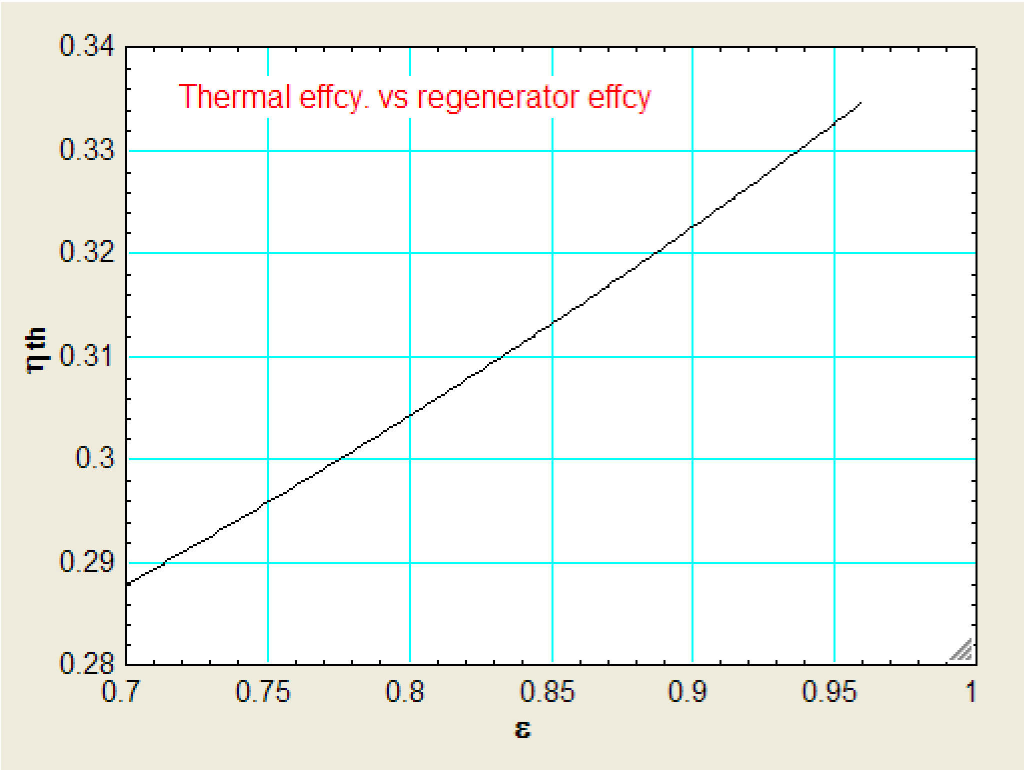
Thermal effcy. = eta_th = 0.3042 = 30.42% … Ans.

(b) Plot eta_th vs regenerator efficiency, ε:

First, compute the Parametric Table:

1..14	1 ε	2 η_{th}
Run 1	0.7	0.2878
Run 2	0.72	0.2909
Run 3	0.74	0.2941
Run 4	0.76	0.2974
Run 5	0.78	0.3007
Run 6	0.8	0.3042
Run 7	0.82	0.3077
Run 8	0.84	0.3112
Run 9	0.86	0.3149
Run 10	0.88	0.3187
Run 11	0.9	0.3225
Run 12	0.92	0.3265
Run 13	0.94	0.3305
Run 14	0.96	0.3346

Now, plot the results:

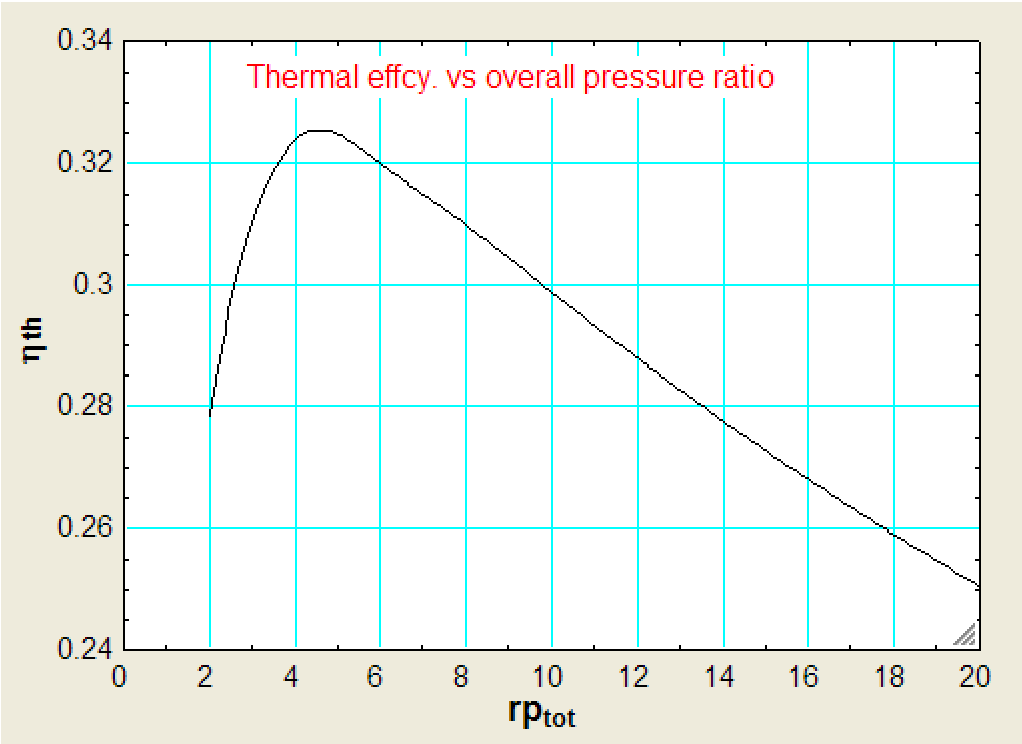


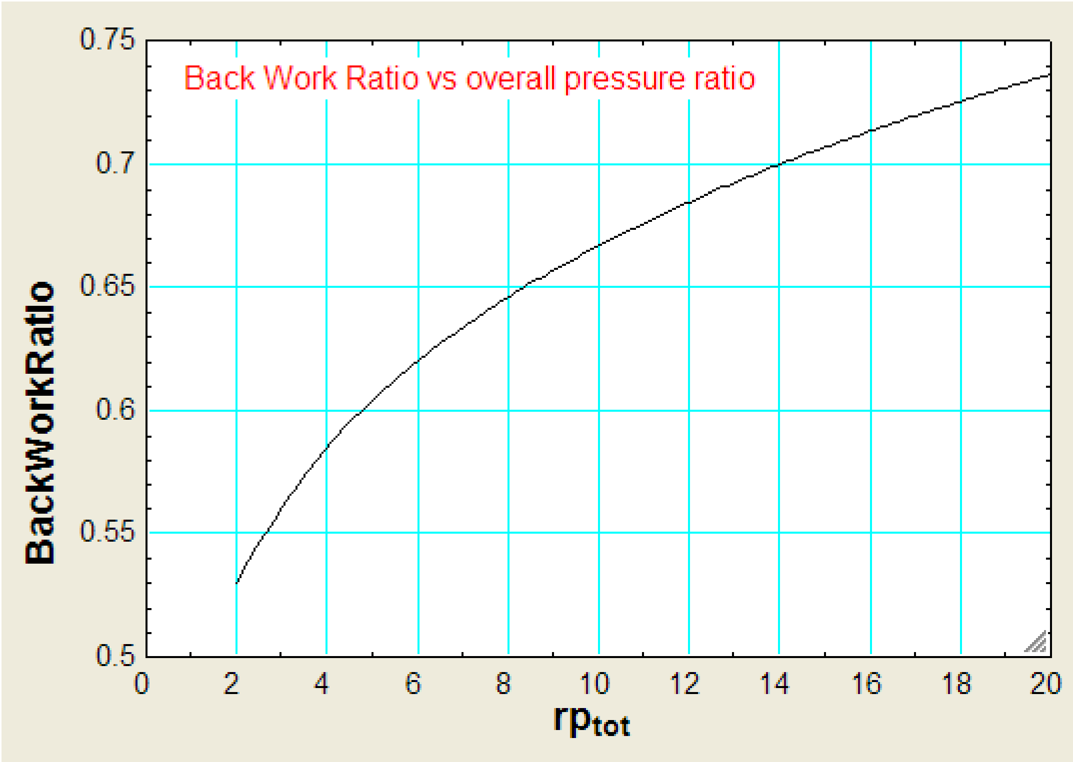
(c) Plot (i) thermal efficiency, (ii) Back work ratio, (iii) net work developed in kJ/kg, when pressure ratio varies from 2 to 20, other conditions remaining the same:

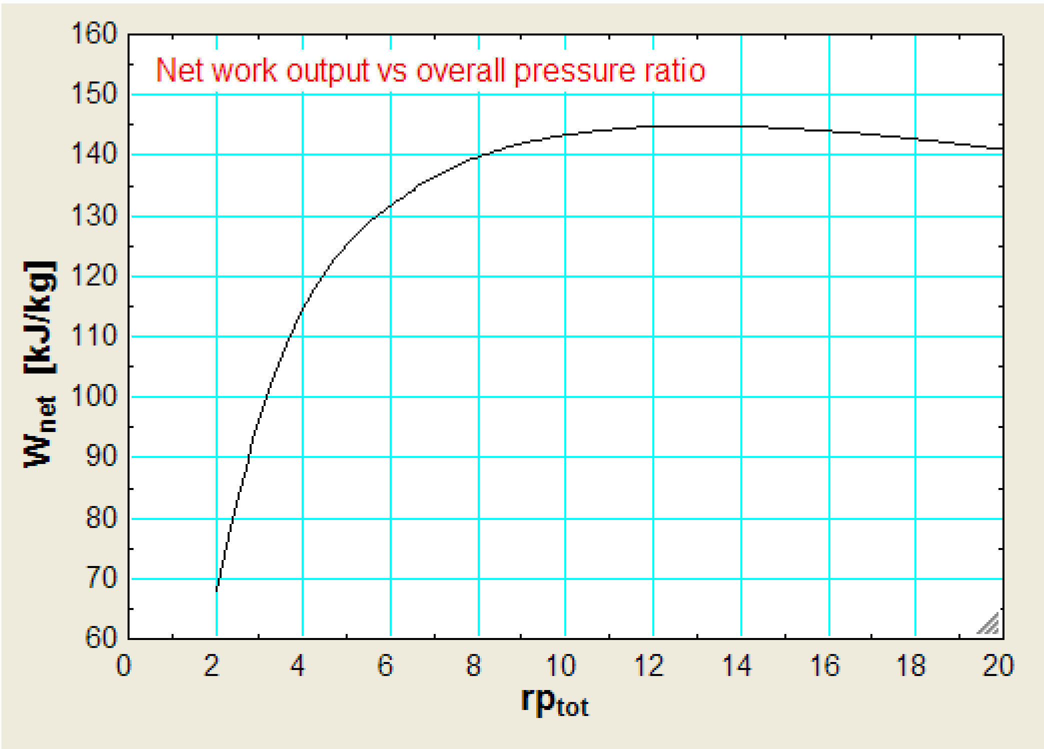
Parametric Table:

1..10	rp_{tot}	η_{th}	BackWorkRatio	W_{net} [kJ/kg]
Run 1	2	0.2786	0.5298	68.02
Run 2	4	0.3236	0.5849	114.4
Run 3	6	0.3198	0.6198	131.7
Run 4	8	0.3097	0.6458	139.7
Run 5	10	0.2986	0.6667	143.3
Run 6	12	0.2878	0.6843	144.7
Run 7	14	0.2776	0.6995	144.8
Run 8	16	0.2679	0.713	144
Run 9	18	0.2589	0.7251	142.7
Run 10	20	0.2504	0.7361	141

Now, plot the results:




Back Work Ratio vs overall pressure ratio
BackWorkRatio
0.75
0.7
0.65
0.6
0.55
0.5
0
2
4
6
8
10
12
14
16
18
20
rptot


Net work output vs overall pressure ratio
Wnet [kJ/kg]
160
150
140
130
120
110
100
90
80
70
60
0
2
4
6
8
10
12
14
16
18
20
rptot

==

"**Prob.2.19**. In a regenerative gas turbine cycle, air enters the compressor at 1 bar, 15 C. Pressure ratio = 6. The isentropic efficiencies of compressor and turbine are respectively 0.8 and 0.85. Max. temp in the cycle is 800 C. The regenerator efficiency = 0.78. Assume cp = 1.1 kJ/kg.K and gamma = 1.32 for the combustion products and find the cycle efficiency. [VTU – ATD – July 2003]

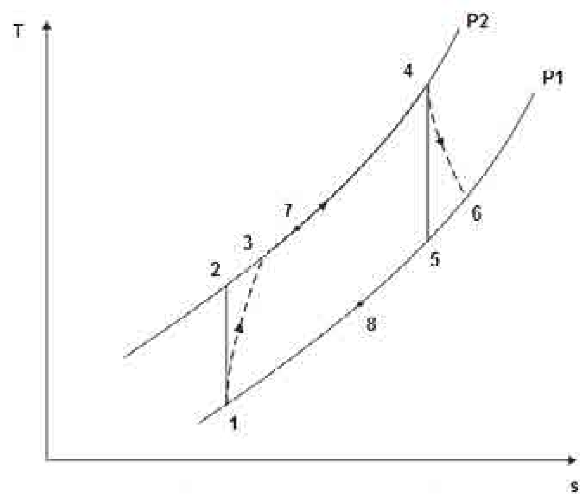


Fig.Prob.2.19

EES Solution:

"Data:"

P1=100"kPa"

T1=15+273"K"

rp = 6 "…pressure ratio"

P2=P1 * rp "kPa"

"P3=P2"

P5=P1

P6=P1

P7=P2

P3=P2

P4=P2

P8=P1

gamma=1.4

cp=1.005"kJ/kg.K"

eta_comp=0.8

eta_turb=0.85

eta_regen=0.78

cpg=1.1"kJ/kg.K"

gamma_g=1.32

T4=800+273"K"

"Calculations:"

T2/T1=(rp)^((gamma-1)/gamma)"…finds T2"

{(T2-T1)/(T3-T1)=eta_comp"..finds T3"}

T3 = T1 + (T2 – T1) / eta_comp "….finds T3"

T4/T5=(P4/P5)^((gamma_g-1)/gamma_g)"..finds T5"

(T4-T6)/(T4-T5)=eta_turb"…finds T6"

cp * (T7 – T3)/(cp * (T6 – T3)) = eta_regen "…finds T7"

cpg * (T6-T8) = cp * (T7-T3)"….finds T8"

W_C=cp * (T3-T1)"kJ/kg"

W_T=cpg * (T4-T6)"kJ/kg"

W_net=W_T – W_C"kJ/kg"

Q_in = cpg * (T4 – T7) "kJ/kg"

eta_th=W_net/Q_in "…thermal effcy."

Results:

Unit Settings: SI C kPa kJ mass deg

cp = 1.005 [kJ/kg-K]	cpg = 1.1 [kJ/kg-K]	η_{comp} = 0.8	η_{regen} = 0.78
η_{th} = 0.2739	η_{turb} = 0.85	γ = 1.4	γ_g = 1.32
P1 = 100 [kPa]	P2 = 600 [kPa]	P3 = 600 [kPa]	P4 = 600 [kPa]
P5 = 100 [kPa]	P6 = 100 [kPa]	P7 = 100 [kPa]	P8 = 600 [kPa]
Q_{in} = 407.4 [kJ/kg]	rp = 6	T1 = 288 [K]	T2 = 480.5 [K]
T3 = 528.7 [K]	T4 = 1073 [K]	T5 = 695 [K]	T6 = 751.7 [K]
T7 = 702.6 [K]	T8 = 592.7 [K]	W_C = 241.9 [kJ/kg]	W_{net} = 111.6 [kJ/kg]
W_T = 353.5 [kJ/kg]			

Thus:

Net work output = W_net = 111.6 kJ/kg …. Ans.

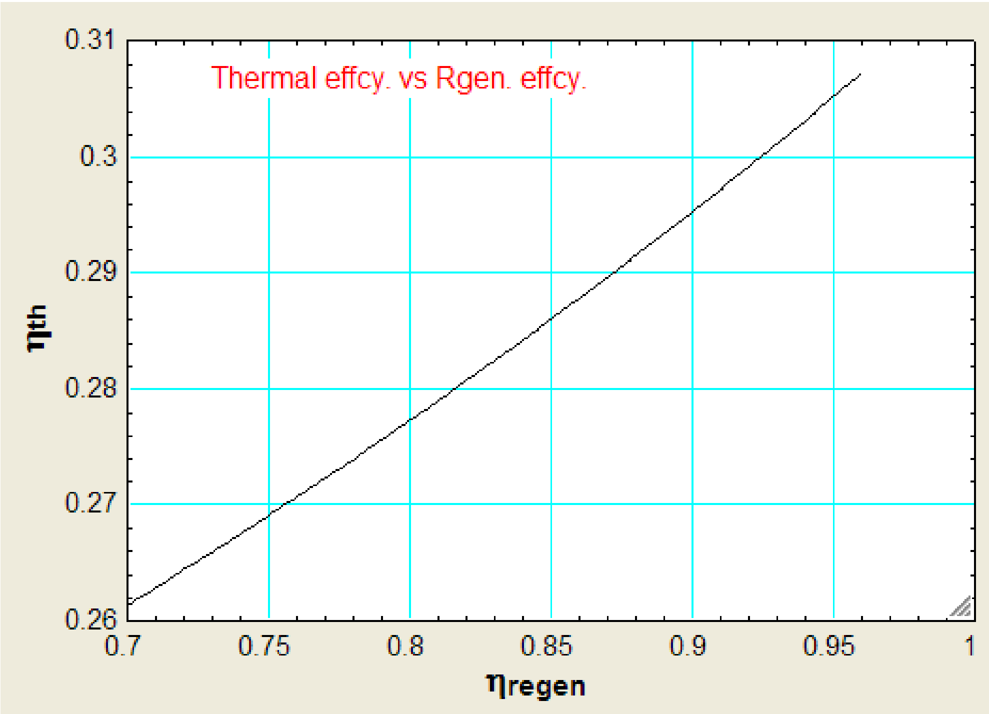
Thermal effcy. = eta_th = 0.2739 = 27.39% …. Ans.

(b) Plot the variation of eta_th with regen. effcy.:

First, compute the Parametric Table:

1..14	1 η_{regen}	2 η_{th}
Run 1	0.7	0.2613
Run 2	0.72	0.2644
Run 3	0.74	0.2675
Run 4	0.76	0.2707
Run 5	0.78	0.2739
Run 6	0.8	0.2773
Run 7	0.82	0.2807
Run 8	0.84	0.2842
Run 9	0.86	0.2878
Run 10	0.88	0.2915
Run 11	0.9	0.2952
Run 12	0.92	0.2991
Run 13	0.94	0.3031
Run 14	0.96	0.3072

Now, plot the results:



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Prob.2.20. The extreme pressures and temps in an open cycle gas turbine plant are 1 bar and 5 bar, and 27 C and 550 C respectively. Calculate the efficiency of the cycle when (i) there is no regenerator, (ii) there is a regenerator with 60% effectiveness. Take $\gamma = 1.4$ [VTU-Jan. 2003]

Note: This is the same as Prob.2.8, solved with Mathcad. Now, we shall solve it with EES, using the EES Procedures already written in Prob. 2.12.

EES Solution:

a) **Without regenerator:**

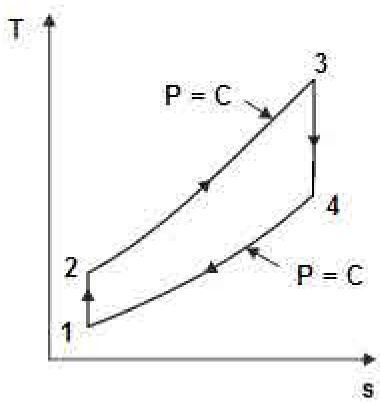


Fig.Prob.2.20a

"Data:"

P1=100"kPa"

T1=27+273"K"

P2=500"kPa"

P3=P2

P4=P1

gamma=1.4

cp=1005"J/kg.K"

T3=550+273"K"

rp = 5 "Pressure ratio"

"Calculations:"

"Without regenerator:"

CALL Simple_Brayton_ideal(cp, gamma,P1, T1, rp,T3 :T2, T4, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

Results:

Unit Settings: SI C kPa kJ mass deg

BackWorkRatio = 0.5773	cp = 1.005 [kJ/kg-K]	η_{th} = 0.3686
γ = 1.4	P1 = 100 [kPa]	P2 = 500 [kPa]
P3 = 500 [kPa]	P4 = 100 [kPa]	Q_{in} = 349.6 [kJ/kg]
rp = 5	T1 = 300 [K]	T2 = 475.1 [K]
T3 = 823 [K]	T4 = 519.6 [K]	W_{comp} = 176 [kJ/kg]
W_{net} = 128.9 [kJ/kg]	W_{turb} = 304.9 [kJ/kg]	

Thus:

Net work output = W_net = 128.9 kJ/kg … Ans.

Thermal effcy. = eta_th = 0.3686 = 36.85% … Ans.

b) **With regenerator:**

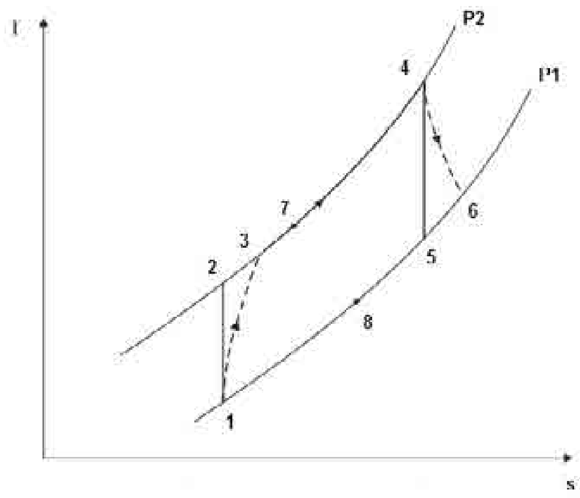


Fig.Prob.2.20b

"Data:"

P1=100"kPa"

T1=27+273"K"

P2=500"kPa"

P3=P2

P5=P2

P6=P1

P4=P1

gamma=1.4

cp=1.005"kJ/kg.K"

epsilon=0.60 "..regen. effcy."

T4=550+273"K"

rp = 5

eta_comp = 1 "…compressor isentropic effcy."

eta_turb = 1 "…turbine isentropic effcy."

"Calculations:"

"With regenerator:"

CALL Regen_Brayton_actual(cp, gamma,P1, T1, rp,T4,eta_comp, eta_turb, epsilon:T3, T6, T7, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

Results:

Unit Settings: SI C kPa kJ mass deg

BackWorkRatio = 0.5773	cp = 1.005 [kJ/kg-K]	ε = 0.6
η_{comp} = 1	η_{th} = 0.3992	η_{turb} = 1
γ = 1.4	P1 = 100 [kPa]	P2 = 500 [kPa]
P3 = 500 [kPa]	P4 = 100 [kPa]	P5 = 500 [kPa]
P6 = 100 [kPa]	Q_{in} = 322.8 [kJ/kg]	rp = 5
T1 = 300 [K]	T3 = 475.1 [K]	T4 = 823 [K]
T6 = 519.6	T7 = 501.8	W_{comp} = 176 [kJ/kg]
W_{net} = 128.9 [kJ/kg]	W_{turb} = 304.9 [kJ/kg]	

Thus:

Net work output = W_net = 128.9 kJ/kg … Ans.

Heat supplied = Q_in = 322.8 kJ/kg … Ans.

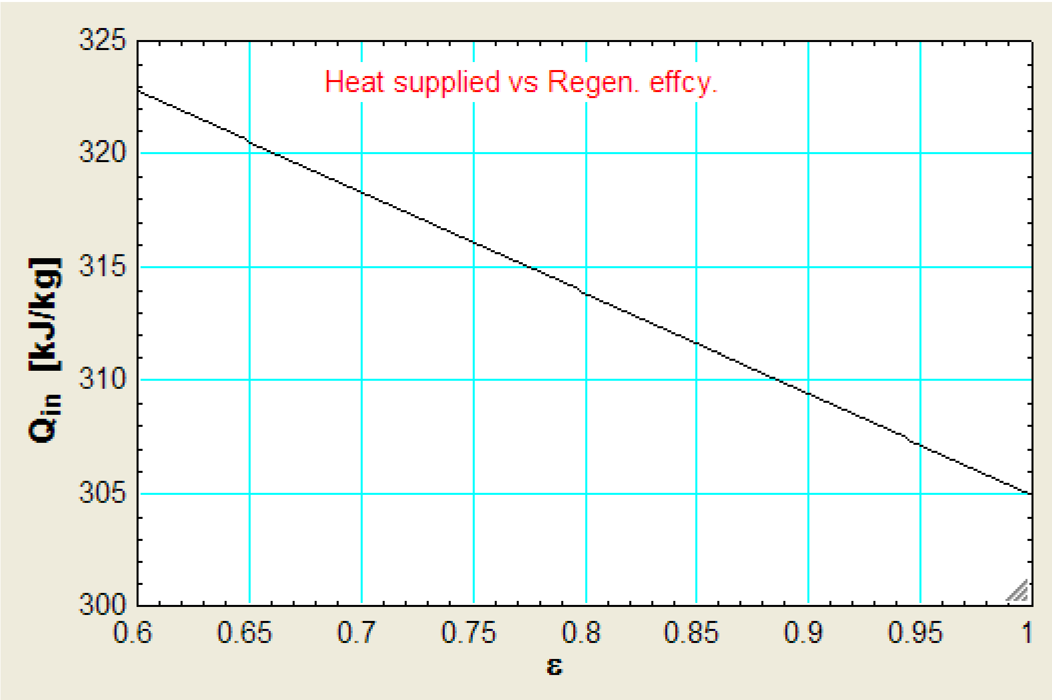
Thermal effcy. = eta_th = 0.3992 = 39.92% … Ans.

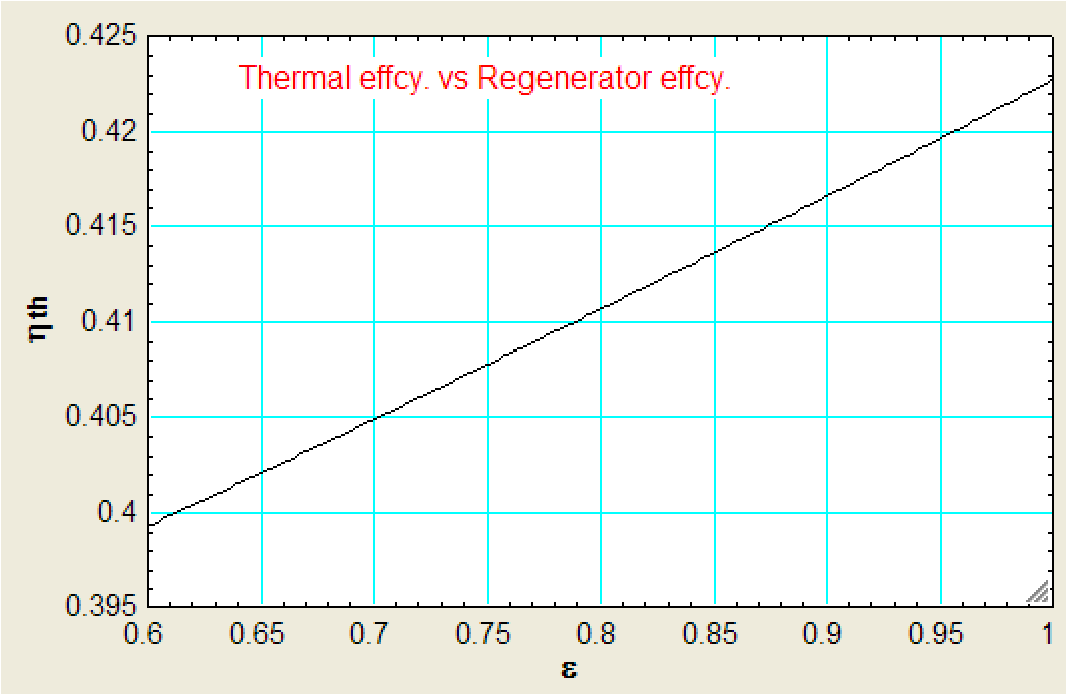
Plot Heat supplied (Q_in) and Thermal effcy. (eta_th) against regenerator effcy (ε):

First, compute the Parametric Table:

1..9	ε	Q_{in} [kJ/kg]	η_{th}
Run 1	0.6	322.8	0.3992
Run 2	0.65	320.5	0.402
Run 3	0.7	318.3	0.4049
Run 4	0.75	316.1	0.4077
Run 5	0.8	313.8	0.4106
Run 6	0.85	311.6	0.4136
Run 7	0.9	309.4	0.4166
Run 8	0.95	307.1	0.4196
Run 9	1	304.9	0.4227

Now, plot the results:




Thermal effcy. vs Regenerator effcy.
ηth
ε
0.425
0.42
0.415
0.41
0.405
0.4
0.395
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1

===

"**Prob.2.21.** A simple gas turbine plant operating on Brayton cycle has air entering the compressor at 100 kPa and 27 C. Pressure ratio = 9. Max. cycle temp = 727 C. What will be the percentage change in cycle effcy. and net work output if the expansion in the turbine is divided in to two stages, each of pressure ratio 3, with intermediate reheating to 727 C? Assume compression and expansion are ideal, isentropic. [VTU – ATD – July 2006]"

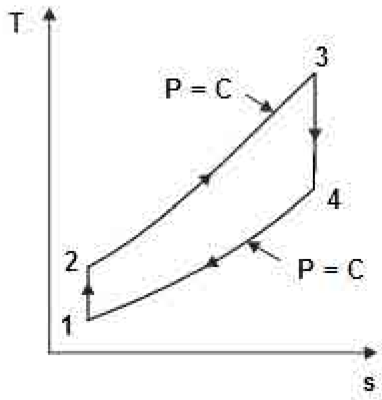


Fig.Prob.2.21a.

EES Solution:

"Case 1. Simple, ideal Brayton cycle:"

"Data:"

P1=100"kPa"

T1=27+273"K"

P3=P2

P4=P1

gamma=1.4

cp=1.005"kJ/kg.K"

T3=727+273"K"

rp = 9 "…Pressure ratio"

P2 = P1 * rp

"Calculations:"

CALL Simple_Brayton_ideal(cp, gamma,P1, T1, rp,T3 :T2, T4, Q_in,W_comp, W_turb, W_net, eta_th, BackWorkRatio)

Results:

Unit Settings: SI C kPa kJ mass deg

BackWorkRatio = 0.562	cp = 1.005 [kJ/kg-K]	η_{th} = 0.4662
γ = 1.4	P1 = 100 [kPa]	P2 = 900 [kPa]
P3 = 900 [kPa]	P4 = 100 [kPa]	Q_{in} = 440.2 [kJ/kg]
rp = 9	T1 = 300 [K]	T2 = 562 [K]
T3 = 1000 [K]	T4 = 533.8 [K]	W_{comp} = 263.3 [kJ/kg]
W_{net} = 205.2 [kJ/kg]	W_{turb} = 468.6 [kJ/kg]	

Thus, for simple, ideal Brayton cycle:

W_net = 205.2 kJ/kg …Ans.

eta_th = 0.4662 = 46.62% … Ans.

"Case 2. Simple, ideal Brayton cycle, with two stage expansion:"

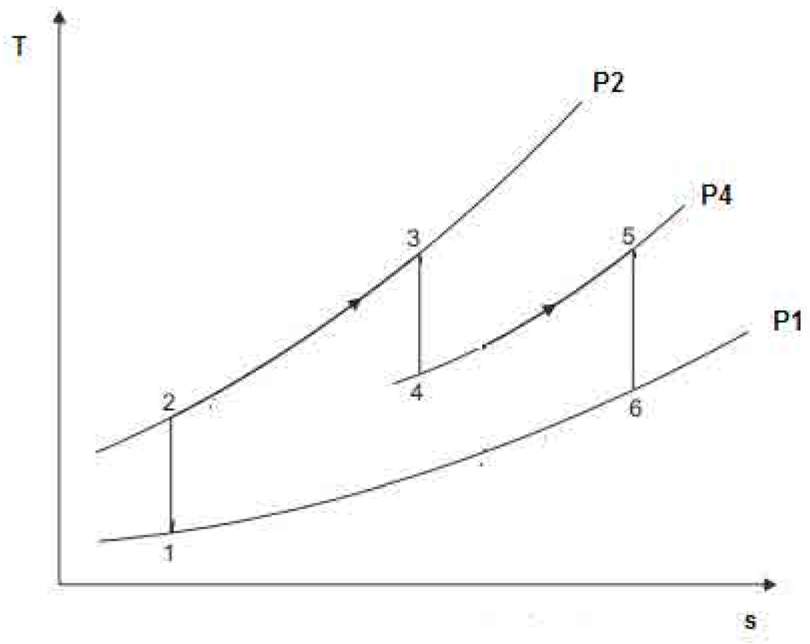


Fig.Prob.2.21b.

"Data:"

P1=100"kPa"

T1=27+273"K"

P3=P2

P6=P1

gamma=1.4

cp=1.005"kJ/kg.K"

T3=727+273"K"

rp_comp = 9 "…pressure ratio for compression"

rp_expn= 3 "…pressure ratio for each stage of expansion"

"Calculations:"

P2 = P1 * rp_comp "…pressure at exit of compressor"

P3/P4 = rp_expn^((gamma – 1)/gamma)"…finds P4"

P5 = P4

T2/T1 = rp_comp^((gamma – 1)/gamma)"…finds T2"

T3/T4 = rp_expn^((gamma – 1)/gamma)"…finds T4"

T5 = T3

T5/T6 = rp_expn^((gamma – 1)/gamma)"…finds T6"

"Compressor work:"

W_comp = cp * (T2 – T1) "kJ/kg"

"Turbine work, total for both the stages:"

W_turb_tot = cp * (T3 – T4) + cp * (T5 – T6) "kJ/kg"

"Net work output:"

W_net = W_turb_tot – W_comp "kJ/kg"

"Heat supplied:"

Q_in = cp * (T3 – T2) + cp * (T5 – T4)"kJ/kg"

"Thermal effcy."

eta_th = W_net / Q_in

Results:

Unit Settings: SI C kPa kJ mass deg

cp = 1.005 [kJ/kg-K]	η_{th} = 0.3913	γ = 1.4
P1 = 100 [kPa]	P2 = 900 [kPa]	P3 = 900 [kPa]
P4 = 657.5 [kPa]	P5 = 657.5 [kPa]	P6 = 100 [kPa]
Q_{in} = 710.9 [kJ/kg]	rp_{comp} = 9	rp_{expn} = 3
T1 = 300 [K]	T2 = 562 [K]	T3 = 1000 [K]
T4 = 730.6 [K]	T5 = 1000 [K]	T6 = 730.6 [K]
W_{comp} = 263.3 [kJ/kg]	W_{net} = 278.2 [kJ/kg]	$W_{turb,tot}$ = 541.5 [kJ/kg]

Thus, for simple, ideal Brayton cycle, with two stage expansion:

W_net = 278.2 kJ/kg …Ans.

eta_th = 0.3913 = 39.13% … Ans.

Therefore,

Change in Net work output = (278.2 – 205.2) * 100 / 205.2

i.e. $\frac{278.2 - 205.2}{205.2} \cdot 100 = 35.575$ **% .... Ans.**

i.e. Net work output has increased by 35.575%.

Change in Thermal effcy. = (0.3913 – 0.4662) * 100 / 0.4662

i.e. $\frac{0.3913 - 0.4662}{0.4662} \cdot 100 = -16.066$ **% .... Ans.**

i.e. Thermal effcy. has decreased by 16.066%. (This is due to the fact that heat supplied also has increased due to reheating)

==

Prob.2.22. Write an EES Procedure for Propulsive efficiency etc of an ideal jet propulsion cycle.

T_s diagram for Ideal Jet propulsion cycle is shown below:

Remember:

1-2: Isentropic compression in diffuser

2-3: Isentropic compression in compressor

3-4: constant pressure heat addition in burner

4-5: Isentropic expansion in turbine

5-6: Isentropic expansion in nozzle

6-1: Constant pressure heat rejection

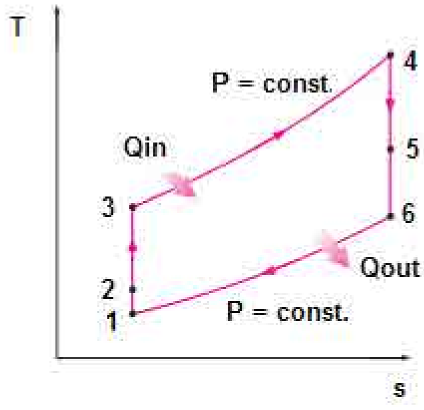


Fig.Prob.2.22

$UnitSysyem SI Pa, K, kJ

PROCEDURE Ideal_JetPropulsion_cyclel(m, cp, gamma,P1, T1, rp,T4,V1 :P2, P3, P5, T2, T3, T5, T6, V6, F, W_P,Q_in,W_comp, W_turb, eta_P,KE_exit,Q_exit)

"Thermal effcy. etc of Ideal Jet propulsion cycle"

"**Inputs:** m (kg/s), cp, gamma, P1(kPa), T1 (K), rp,T4 (K), V1 (m/s)"

"P1, T1 .. at diffusor inlet; T2 …diffusor exit temp after isentropic comprn;

rp = compressor pressure ratio; T4 …at turbine inlet "

"**Outputs:** P2(kPa), P3, P5, T2, T3, T4.T5, T6, V6, F(N), W_P(kW),Q_in(kW),W_comp(kW), W_turb(kW), eta_P,KE_exit(kW),Q_exit(kW)"

T2:= T1 +V1^2/(2 * cp*1000) "…finds T2 (K)"

P2:= P1 * (T2/T1)^(gamma /(gamma – 1)) "kPa"

P3:=P2 * rp "kPa"

T3 := T2 * rp^((gamma – 1)/gamma) "K"

T5 := T4 – T3 +T2 "K"

P4 := P3 "kPa"

P5:=P4 * (T5/T4)^(gamma / (gamma – 1)) "kPa"

P6 := P1"kPa"

T6 := T5 * (P6/P5)^((gamma-1)/gamma) "….finds exit jet temp, T6(K)"

V6 := sqrt(2 * cp*1000 * (T5 – T6)) "m/s … velocity of exit jet"

F := m * (V6 – V1) "N … Net Thrust"

W_P := F * V1/1000 "kW … Propulsive power"

Q_in := m * cp * (T4 – T3) "kW … heat supplied"

W_comp := m* cp *(T3-T2) "kW … compressor work input"

W_turb := W_comp "kW …. turbine work "

eta_P := W_P/Q_in "….Propulsive effcy."

KE_exit := (m * (V6 – V1)^2 / 2)/1000 “kW”

Q_exit = m * cp * (T6 – T1) “kW”

END

“===”

Prob. 2.23. A turbojet aircraft flies at a velocity of 900 km/h at an altitude where pressure and temp are 40 kPa and -35 C. Compressor pressure ratio is 10 and inlet temp of gases to turbine is 950 C. Air flow rate is 45 kg/s. Using cold air standard assumptions, determine: (a) temp and pressure of gases at turbine exit, (b) velocity of gases at nozzle exit, and (c) propulsive power, heat supplied and the propulsive efficiency.

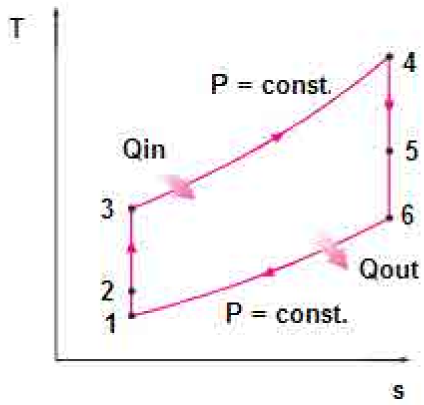


Fig.Prob.2.23

EES Solution: We shall use the EES Procedure written above.

“Data:”

m = 45 “kg/s”
cp = 1.005 “kJ/kg.K”
gamma = 1.4
P1 = 40 “kPa”
T1 = -35 + 273 “K”
rp = 10
T4 = 950 + 273 “K”
V1 = 9E05/3600 “m/s”

"Calculations:"

CALL Ideal_JetPropulsion_cyclel(m, cp, gamma,P1, T1, rp,T4,V1 :P2, P3, P5, T2, T3, T5, T6, V6, F, W_P,Q_in,W_comp, W_turb, eta_P,KE_exit,Q_exit)

Results:

Unit Settings: SI K Pa kJ mass deg

cp = 1.005 [kJ/kg-K]	η_P = 0.2335	F = 29715 [N]	γ = 1.4
KE_{exit} = 9811 [kW]	m = 45 [kg/s]	P1 = 40 [kPa]	P2 = 61.48 [kPa]
P3 = 614.8 [kPa]	P5 = 275.7 [kPa]	Q_{exit} = 14574 [kW]	Q_{in} = 31814 [kW]
rp = 10	T1 = 238 [K]	T2 = 269.1 [K]	T3 = 519.5 [K]
T4 = 1223 [K]	T5 = 972.6 [K]	T6 = 560.3 [K]	V1 = 250 [m/s]
V6 = 910.3 [m/s]	W_{comp} = 11326 [kW]	W_P = 7429 [kW]	W_{turb} = 11326 [kW]

Thus:

At turbine exit: T5 = 972.6 K, P5 = 275.7 kPa …. Ans.

Velocity of gases at nozzle exit = V6 = 910.3 m/s …. Ans.

Propulsive power = W_P = 7429 kW …. Ans.

Heat supplied = Q_in = 31814 kW ….Ans.

Propulsive efficiency = eta_P = 0.2335 = 23.35% … Ans.

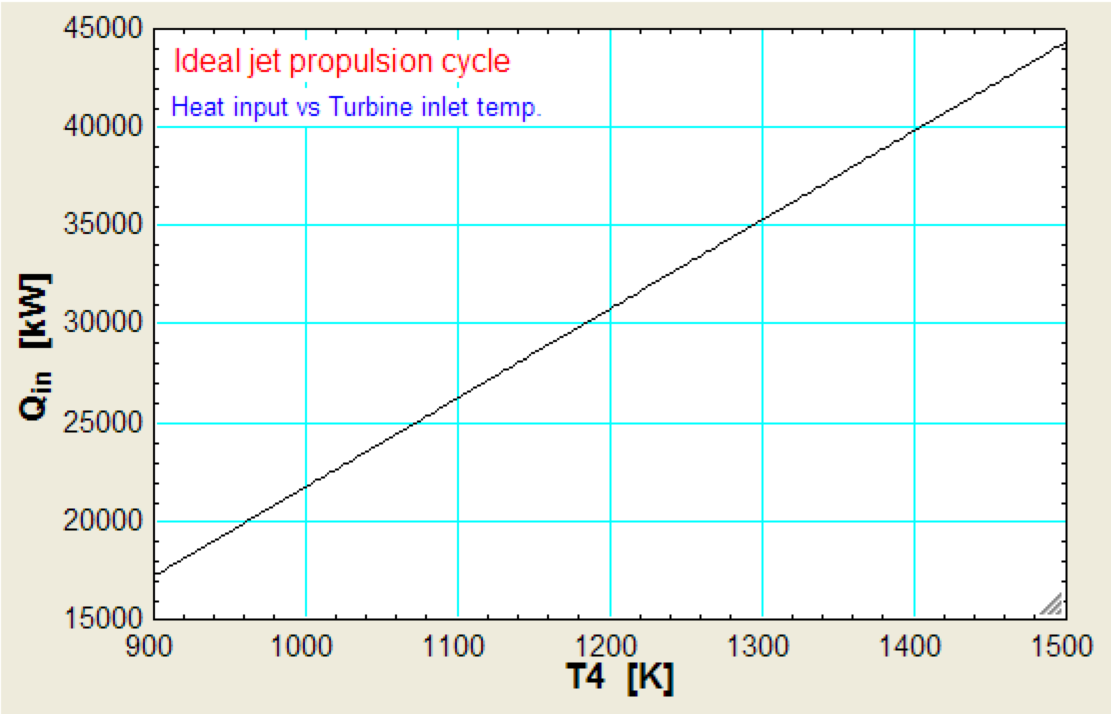
Also:

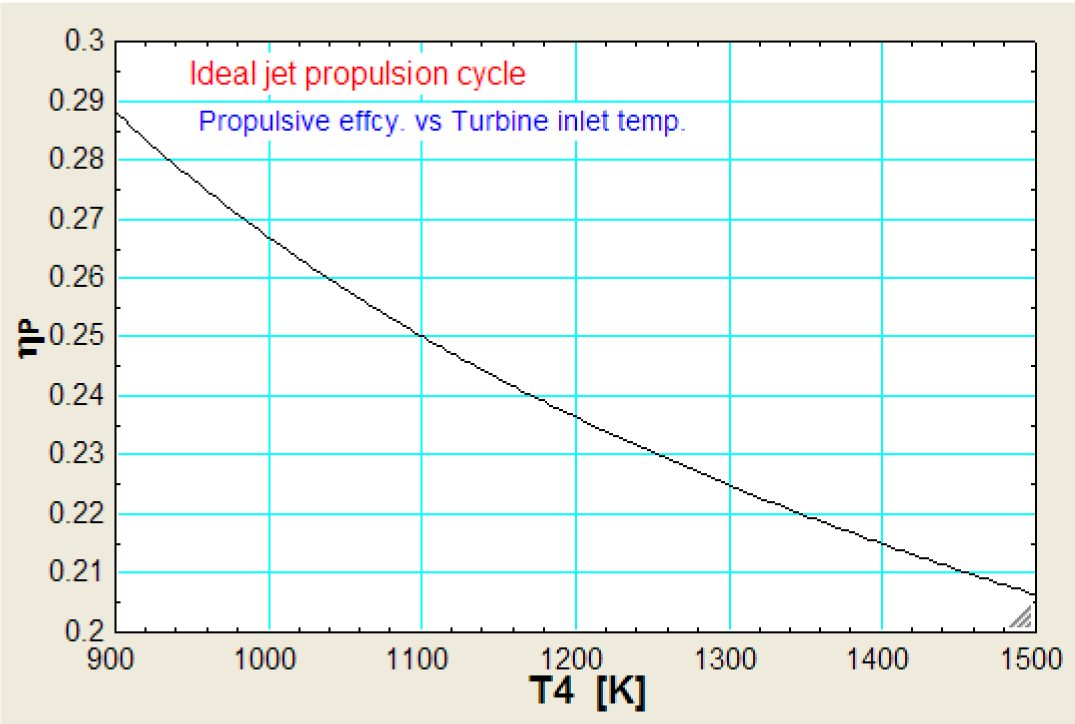
Plot the variation of heat supplied and Propulsive efficiency as turbine inlet temp, T4 varies from 900 K to 1500 K, other conditions remaining same:

First, compute the Parametric Table:

1..13	T4 [K]	Q_{in} [kW]	η_P
Run 1	900	17206	0.2881
Run 2	950	19468	0.2768
Run 3	1000	21729	0.2668
Run 4	1050	23990	0.258
Run 5	1100	26251	0.2501
Run 6	1150	28513	0.2429
Run 7	1200	30774	0.2363
Run 8	1250	33035	0.2303
Run 9	1300	35296	0.2248
Run 10	1350	37558	0.2197
Run 11	1400	39819	0.2149
Run 12	1450	42080	0.2105
Run 13	1500	44341	0.2063

Now, plot the results:





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"**Prob.2.24.** In problem 2.23, if the isentropic efficiencies of compressor, turbine and nozzle are 80%, 85% and 90% respectively, other conditions remaining the same, find out the propulsive efficiency etc."

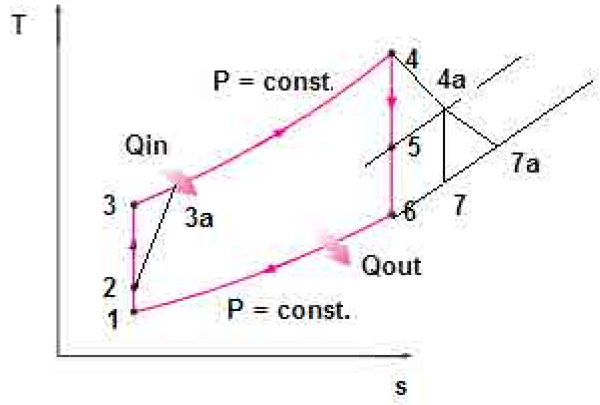


Fig.Prob.2.24

EES Solution:

"Data:"

m = 45 "kg/s"

cp = 1.005 "kJ/kg.K"

gamma = 1.4

```
P1 = 40 "kPa"
T1 = -35 + 273 "K"
rp = 10
T4 = 950 + 273 "K"
V1 = 9E05/3600 "m/s"

eta_comp = 0.8 "…compressor isentropic effcy."
eta_turb = 0.85 "…turbine isentropic effcy."
eta_nozzle = 0.9 "…nozzler isentropic effcy."

"Calculations:"

T2 = T1 +V1^2/(2 * cp*1000) "…finds T2 (K)"

P2 = P1 * (T2/T1)^(gamma /(gamma – 1)) "kPa"

P3 =P2 * rp "kPa"

T3 = T2 * rp^((gamma – 1)/gamma) "K"

(T3a – T2) = (T3 – T2) / eta_comp "….finds T3a (K)"

W_comp = m * cp * (T3a – T2) "kJ….compressor work"

W_turb = m * cp * (T4 – T4a) "kJ …. turbine work"

W_comp = W_turb "…. finds T4a (K)"

(T4 – T4a) = eta_turb * (T4 – T5) "….finds T5 (K)"

P4 = P3 "kPa"

P5 =P4 * (T5/T4)^(gamma / (gamma – 1)) " … finds P5 = P4a, kPa"

P4a = P5 "kPa"

P7 = P1"kPa"

P7a = P1 "kPa"

T7 = T4a * (P7/P4a)^((gamma-1)/gamma) "….finds T7(K)"
```

(T4a – T7a) = eta_nozzle * (T4a – T7) "…finds T7a (K)"

V7a = sqrt(2 * cp*1000 * (T4a – T7a)) "m/s … velocity of exit jet"

F = m * (V7a – V1) "N … Net Thrust"

W_P = F * V1/1000 "kW … Propulsive power"

Q_in = m * cp * (T4 – T3a) "kW … heat supplied"

eta_P = W_P/Q_in "….Propulsive effcy."

KE_exit = (m * (V7a – V1)^2 / 2)/1000 "kW"

Q_exit = m * cp * (T7a – T1) "kW"

Results:

Unit Settings: SI K Pa kJ mass deg

cp = 1.005 [kJ/kg-K]	η_{comp} = 0.8	η_{nozzle} = 0.9	η_P = 0.1953
η_{turb} = 0.85	F = 22637 [N]	γ = 1.4	KE_{exit} = 5694 [kW]
m = 45 [kg/s]	P1 = 40 [kPa]	P2 = 61.48 [kPa]	P3 = 614.8 [kPa]
P4 = 614.8 [kPa]	P4a = 175.4 [kPa]	P5 = 175.4 [kPa]	P7 = 40 [kPa]
P7a = 40	Q_{exit} = 17629 [kW]	Q_{in} = 28982 [kW]	rp = 10
T1 = 238 [K]	T2 = 269.1 [K]	T3 = 519.5 [K]	T3a = 582.2 [K]
T4 = 1223 [K]	T4a = 909.9 [K]	T5 = 854.7 [K]	T7 = 596.5 [K]
T7a = 627.8 [K]	V1 = 250 [m/s]	V7a = 753 [m/s]	W_{comp} = 14158 [kW]
W_P = 5659 [kW]	W_{turb} = 14158 [kW]		

Thus:

At turbine exit: T4a = 909.9 K, P4a = 175.4 kPa …. Ans.

Velocity of gases at nozzle exit = V7a = 753 m/s …. Ans.

Propulsive power = W_P = 5659 kW …. Ans.

Heat supplied = Q_in = 28982 kW ….Ans.

Propulsive efficiency = eta_P = 0.1953 = 19.53% … Ans.

Also:

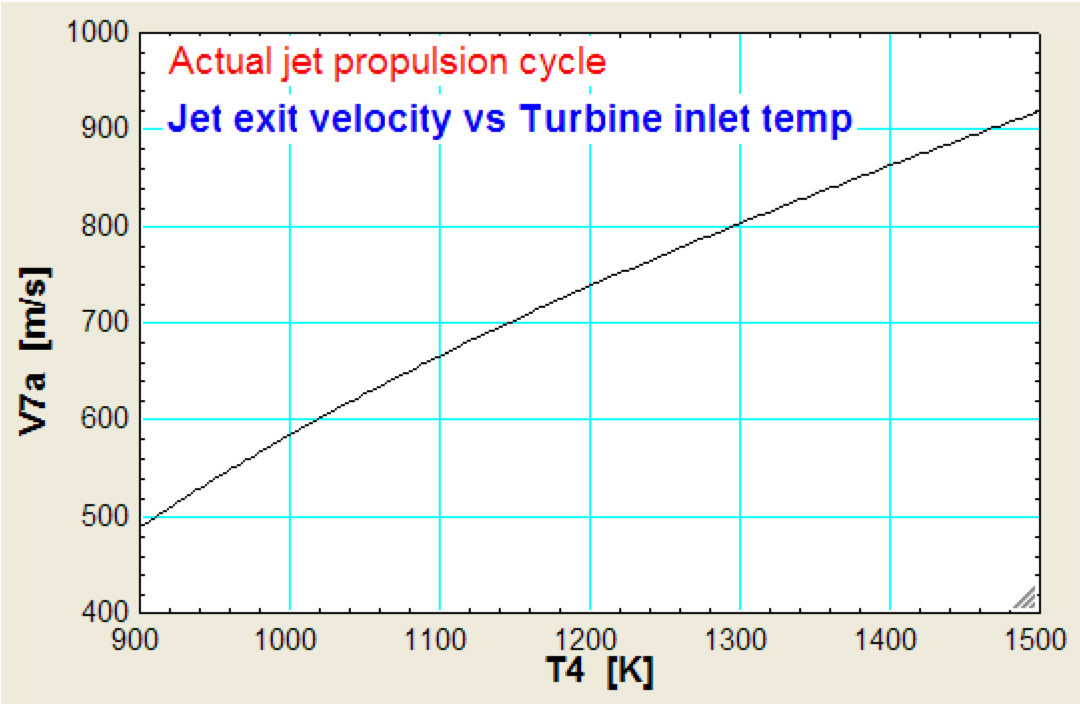
Plot the variation of exit jet velocity (V7a), Propulsive power (W_P), heat supplied(Q_in) and Propulsive efficiency(eta_P) as turbine inlet temp (T4) varies from 900 K to 1500 K, other conditions remaining same:

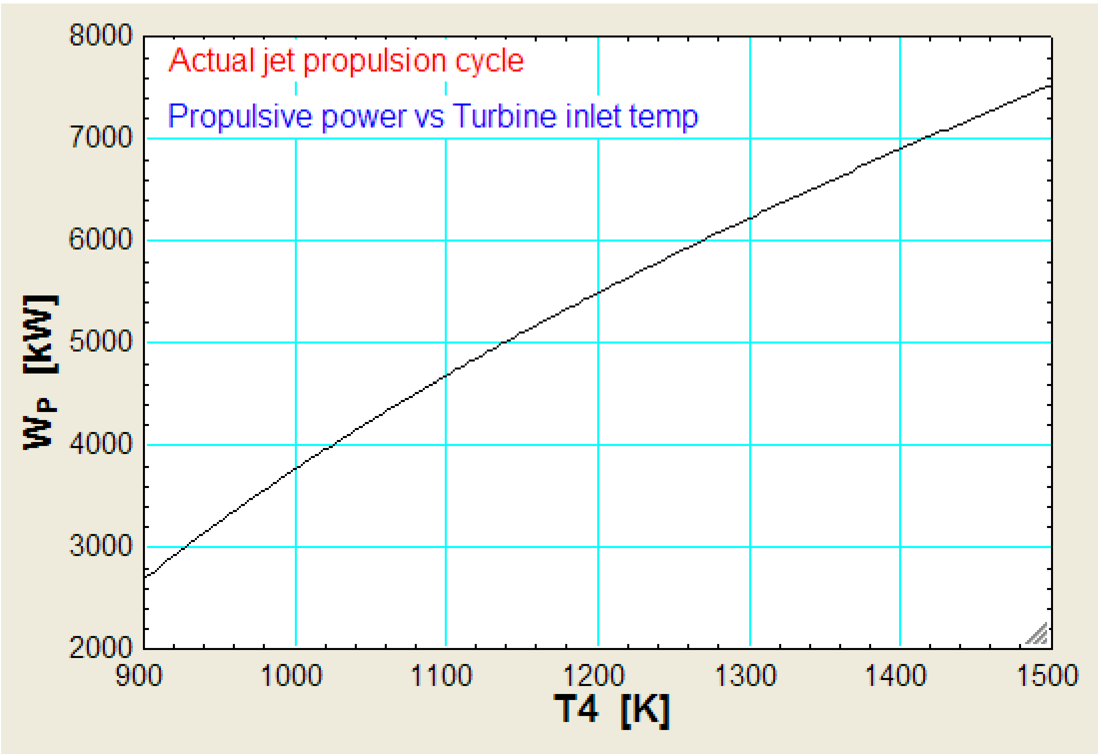
First, compute the Parametric Table:

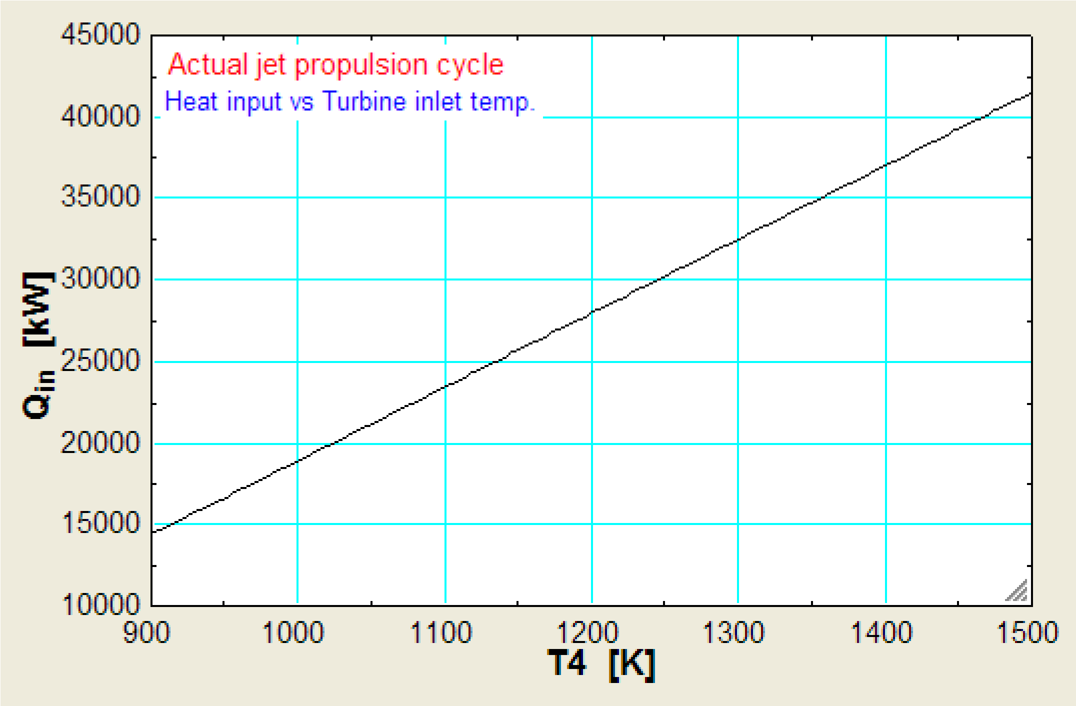
1..13	T4 [K]	V7a [m/s]	W_P [kW]
Run 1	900	488.3	2681
Run 2	950	538.7	3248
Run 3	1000	584.4	3762
Run 4	1050	626.5	4235
Run 5	1100	665.7	4677
Run 6	1150	702.6	5092
Run 7	1200	737.6	5405
Run 8	1250	770.8	5859
Run 9	1300	802.6	6217
Run 10	1350	833.1	6560
Run 11	1400	862.5	6891
Run 12	1450	890.9	7210
Run 13	1500	918.4	7519

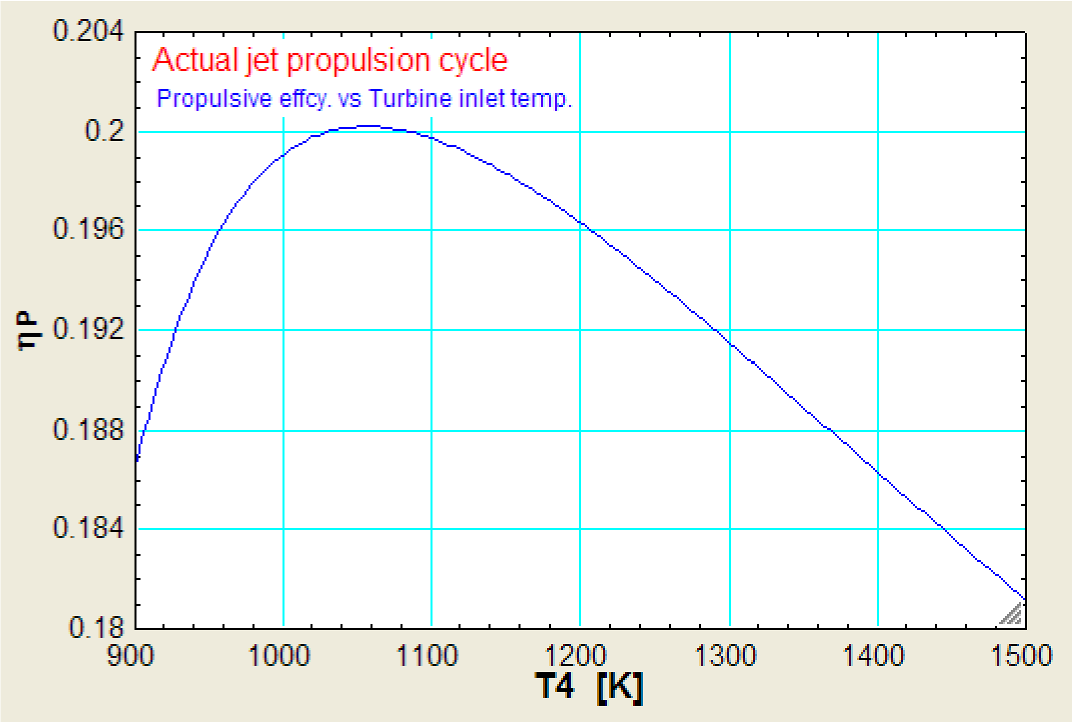
1..13	T4 [K]	Q_{in} [kW]	η_P
Run 1	900	14375	0.1865
Run 2	950	16636	0.1952
Run 3	1000	18897	0.1991
Run 4	1050	21158	0.2002
Run 5	1100	23420	0.1997
Run 6	1150	25681	0.1983
Run 7	1200	27942	0.1963
Run 8	1250	30203	0.194
Run 9	1300	32465	0.1915
Run 10	1350	34726	0.1889
Run 11	1400	36987	0.1863
Run 12	1450	39248	0.1837
Run 13	1500	41510	0.1811

Now, plot the results:






Actual jet propulsion cycle
Heat input vs Turbine inlet temp.
Qin [kW]
T4 [K]
45000
40000
35000
30000
25000
20000
15000
10000
900
1000
1100
1200
1300
1400
1500


Actual jet propulsion cycle
Propulsive effcy. vs Turbine inlet temp.
ηP
T4 [K]
0.204
0.2
0.196
0.192
0.188
0.184
0.18
900
1000
1100
1200
1300
1400
1500

==

2.4 Problems solved with TEST:

Prob.2.25. A GasTurbine power plant operates on simple Brayton cycle with air as working fluid and delivers 32 MW of power. Min. and max. temp. in cycle are 310K and 900K. Pressure at exit of compressor is 8 times the value at the inlet. Assuming isentropic eff. of 80% and 86% for compressor and turbine, determine the mass flow rate of air through the cycle. [VTU-ATD-July 2008]

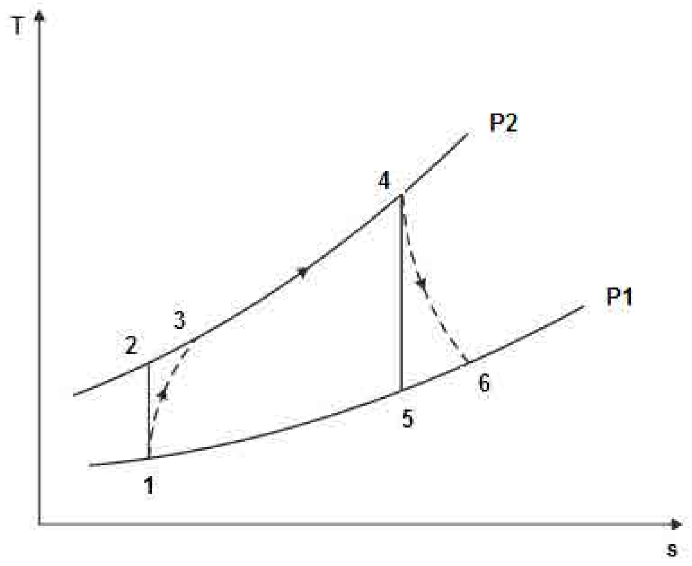


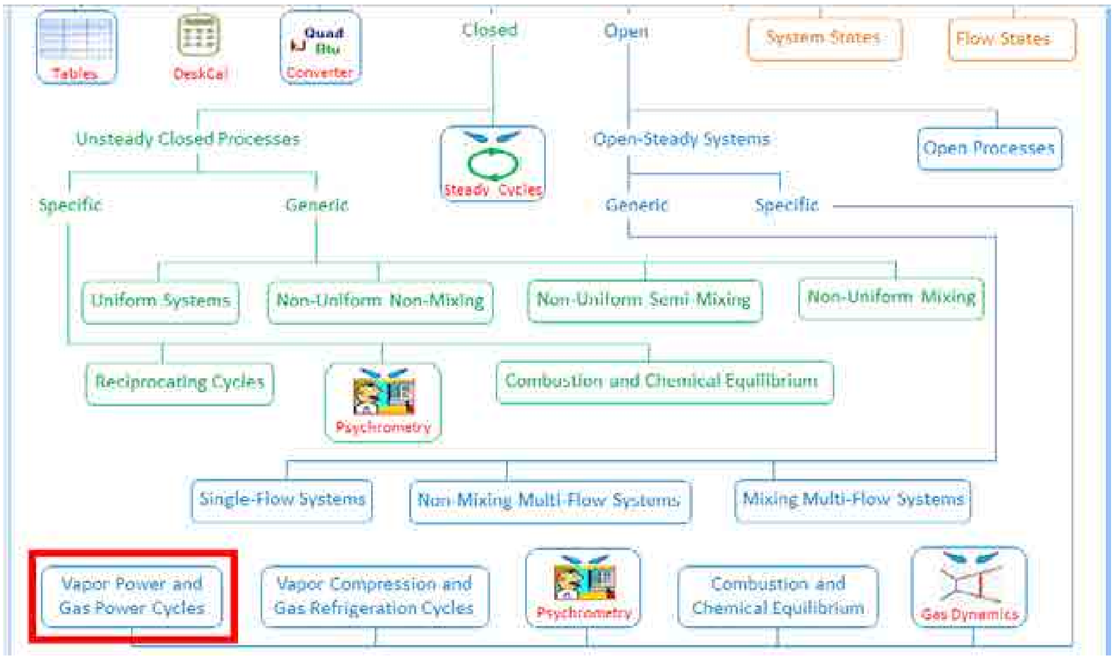
Fig.Prob.2.25

TEST Solution:

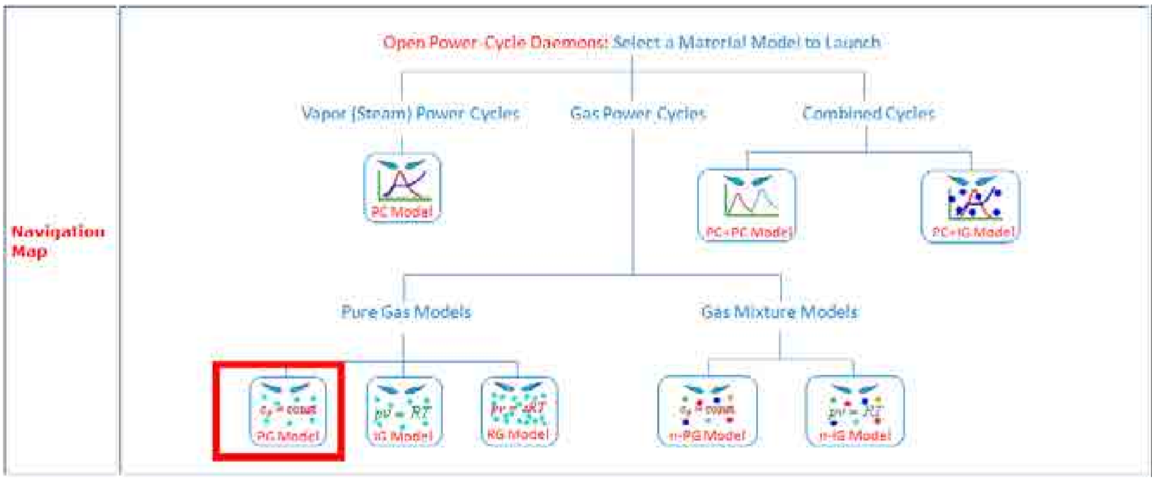
Following are the steps:

We shall do the calculations assuming that the air mass flow rate is 1 kg/s and find out the net power produced. Then, it is a simple matter to compute the mass flow required to produce 32 MW.

1. From the TEST daemon tree, select the 'Vapour Power and Gas Power cycles' daemon:



2. Clicking on 'Vapour Power and Gas Power cycles' brings up the window for material selection.



3. Choose PG model (i.e. const. sp. heat), and select Air for working substance. Fill in the conditions for State 1, i.e. state at entry to compressor: p1= 100 kPa, T1= 310 K, and mdot1 = 1 kg/s. Press Enter. Immediately, all properties at State 1 are calculated:

4. For State 2: Enter p2, s2 = s1 (for isentropic process 1-2), and mdot2 = mdot1. Hit Enter. We get:

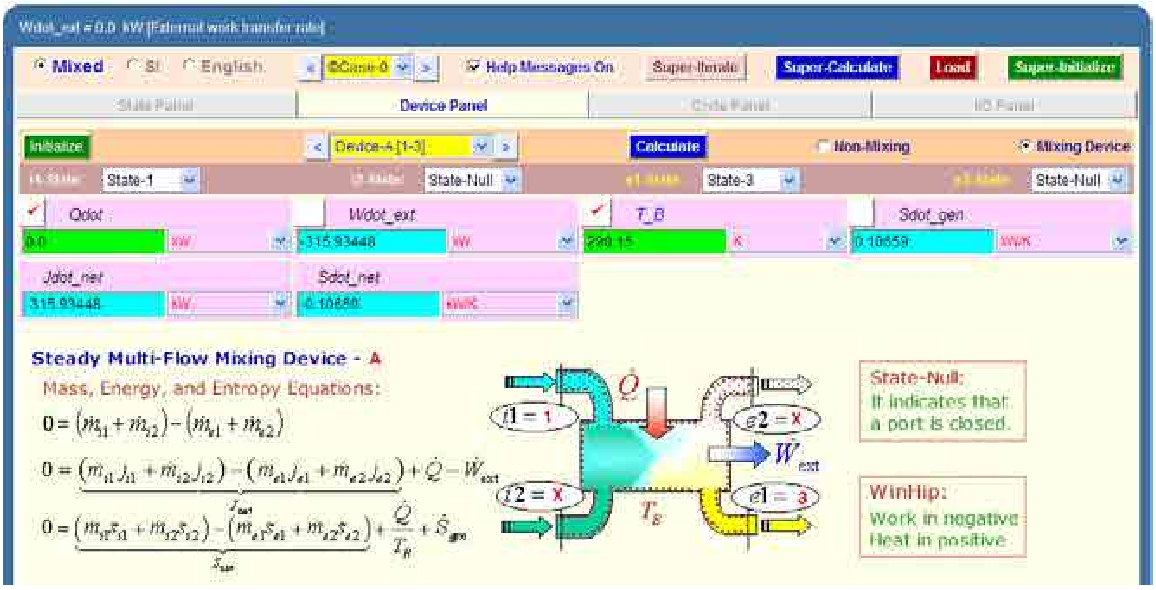
5. For State 3: It represents the state after actual compression, taking in to account the isentropic effcy. of compressor. Enter p3 = p2, T3 = T1 + (T2 – T1) / 0.8 where 0.8 is the compressor effcy. and mdot3 = mdot1. Hit Enter. We get:

6. For State 4: we have: p4 = p3, T4 = 900 K, mdot4 = mdot1. Hit Enter. We get:

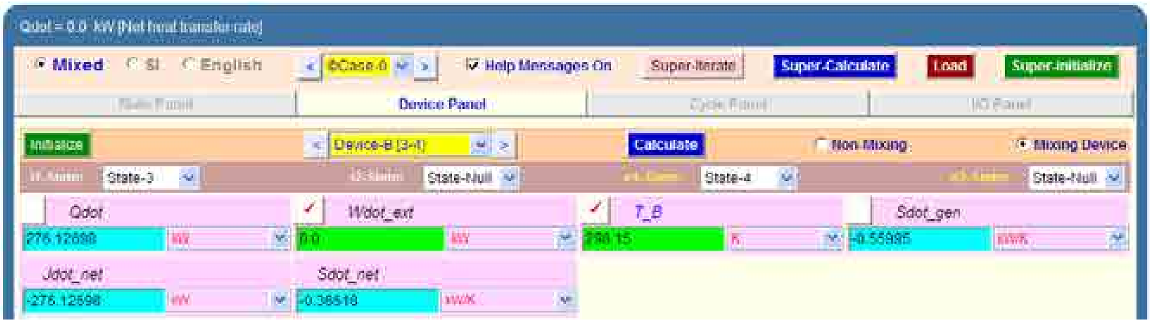
7. For State 5: Enter p5 = p1, s5 = s4, mdot5 = mdot1, and hit Enter. We get:

8. For State 6: i.e. actual exit of turbine: Enter p6 = p5, T6 = T4 – 0.85 * (T4 – T5) where 0.85 is isentropic effcy. of turbine. And mdot6 = mdot1. Hit Enter. We get:

9. Now, go to Device panel. For device A, enter State 1 and State 3 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And Qdot1 = 0 since in this process there is no external heat transfer. Hit Enter. We get:



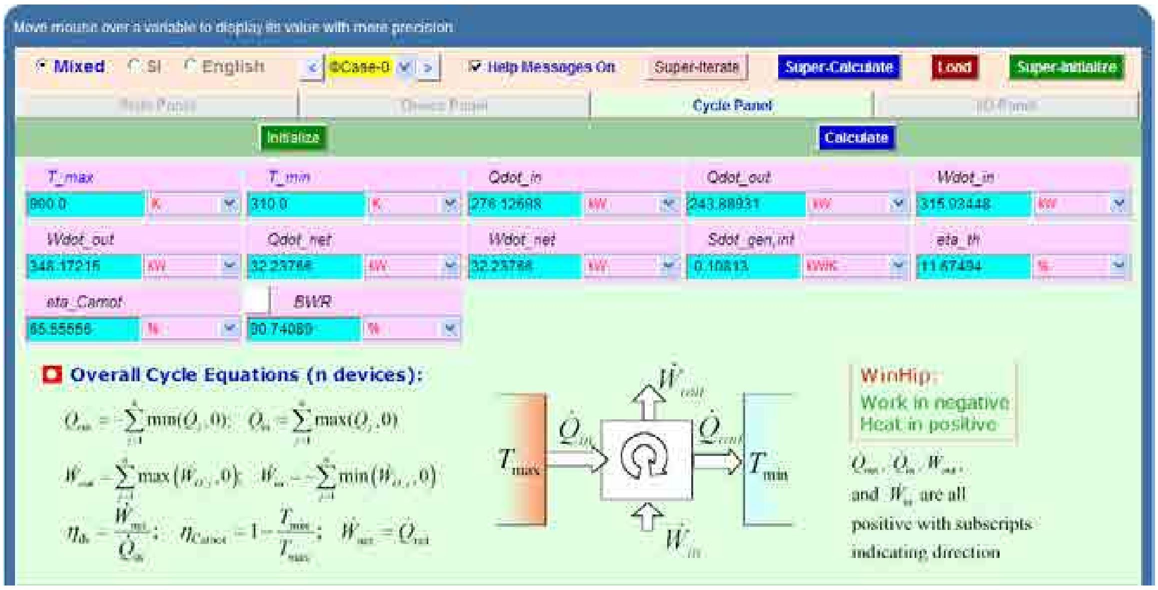
10. Similarly for Device B: enter State 3 and State 4 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process no external work transfer occurs. Hit Enter. We get:



11. And, for Device C: enter State 4 and State 6 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Qdot = 0 since for this process no external heat transfer occurs. Hit Enter. We get:

12. And, for Device D: enter State 6 and State 1 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process no external work transfer occurs. Hit Enter. And, SuperCalculate. We get:

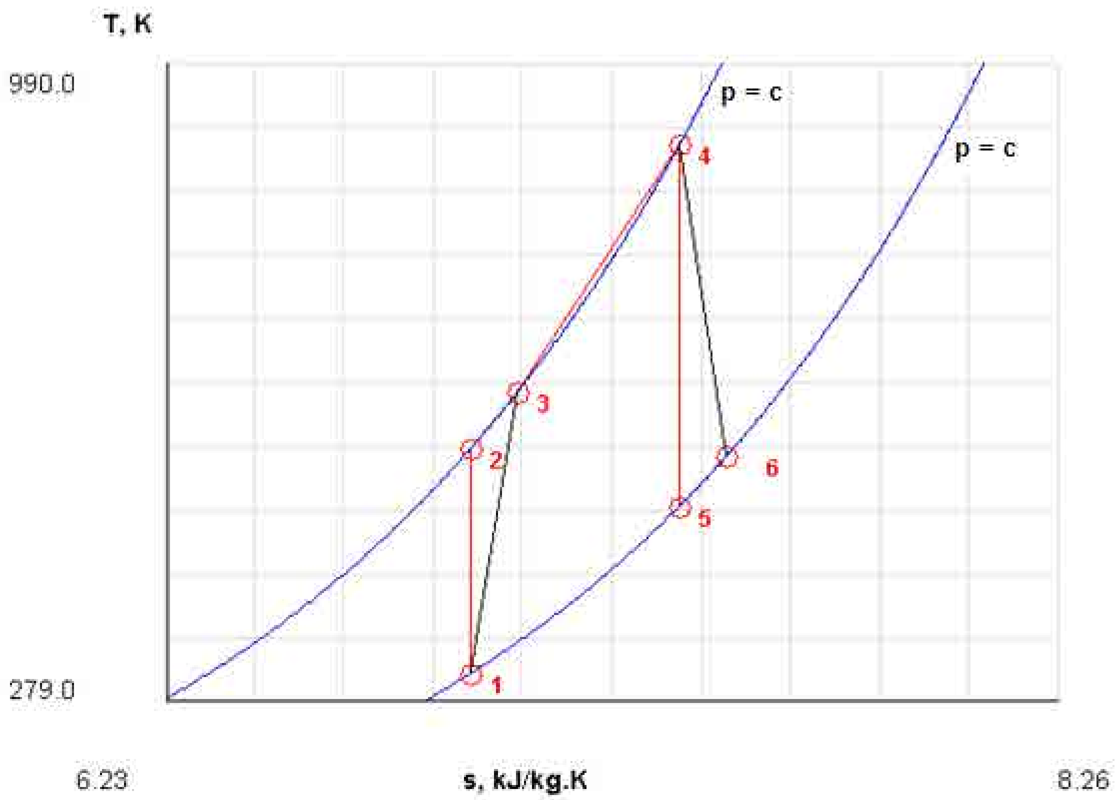
13. Now, go to cycle panel. It gives the major parameters of this cycle:



We observe that Wdot_net = 32.23766 kW.

This is the net power developed when the air flow rate is 1 kg/s.**Therefore, to produce 32 MW, we need a flow rate of 32E06/32237.66 = 992.63 kg/s …. Ans.**

14. From the Plots widget, choose T-s diagram, and we get:



15. And I/O panel gives the TEST code etc:

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

#         Daemon Path: Systems>Open>SteadyState>Specific>PowerCycle>PG-Model; v-10.ca08

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

 States   {

          State-1: Air;

          Given: { p1= 100.0 kPa; T1= 310.0 K; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 1.0 kg/s; }

          State-2: Air;

          Given: { p2= 800.0 kPa; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= "mdot1" kg/s; }

          State-3: Air;

          Given: { p3= "p2" kPa; T3= "T1+(T2-T1)/0.8" K; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= "mdot1" kg/s; }

          State-4: Air;

          Given: { p4= "p3" kPa; T4= 900.0 K; Vel4= 0.0 m/s; z4= 0.0 m; mdot4= "mdot1" kg/s; }

          State-5: Air;

          Given: { p5= "p1" kPa; s5= "s4" kJ/kg.K; Vel5= 0.0 m/s; z5= 0.0 m; mdot5= "mdot1" kg/s; }

          State-6: Air;

          Given: { p6= "p5" kPa; T6= "T4-0.86*(T4-T5)" K; Vel6= 0.0 m/s; z6= 0.0 m; mdot6= "mdot1" kg/s; }

          }
```

Analysis {

Device-A: i-State = State-1; e-State = State-3; Mixing: true;

Given: { Qdot= 0.0 kW; T_B= 298.15 K; }

Device-B: i-State = State-3; e-State = State-4; Mixing: true;

Given: { Wdot_ext= 0.0 kW; T_B= 298.15 K; }

Device-C: i-State = State-4; e-State = State-6; Mixing: true;

Given: { Qdot= 0.0 kW; T_B= 298.15 K; }

Device-D: i-State = State-6; e-State = State-1; Mixing: true;

Given: { 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	310.0	0.8897	-77.07	11.89	6.926
#	2	800.0	561.9	0.2016	103.39	264.64	6.926
#	3	800.0	624.8	0.2241	148.51	327.83	7.032
#	4	800.0	900.0	0.3229	345.66	603.95	7.399
#	5	100.0	496.6	1.4251	56.6	199.1	7.399
#	6	100.0	553.0	1.5872	97.07	255.78	7.507

#--------Property spreadsheet ends--

 # Mass, Energy, and Entropy Analysis Results:

Device-A: i-State = State-1; e-State = State-3; Mixing: true;

Given: Qdot= 0.0 kW; T_B= 298.15 K;

Calculated: Wdot_ext= -315.93448 kW; Sdot_gen= 0.10659171 kW/K; Jdot_net= -315.93448 kW; Sdot_net= -0.10659171 kW/K;

\# Device-B: i-State = State-3; e-State = State-4; Mixing: true;
\# Given: Wdot_ext= 0.0 kW; T_B= 298.15 K;
\# Calculated: Qdot= 276.12698 kW; Sdot_gen= -0.5599514 kW/K; Jdot_net= -276.12698 kW; Sdot_net= -0.366183 kW/K;
\# Device-C: i-State = State-4; e-State = State-6; Mixing: true;
\# Given: Qdot= 0.0 kW; T_B= 298.15 K;
\# Calculated: Wdot_ext= 348.17215 kW; Sdot_gen= 0.10810609 kW/K; Jdot_net= 348.17215 kW; Sdot_net= -0.10810609 kW/K;
\# Device-D: i-State = State-6; e-State = State-1; Mixing: true;
\# Given: Wdot_ext= 0.0 kW; T_B= 298.15 K;
\# Calculated: Qdot= -243.88931 kW; Sdot_gen= 0.23712797 kW/K; Jdot_net= 243.88931 kW; Sdot_net= 0.5808808 kW/K;

 # Cycle Analysis Results:
\# Calculated: T_max= 900.0 K; T_min= 310.0 K; Qdot_in= 276.12698 kW;
\# Qdot_out= 243.88931 kW; Wdot_in= 315.93448 kW; Wdot_out= 348.17215 kW;
\# Qdot_net= 32.23766 kW; **Wdot_net= 32.23766 kW**; Sdot_gen,int= -0.10813 kW/K;
\# **eta_th= 11.67494 %;** eta_Carnot= 65.55556 %**; BWR= 90.74089 %;**

#

#******CALCULATE VARIABLES: Type in an expression starting with an '=' sign ('= mdot1*(h2-h1)', '= sqrt(4*A1/PI)', etc.) and press the Enter key)*********

#Mass flow rate of air: mdot = 32*MW / Wdot_net = 32*10^6/(32.23766*10^3) kg/s

=32*10^6/(32.23766*10^3) = **992.6278768372147 kg/s ….required mass flow rate of air… Ans.**

===

Prob.2.26. In an open cycle constant pressure gas turbine, air enters the compressor at 1 bar, 27 C. Pressure of air after compression is 5 bar. Isentropic efficiencies of compressor and turbine are 80% and 84% respectively. The air fuel ratio is 75 : 1. The air flow rate is 2.5 kg/s. Determine the power developed and the thermal efficiency of the cycle. For both air and combustion gases, take cp = 1.005 kJ/kg.K and γ = 1.4. Calorific Value of fuel = 42000 kJ/kg. [VTU- ATD-July 2004]

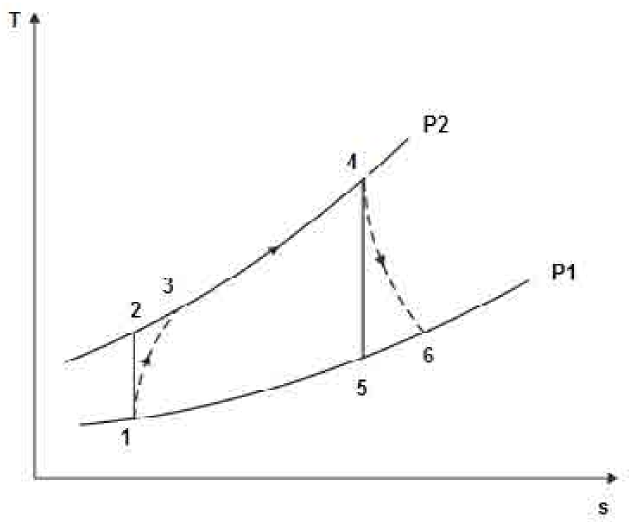


Fig.Prob.2.26

TEST Solution:

Following are the steps:

Steps 1 and 2 are the same as for Prob.2.25.i.e. select 'Vapour Power and Gas Power cycles' daemon from the 'daemon tree' and, for material model chose PG model (i.e. const. sp. heat) and select air as the working substance.

3. Choose PG model (i.e. const. sp. heat), and select Air for working substance. Fill in the conditions for State 1, i.e. state at entry to compressor: p1= 100 kPa,, T1= 27 C, and mdot1 = 2.5 kg/s. Hit Enter. Immediately, all properties at State 1 are calculated:

4. For State 2: Enter p2, s2 = s1 (for isentropic process 1-2), and mdot2 = mdot1. Hit Enter. We get:

5. For State 3: It represents the state after actual compression, taking in to account the isentropic effcy. of compressor. Enter p3 = p2, T3 = T1 + (T2 – T1) / 0.8 where 0.8 is the compressor effcy. and mdot3 = mdot1. Hit Enter. We get:

6. For State 4: we have: p4 = p3. To find T4, use the fact that energy supplied by the fuel is equal to increase in enthalpy of the gases as they pass through the combustion chamber. i.e.

$$m_f \cdot CV = cp(m_a + m_f) \cdot (T4 - T3)$$

i.e. $$CV = cp \cdot \left(1 + \frac{m_a}{m_f}\right) \cdot (T4 - T3)$$

i.e. $$T4 = T3 + \frac{CV}{\left[cp \cdot \left(1 + \frac{m_a}{m_f}\right)\right]}$$

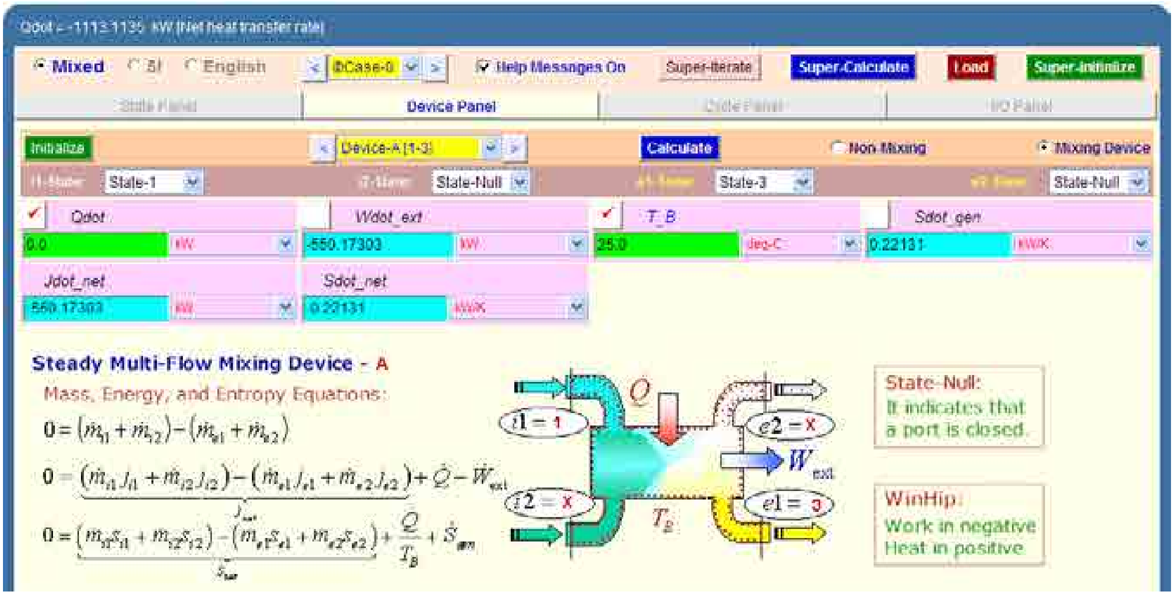
i.e. $$T4 = T3 + \frac{42000}{1.005 \cdot (1 + 75)}$$

Also, mdot4 = mdot3 + mdot3/75. Hit Enter. We get:

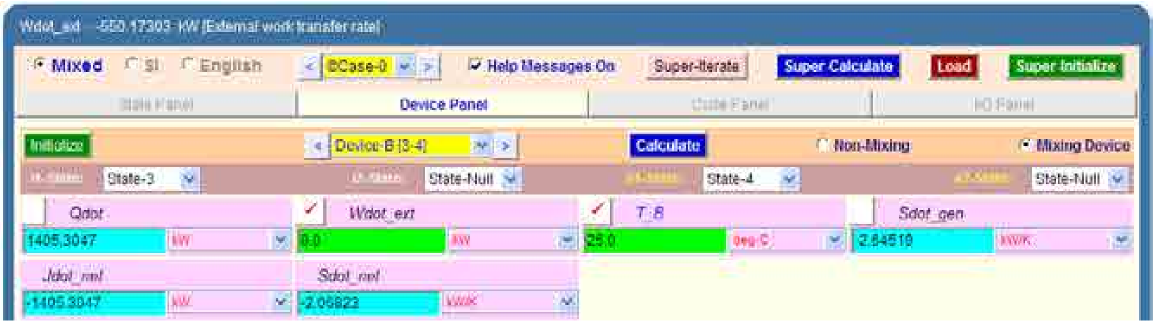
7. For State 5: Enter p5 = p1, s5 = s4, mdot5 = mdot4, and hit Enter. We get:

8. For State 6: i.e. actual exit of turbine: Enter p6 = p5, T6 = T4 – 0.84 * (T4 – T5) where 0.84 is isentropic effcy. of turbine. And mdot6 = mdot5. Hit Enter. We get:

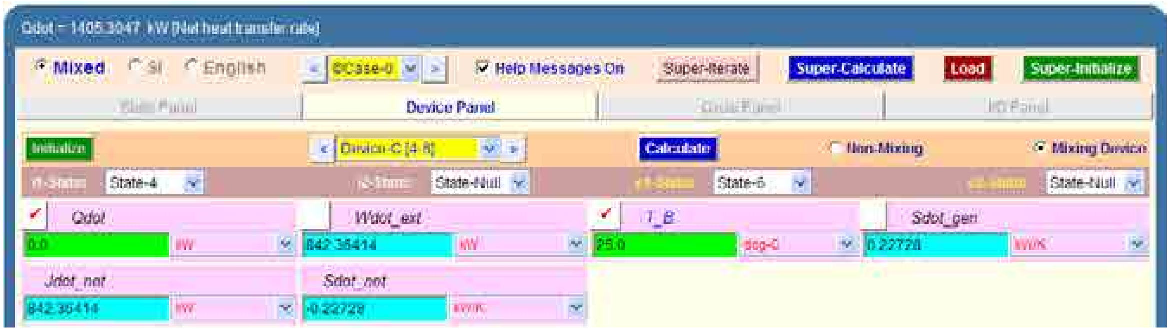
9. Now, go to Device panel. For device A, enter State 1 and State 3 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And Qdot1 = 0 since in this process there is no external heat transfer. Hit Enter. We get:



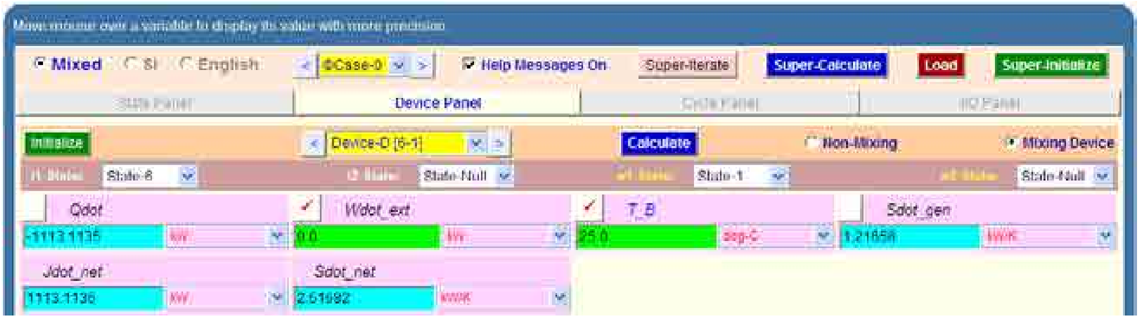
10. Similarly for Device B: enter State 3 and State 4 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process, no external work transfer occurs. Hit Enter. We get:



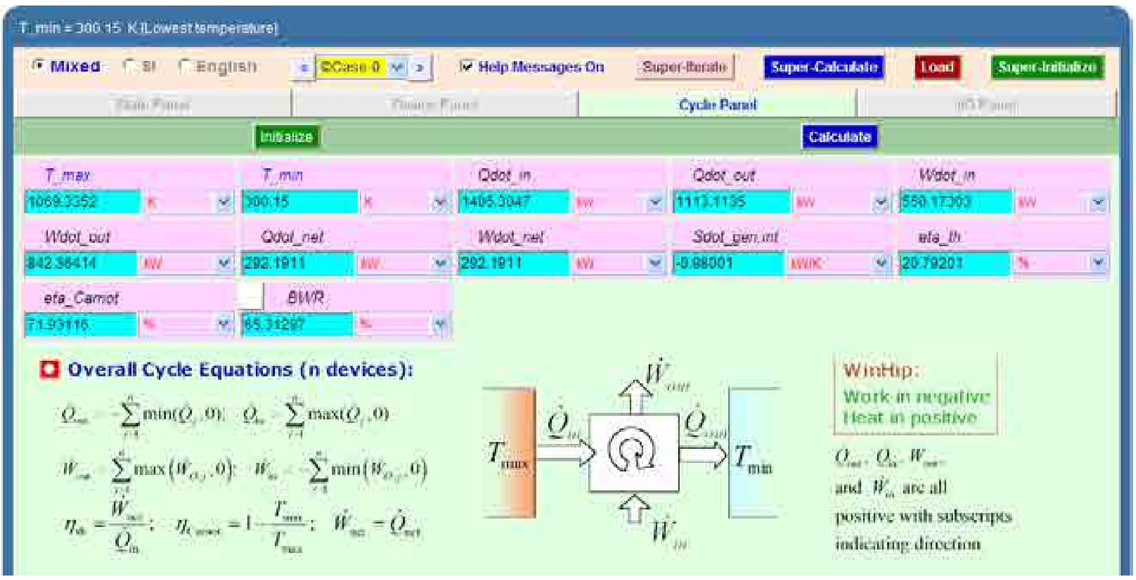
11. And, for Device C: enter State 4 and State 6 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Qdot = 0 since for this process, no external heat transfer occurs. Hit Enter. We get:



12. And, for Device D: enter State 6 and State 1 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process, no external work transfer occurs. Hit Enter. And, SuperCalculate. We get:



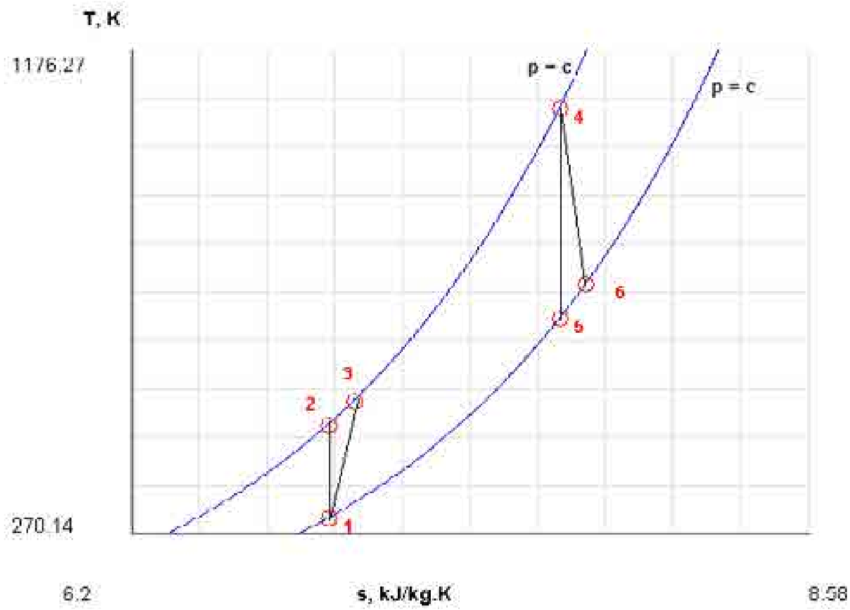
13. Now, go to cycle panel. It gives the major parameters of this cycle:



We observe that: Wdot_net = 292.1911 kW = Power developed …. Ans.

And, thermal efficiency = eta_th = 20.792% …. Ans.

14. From the Plots widget, choose T-s diagram, and we get:



15. And I/O panel gives the TEST code etc:

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

Daemon Path: Systems>Open>SteadyState>Specific>PowerCycle>PG-Model; v-10.ca08

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

States {

State-1: Air;

Given: { p1= 100.0 kPa; T1= 27.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 2.5 kg/s; }

State-2: Air;

Given: { p2= 500.0 kPa; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= "mdot1" kg/s; }

State-3: Air;

Given: { p3= "p2" kPa; T3= "T1+(T2-T1)/0.8" deg-C; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= "mdot1" kg/s; }

State-4: Air;

Given: { p4= "p3" kPa; T4= "T3+42000/(76*1.005)" deg-C; Vel4= 0.0 m/s; z4= 0.0 m; mdot4= "mdot3+(mdot3/75)" kg/s; }

State-5: Air;

Given: { p5= "p1" kPa; s5= "s4" kJ/kg.K; Vel5= 0.0 m/s; z5= 0.0 m; mdot5= "mdot4" kg/s; }

State-6: Air;

Given: { p6= "p5" kPa; T6= "T4-0.84*(T4-T5)" deg-C; Vel6= 0.0 m/s; z6= 0.0 m; mdot6= "mdot5" kg/s; }

}

Analysis {

Device-A: i-State = State-1; e-State = State-3; Mixing: true;

Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

Device-B: i-State = State-3; e-State = State-4; Mixing: true;

Given: { Wdot_ext= 0.0 kW; T_B= 25.0 deg-C; }

Device-C: i-State = State-4; e-State = State-6; Mixing: true;

Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

Device-D: i-State = State-6; e-State = State-1; Mixing: true;

Given: { Wdot_ext= 0.0 kW; T_B= 25.0 deg-C; }

}

#----------------------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	300.2	0.8614	-84.13	2.01	6.893
#	2	500.0	475.6	0.273	41.57	178.06	6.893
#	3	500.0	519.5	0.2982	73.0	222.08	6.982
#	4	500.0	1069.3	0.6138	466.99	773.88	7.706
#	5	100.0	674.9	1.9368	184.35	378.03	7.706
#	6	100.0	738.0	2.1179	229.58	441.37	7.796

#--------Property spreadsheet ends--

 # Mass, Energy, and Entropy Analysis Results:

Device-A: i-State = State-1; e-State = State-3; Mixing: true;

Given: Qdot= 0.0 kW; T_B= 25.0 deg-C;

Calculated: Wdot_ext= -550.17303 kW; Sdot_gen= 0.22130843 kW/K; Jdot_net= -550.17303 kW; Sdot_net= -0.22130843 kW/K;

Device-B: i-State = State-3; e-State = State-4; Mixing: true;

Given: Wdot_ext= 0.0 kW; T_B= 25.0 deg-C;

Calculated: Qdot= 1405.3047 kW; Sdot_gen= -2.6451857 kW/K; Jdot_net= -1405.3047 kW; Sdot_net= -2.068229 kW/K;
Device-C: i-State = State-4; e-State = State-6; Mixing: true;
Given: Qdot= 0.0 kW; T_B= 25.0 deg-C;
Calculated: Wdot_ext= 842.36414 kW; Sdot_gen= 0.22728187 kW/K; Jdot_net= 842.36414 kW; Sdot_net= -0.22728187 kW/K;
Device-D: i-State = State-6; e-State = State-1; Mixing: true;
Given: Wdot_ext= 0.0 kW; T_B= 25.0 deg-C;
Calculated: Qdot= -1113.1135 kW; Sdot_gen= 1.2165818 kW/K; Jdot_net= 1113.1135 kW; Sdot_net= 2.5168192 kW/K;
 # Cycle Analysis Results:
Calculated: T_max= 1069.3352 K; T_min= 300.15 K; Qdot_in= 1405.3047 kW;
Qdot_out= 1113.1135 kW; Wdot_in= 550.17303 kW; Wdot_out= 842.36414 kW;
Qdot_net= 292.1911 kW; **Wdot_net= 292.1911 kW**; Sdot_gen,int= -0.98001 kW/K;
eta_th= 20.79201 %; eta_Carnot= 71.93116 %; **BWR= 65.31297 %;**

==

Prob.2.27. In a reheat gas turbine cycle, comprising one compressor and two turbines, air is compressed from 1 bar, 27 C to 6 bar. The highest temp in the cycle is 900 C. The expansion in the first stage turbine is such that the work from it just equals the work required by the compressor. Air is reheated between the two stages of expansion to 850 C. Assume that the isentropic efficiencies of the compressor, the first stage and the second stage turbines are 85% each and that the working substance is air. Calculate the cycle efficiency. [VTU-ATD-July 2004]

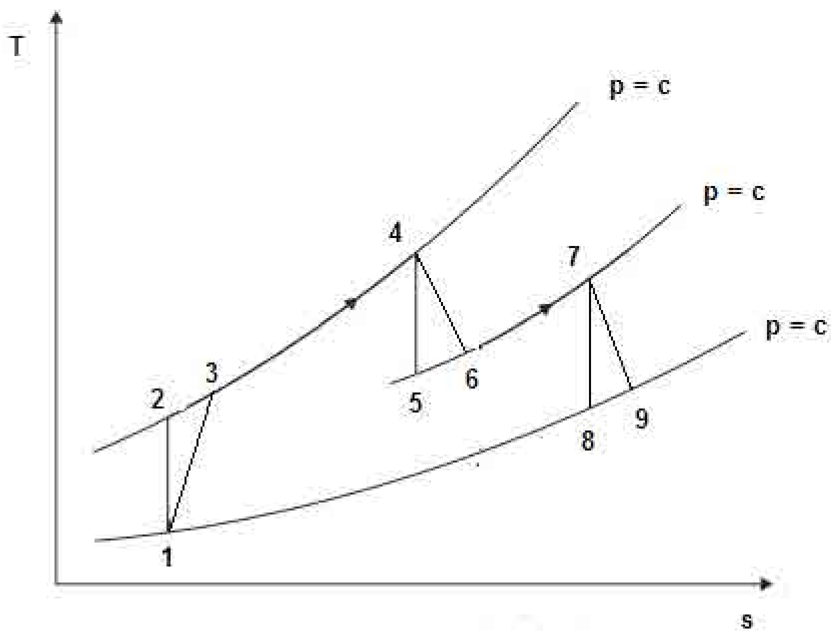


Fig.Prob.2.27

TEST Solution:

Following are the steps:

Steps 1 and 2 are the same as for Prob.2.25.i.e. select 'Vapour Power and Gas Power cycles' daemon from the 'daemon tree' and, for material model chose PG model (i.e. const. sp. heat) and select air as the working substance.

3. Choose PG model (i.e. const. sp. heat), and select Air for working substance. Fill in the conditions for State 1, i.e. state at entry to compressor: p1= 100 kPa, T1= 27 C, and mdot1 = 1 kg/s. Hit Enter. Immediately, all properties at State 1 are calculated:

4. For State 2: Enter p2 = 600 kPa, s2 = s1 (for isentropic process 1-2), and mdot2 = 1kg/s. Hit Enter. We get:

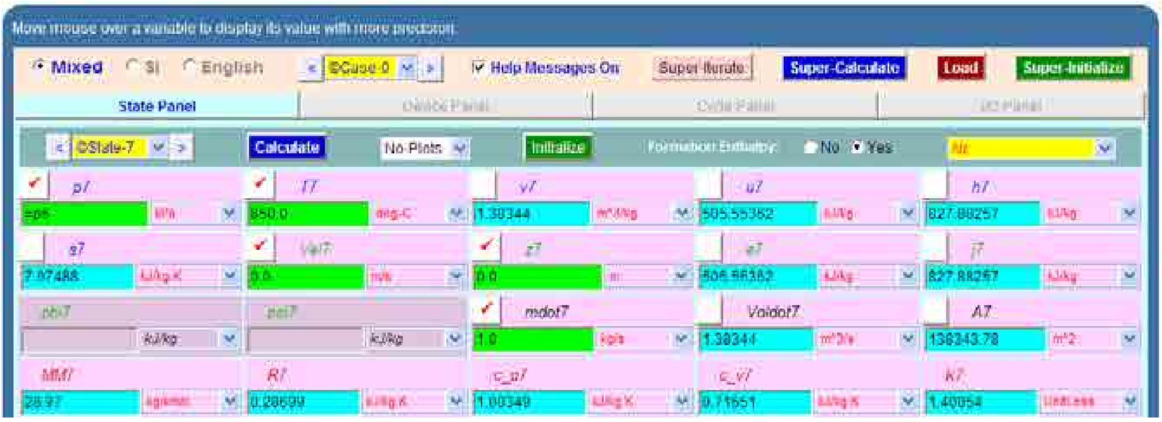
5. For State 3: It represents the state after actual compression, taking in to account the isentropic effcy. of compressor. Enter p3 = p2, T3 = T1 + (T2 – T1) / 0.85 where 0.85 is the compressor effcy. and mdot3 = 1kg/s. Hit Enter. We get:

6. For State 4: we have: p4 = p3. T4 = 900 C, mdot4 = 1 kg/s. Hit Enter. We get:

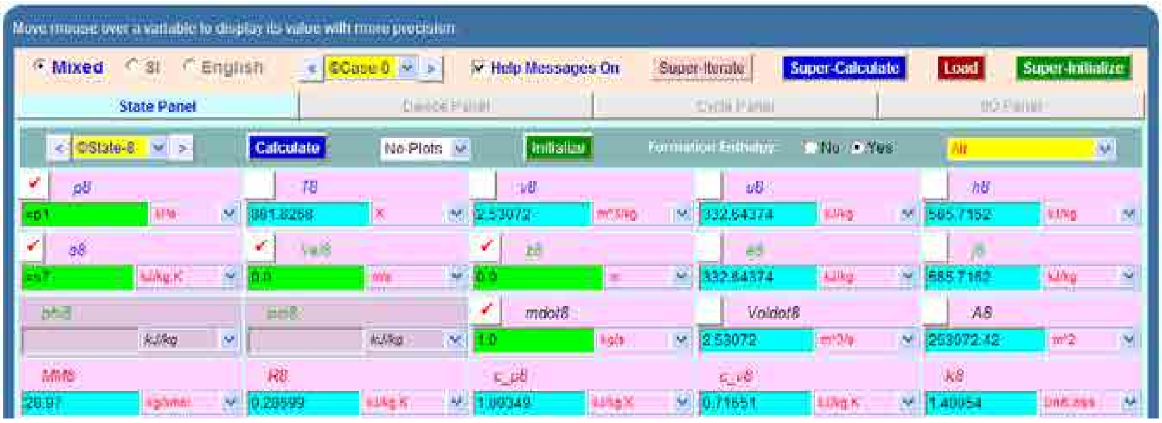
7. For State 5: Enter s5 = s4, mdot5 = 1 kg/s, and T5 = T4 – (T4 – T6)/0.85 where 0.85 is the turbine isentropic effcy. Hit Enter. We get (after SuperCalculate later):

8. For State 6: i.e. actual exit of turbine: Enter p6 = p5, For T6, we have compressor work = first stage turbine work, i.e. cp * (T4 – T6) = cp * (T3 – T1). Therefore, T6 = T4 – (T3 – T1). And mdot6 = mdot5. Hit Enter. We get:

9. For State 7: Temp of reheating is T7 = 850 C, p7 = p6, mdot7 = 1 kg/s. Hit Enter. We get:

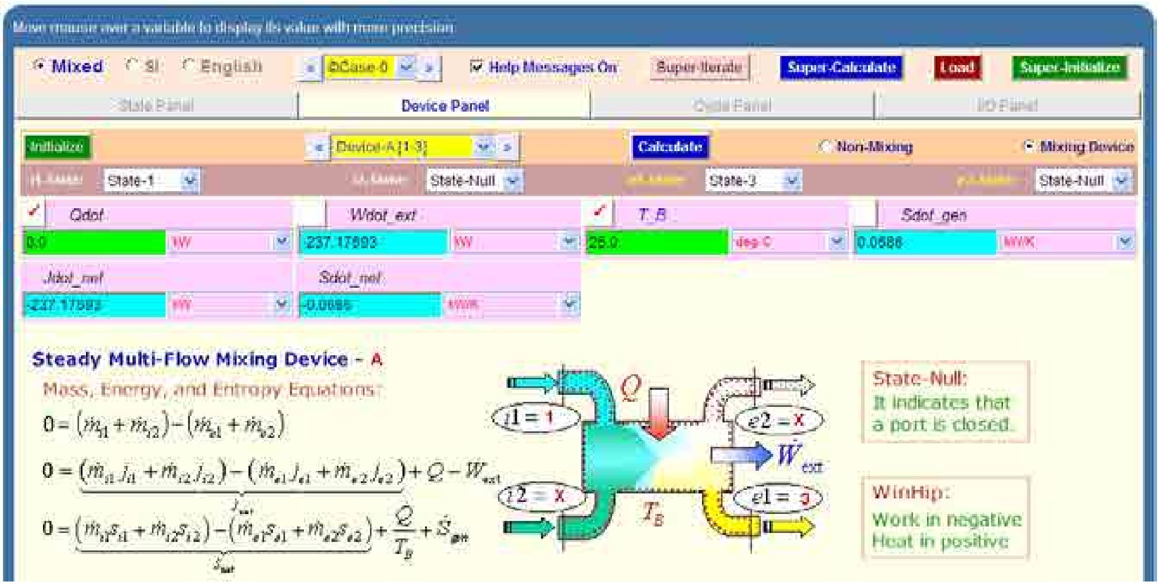


10. State 8: i.e. after isentropic expansion in second stage turbine. Enter p8 = p1, s8 = s7, mdot8 = 1 kg/s. Hit Enter. We get:



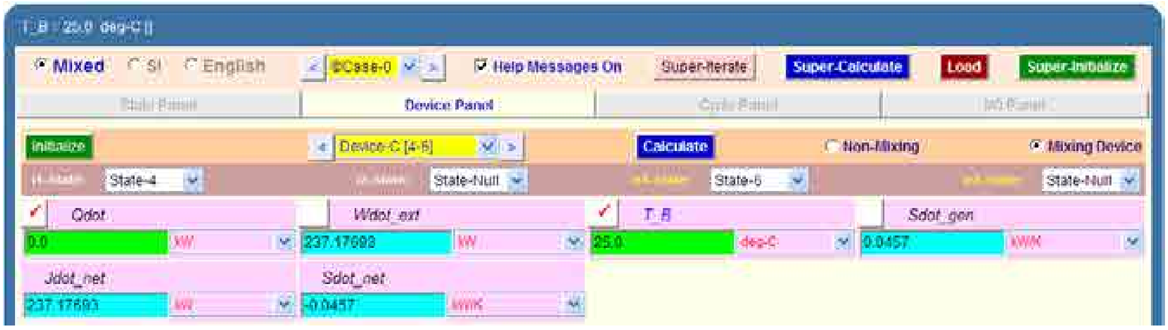
11. State 9: i.e. after actual expansion in second stage turbine. Enter p9 = p8, mdot9 = 1 kg/s, T9 = T7 – (T7 – T8) * 0.85 where 0.85 is the isentropic effcy of second stage turbine. Hit Enter. We get:

12. Now, go to Device panel. For device A, enter State 1 and State 3 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And Qdot1 = 0 since in this process there is no external heat transfer. Hit Enter. We get:

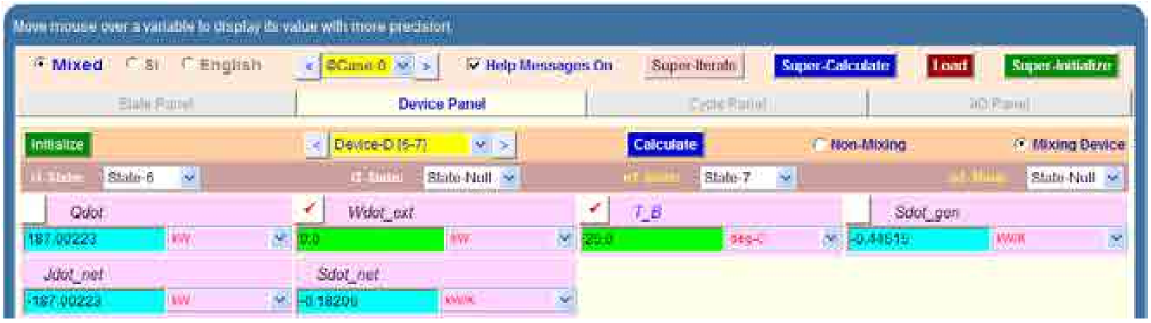


13. Similarly for Device B: enter State 3 and State 4 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process, no external work transfer occurs. Hit Enter. We get:

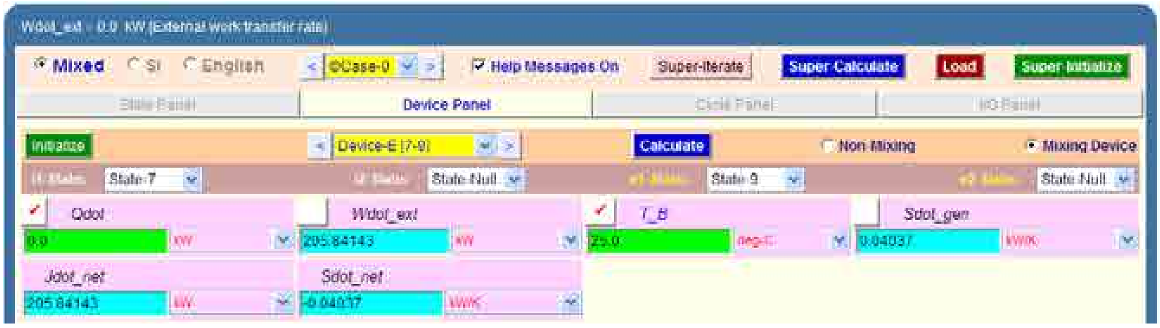
14. And, for Device C: enter State 4 and State 6 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Qdot = 0 since for this process, no external heat transfer occurs. Hit Enter. We get:



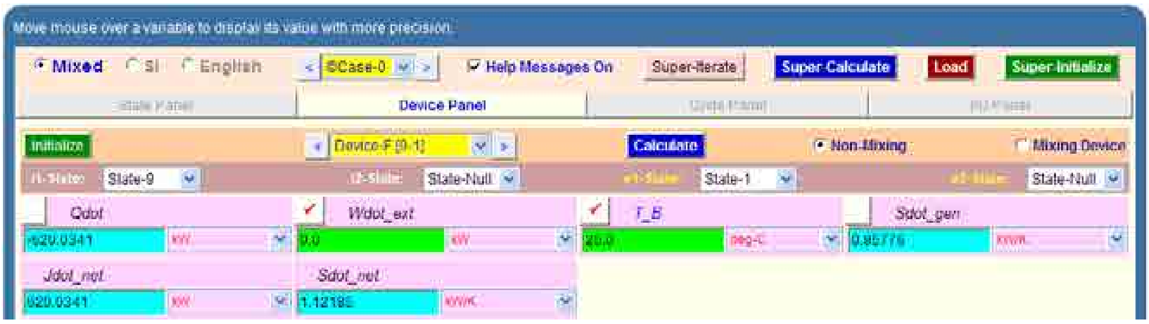
15. And, for Device D: enter State 6 and State 7 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process, no external work transfer occurs. Hit Enter. We get:



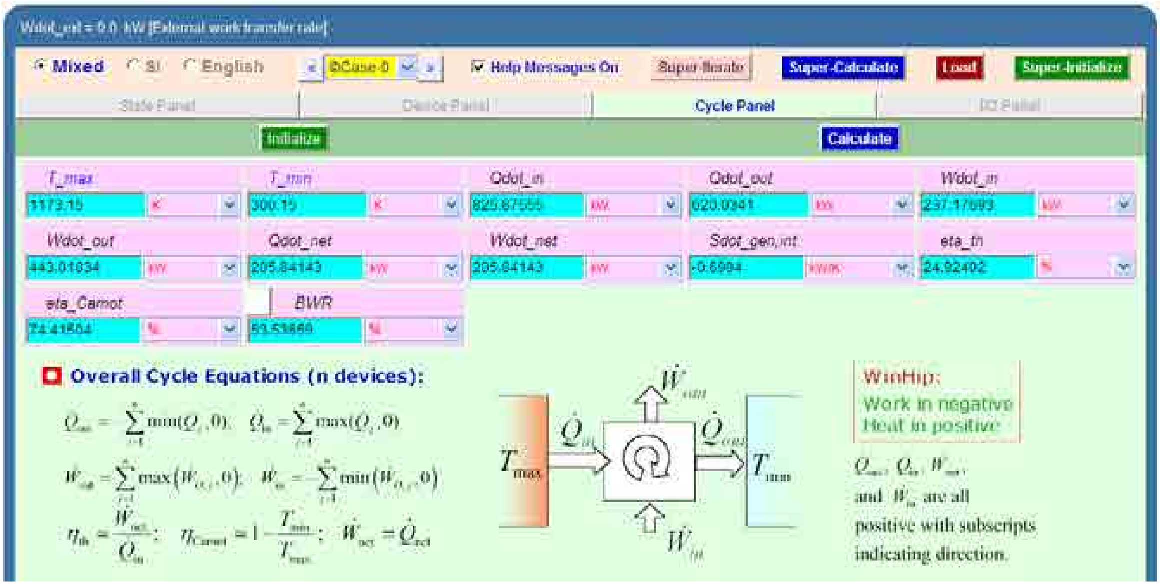
16. For Device E: enter State 7 and State 9 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Qdot = 0 since for this process, no heat transfer occurs. Hit Enter. We get:



17. For Device F: enter State 9 and State 1 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process, no external work transfer occurs. Hit Enter and SuperCalculate. We get:



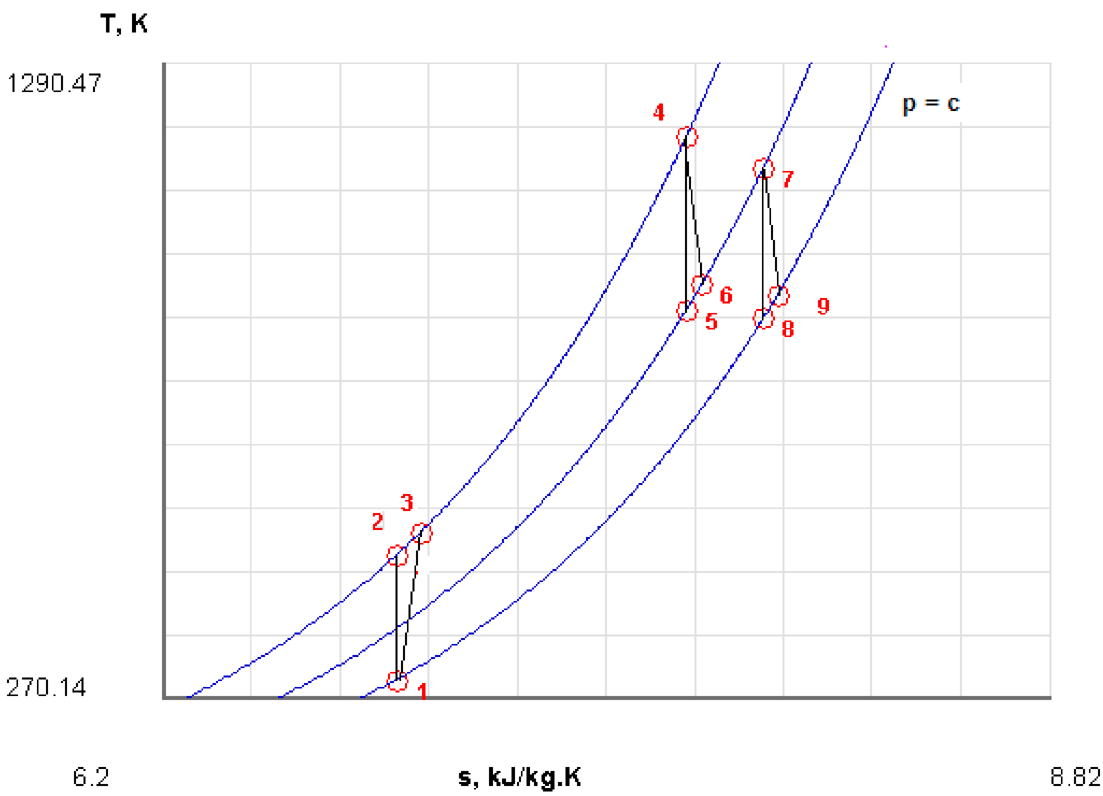
18. Now, go to cycle panel. It gives the major parameters of this cycle:



We observe that: Wdot_net = 205.84143 kW = Power developed …. Ans.

And, thermal efficiency = eta_th = 24.924% …. Ans.

19. From the Plots widget, choose T-s diagram, and we get:



20. And I/O panel gives the TEST code etc:

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

Daemon Path: Systems>Open>SteadyState>Specific>PowerCycle>PG-Model; v-10.ca08

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

States {

State-1: Air;

Given: { p1= 100.0 kPa; T1= 27.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 1.0 kg/s; }

State-2: Air;

Given: { p2= 600.0 kPa; s2= “s1” kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= 1.0 kg/s; }

State-3: Air;

Given: { p3= “p2” kPa; T3= “T1+(T2-T1)/0.85” deg-C; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= 1.0 kg/s; }

State-4: Air;

Given: { p4= “p3” kPa; T4= 900.0 deg-C; Vel4= 0.0 m/s; z4= 0.0 m; mdot4= 1.0 kg/s; }

State-5: Air;

Given: { T5= “T4-(T4-T6)/0.85” deg-C; s5= “s4” kJ/kg.K; Vel5= 0.0 m/s; z5= 0.0 m; mdot5= 1.0 kg/s; }

State-6: Air;

Given: { p6= “p5” kPa; T6= “T4-(T3-T1)” K; Vel6= 0.0 m/s; z6= 0.0 m; mdot6= 1.0 kg/s; }

State-7: Air;

Given: { p7= “p6” kPa; T7= 850.0 deg-C; Vel7= 0.0 m/s; z7= 0.0 m; mdot7= 1.0 kg/s; }

State-8: Air;

Given: { p8= “p1” kPa; s8= “s7” kJ/kg.K; Vel8= 0.0 m/s; z8= 0.0 m; mdot8= 1.0 kg/s; }

State-9: Air;

Given: { p9= “p8” kPa; T9= “T7-(T7-T8)*0.85” K; Vel9= 0.0 m/s; z9= 0.0 m; mdot9= 1.0 kg/s; }

}

Analysis {

Device-A: i-State = State-1; e-State = State-3; Mixing: true;

Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

Device-B: i-State = State-3; e-State = State-4; Mixing: true;

```
    Given: { Wdot_ext= 0.0 kW; T_B= 25.0 deg-C; }

    Device-C: i-State = State-4; e-State = State-6; Mixing: true;

    Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

    Device-D: i-State = State-6; e-State = State-7; Mixing: true;

    Given: { Wdot_ext= 0.0 kW; T_B= 25.0 deg-C; }

    Device-E: i-State = State-7; e-State = State-9; Mixing: true;

    Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

    Device-F: i-State = State-9; e-State = State-1; Mixing: false;

    Given: { Wdot_ext= 0.0 kW; T_B= 25.0 deg-C; }

   }

#----------------------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    300.2  0.8614      -84.13     2.01       6.893
#   2       600.0    501.0  0.2397      59.81      203.61     6.893
#   3       600.0    536.5  0.2566      85.22      239.18     6.962
#   4       600.0    1173.2 0.5611      541.38     878.06     7.747
#   5       232.99   895.1  1.1025      342.15     599.03     7.747
#   6       232.99   936.8  1.1539      372.03     640.88     7.793
#   7       232.99   1123.2 1.3834      505.55     827.88     7.975
#   8       100.0    881.8  2.5307      332.64     585.72     7.975
#   9       100.0    918.0  2.6346      358.58     622.04     8.015

#--------Property spreadsheet ends-------------------------------------------------------------------
```

 # Cycle Analysis Results:

\# Calculated: T_max= 1173.15 K; T_min= 300.15 K; Qdot_in= 825.87555 kW;

\# Qdot_out= 620.0341 kW; Wdot_in= 237.17693 kW; Wdot_out= 443.01834 kW;

\# Qdot_net= 205.84143 kW; **Wdot_net= 205.84143 kW**; Sdot_gen,int= -0.6904 kW/K;

\# **eta_th= 24.92402 %;** eta_Carnot= 74.41504 %; **BWR= 53.53659 %;**

==

Prob.2.28. A gas turbine plant draws in air at 1.013 bar, 10 C and has a pressure ratio of 5.5. The max. temp in the cycle is limited to 750 C. Compression is conducted in an un-cooled rotary compressor having an isentropic efficiency of 82% and expansion takes place in a turbine with an isentropic efficiency of 85%. A heat exchanger with an efficiency of 70% is fitted between the compressor outlet and combustion chamber. For an air flow of 40 kg/s, find: (i) overall effcy. of the cycle, (ii) turbine output, (iii) air-fuel ratio if the calorific value of fuel used is 45.22 MJ/kg. [VTU – ATD – Jan. 2009]

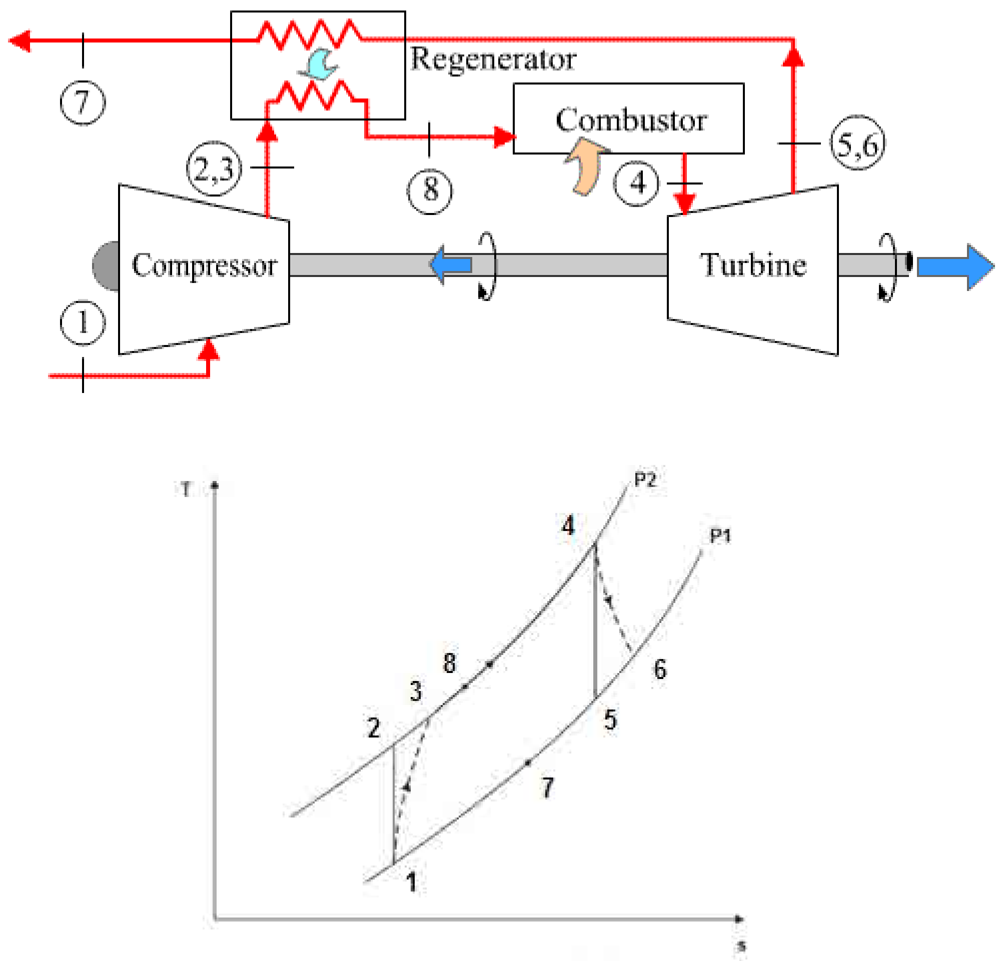


Fig. Prob.2.28 (a) and (b)

Process 1-2: Isentropic compression in Compressor

Process 1-3: Actual compression

Process 4-5: Isentropic expansion in Turbine

Process 4-6: Actual expansion in turbine

Process 3-8: heating in heat exchanger

Process 8-4: heat supply in combustion chamber

Process 6-7: cooling in heat exchanger

Working fluid: Air with const. sp. heat

TEST Solution:

We shall first do the calculations for air mass flow rate of 1 kg/s, and then it is quite easy to find out required quantities for an air flow rate of 40 kg/s.

Following are the steps:

Steps 1 and 2 are the same as for Prob.2.25.i.e. select 'Vapour Power and Gas Power cycles' daemon from the 'daemon tree' and, for material model chose PG model (i.e. const. sp. heat) and select air as the working substance.

3. Choose PG model (i.e. const. sp. heat), and select Air for working substance. Fill in the conditions for State 1, i.e. state at entry to compressor: p1= 1.013 bar, T1= 10 C, and mdot1 = 1 kg/s. Hit Enter. Immediately, all properties at State 1 are calculated:

4. For State 2: Enter p2 = 5.5 * p1, s2 = s1 (for isentropic process 1-2), and mdot2 = mdot1. Hit Enter. We get:

5. For State 3: It represents the state after actual compression, taking in to account the isentropic effcy. of compressor. Enter p3 = p2, T3 = T1 + (T2 – T1) / 0.82 where 0.82 is the compressor effcy. and mdot3 = mdot1. Hit Enter. We get:

6. For State 4: we have: p4 = p3. T4 = 750 C,

Now, to find T4:

Heat supplied by fuel results in increase of enthalpy of the air+fuel mixture reaching the Turbine inlet:

$$m_f \cdot CV = \left[(m_a + m_f)\cdot cp\cdot(T4 - T8)\right] = (m_a + m_f)\cdot(h4 - h8)$$

$$\text{i.e.} \quad CV = \left(\frac{m_a}{m_f} + 1\right)\cdot(h4 - h8)$$

$$\text{i.e.} \quad \frac{m_a}{m_f} = \frac{CV}{(h4 - h8)} - 1 \quad \text{...A/F ratio}$$

$$\text{And:} \quad mdot4 = (m_a + m_f) = m_a\cdot\left(1 + \frac{m_f}{m_a}\right) = mdot1\cdot\left(1 + \frac{h4 - h8}{CV - h4 + h8}\right)$$

Enter these values for State 4, and hit Enter. We get:

7. For State 5: Enter s5 = s4, mdot5 = mdot4, and p5 = p1.Hit Enter. We get:

8. For State 6: i.e. actual exit of turbine: Enter p6 = p5, T6 = T4 – 0.85*(T4 – T5) where 0.85 is the isentropic effcy of turbine. And mdot6 = mdot5. Hit Enter. We get:

9. For State 7: p7 = p1, mdot7 = mdot4.

To find h7: For the heat exchanger, we have:

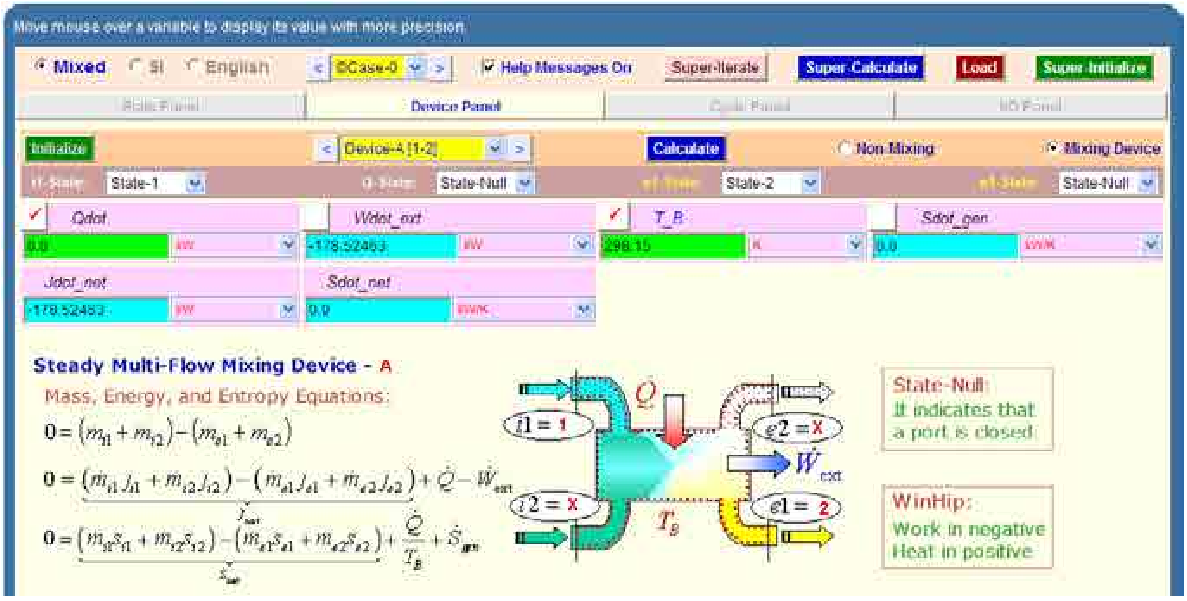
$$h8 - h3 = mdot6 \cdot (h6 - h7) \quad \text{...for air flow of 1 kg/s through compressor}$$

$$\text{i.e.} \quad h7 = h6 - \frac{h8 - h3}{mdot6}$$

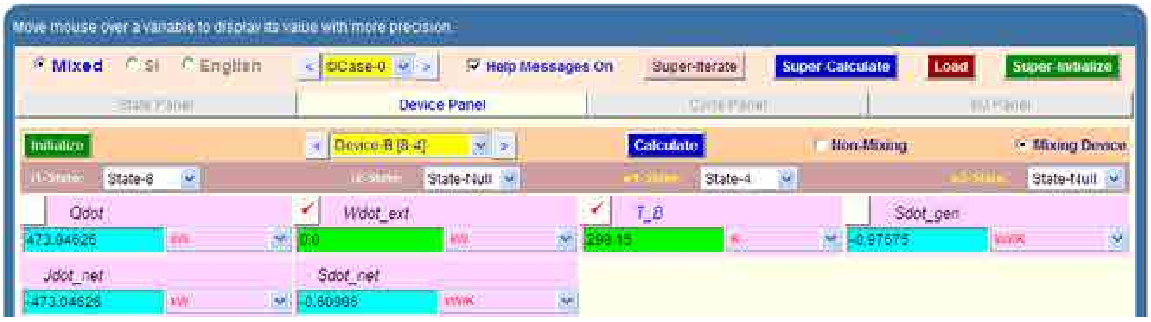
Enter these values as shown below, and hit Enter. We get (after SuperCalculating later):

10. State 8. i.e. exit of high pressure stream from heat exchanger. Enter p8 = p2, mdot8 = mdot4. And, T8 = T6 – 0.7 * (T6 – T3), where 0.7 is the heat exchanger effcy. Hit Enter. We get:

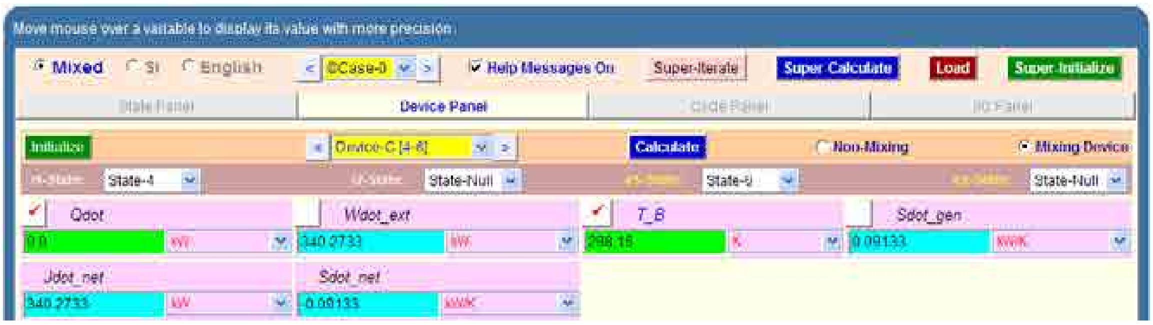
11. Now, go to Device panel. For device A, enter State 1 and State 2 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And Qdot1 = 0 since in this process is isentropic. Hit Enter. We get:



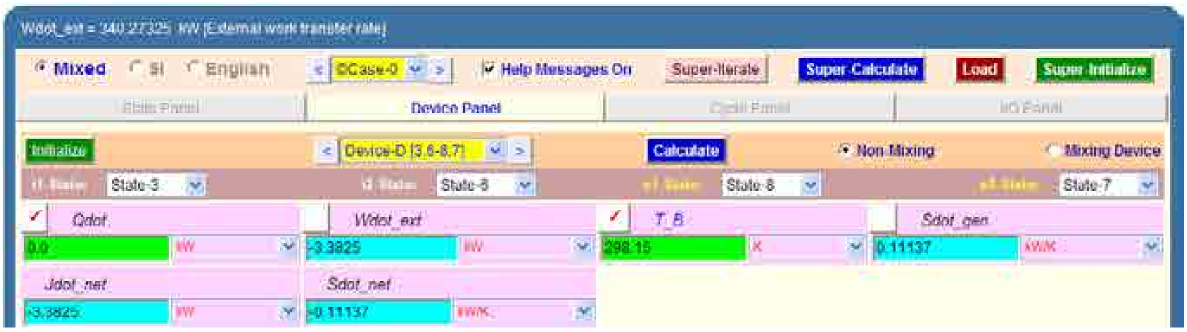
12. Similarly for Device B: enter State 8 and State 4 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process, no external work transfer occurs. Hit Enter. We get:



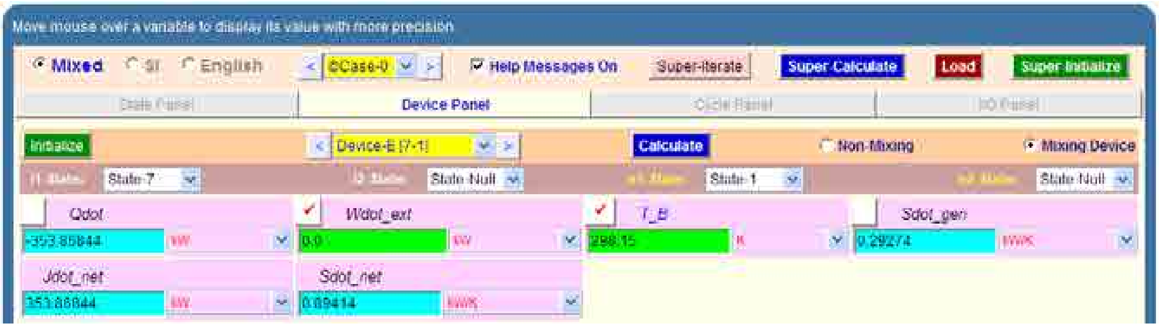
13. And, for Device C: enter State 4 and State 6 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Qdot = 0 since for this process, no external heat transfer occurs. Hit Enter. We get:



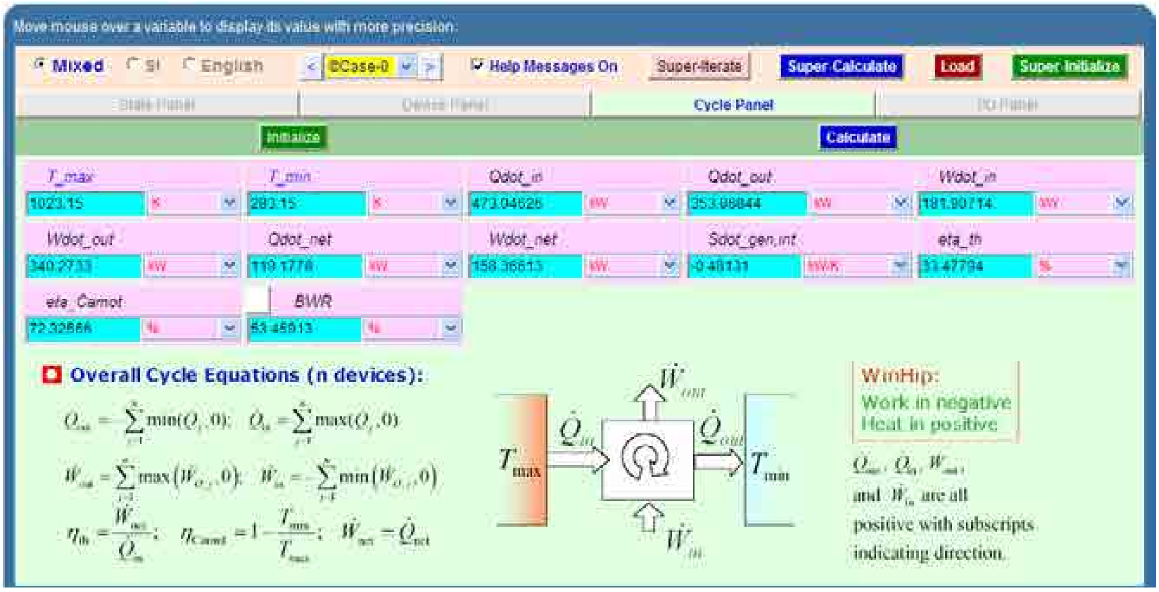
14. And, for Device D: This is the heat exchanger. Enter State 3 and State 8 for i1-state and e1-state respectively. Also, select state 6 for i2-state and state 7 for e2-state. And, Qdot = 0 since for this heat exchanger, no external heat transfer occurs. Hit Enter. We get:



15. For Device E: enter State 7 and State 1 for i1-state and e1-state respectively. Also, since there is only one stream, select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process, no work transfer occurs. Hit Enter. We get:



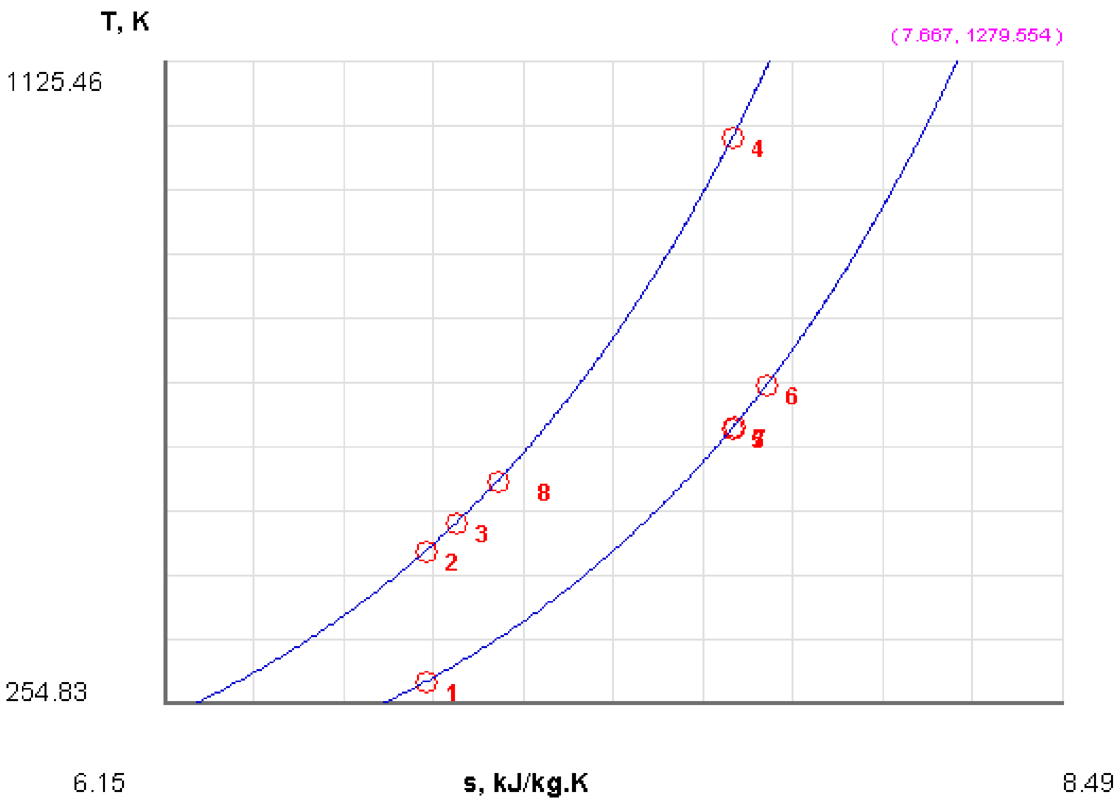
16. Now, go to cycle panel. It gives the major parameters of this cycle:



Note that Net work = Wdot_net = 158.366 kW/kg of air ….Ans.

Thermal efficiency = eta_th = 33.478% … Ans.

17. Go to Plots widget and get the T-s plot:



18. I/O panel gives the TEST code etc:

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

Daemon Path: Systems>Open>SteadyState>Specific>PowerCycle>PG-Model; v-10.ca08

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

States {

State-1: Air;

Given: { p1= 1.013 bar; T1= 10.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 1.0 kg/s; }

State-2: Air;

Given: { p2= "p1*5.5" bar; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= "mdot1" kg/s; }

State-3: Air;

Given: { p3= "p2" bar; T3= "T1+(T2-T1)/0.82" deg-C; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= "mdot1" kg/s; }

State-4: Air;

Given: { p4= "p3" bar; T4= 750.0 deg-C; Vel4= 0.0 m/s; z4= 0.0 m; mdot4= "mdot1*(1+(h4-h8)/(45220-h4+h8))" kg/s; }

State-5: Air;

Given: { p5= "p1" bar; s5= "s4" kJ/kg.K; Vel5= 0.0 m/s; z5= 0.0 m; mdot5= "mdot4" kg/s; }

State-6: Air;

Given: { p6= "p1" bar; T6= "T4-0.85*(T4-T5)" deg-C; Vel6= 0.0 m/s; z6= 0.0 m; mdot6= "mdot5" kg/s; }

State-7: Air;

```
      Given: { p7= "p1" bar; h7= "h6-(h8-h3)/mdot6" kJ/kg; Vel7= 0.0 m/s; z7= 0.0 m; }

      State-8: Air;

      Given: { p8= "p2" bar; T8= "T6-0.7*(T6-T3)" deg-C; Vel8= 0.0 m/s; z8= 0.0 m; }

     }

 Analysis {

      Device-A: i-State = State-1; e-State = State-2; Mixing: true;

      Given: { Qdot= 0.0 kW; T_B= 298.15 K; }

      Device-B: i-State = State-8; e-State = State-4; Mixing: true;

      Given: { Wdot_ext= 0.0 kW; T_B= 298.15 K; }

      Device-C: i-State = State-4; e-State = State-6; Mixing: true;

      Given: { Qdot= 0.0 kW; T_B= 298.15 K; }

      Device-D: i-State = State-3, State-6; e-State = State-8, State-7; Mixing: false;

      Given: { Qdot= 0.0 kW; T_B= 298.15 K; }

      Device-E: i-State = State-7; e-State = State-1; Mixing: true;

      Given: { 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	101.3	283.2	0.8022	-96.31	-15.05	6.831
#	2	557.15	461.1	0.2375	31.16	163.47	6.831
#	3	557.15	500.1	0.2576	59.14	202.66	6.913
#	4	557.15	1023.2	0.527	433.9	727.53	7.631
#	5	101.3	628.4	1.7802	151.03	331.36	7.631
#	6	101.3	687.6	1.9479	193.46	390.78	7.721
#	7	101.3	631.9	1.7902	153.58	334.93	7.637
#	8	557.15	556.3	0.2866	99.43	259.1	7.02

#--------Property spreadsheet ends--

 # Cycle Analysis Results:

Calculated: T_max= 1023.15 K; T_min= 283.15 K; Qdot_in= 473.04626 kW;

Qdot_out= 353.86844 kW; Wdot_in= 181.90714 kW; **Wdot_out= 340.2733 kW;**

Qdot_net= 119.1778 kW; **Wdot_net= 158.36613 kW**; Sdot_gen,int= -0.48131 kW/K;

eta_th= 33.47794 %; eta_Carnot= 72.32566 %; BWR= 53.45913 %;

#******CALCULATE VARIABLES: Type in an expression starting with an '=' sign ('= mdot1*(h2-h1)', '= sqrt(4*A1/PI)', etc.) and press the Enter key)*********

#A/F ratio:

=(45220 – h4 + h8) / (h4 – h8) = **95.534… Ans.**

#Turbine output:

=mdot4*(h4 – h6) = **340.273 kW/ kg of air …(same as Wdot_out in 'Cycle Analysis esults, above)**

Then, for 40 kg/s of air:

Tubine output = 340.273 * 40 = 13610.92 kW … Ans.

==

2.5 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
6. *Domkunndwar et al,* A course in Thermal Engineering, Dhanpat Rai & Co., New Delhi, 2000
7. *HIH Saravanamutto, G.F.C. Rogers & H. Cohen,* Gas Turbine Theory, 5th Ed., Pearson Ed. Ltd., 2001.

3 Vapour Power Cycles

Learning objectives:

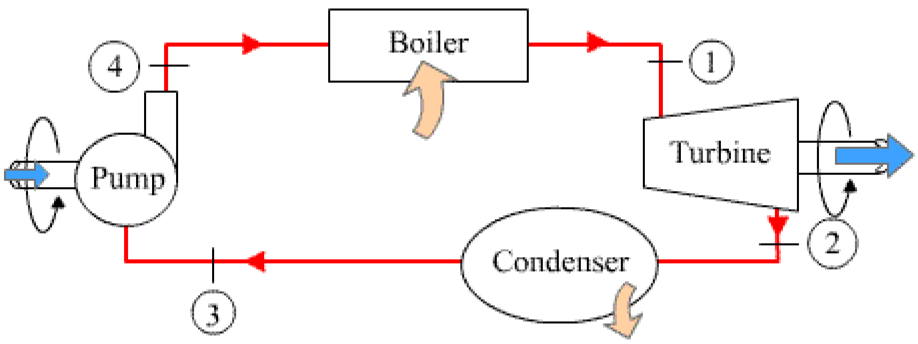
7. In this chapter, 'Vapour Power cycles' are analyzed with particular reference to Rankine cycle and its variations, used in Steam Power Plants.
8. Cycles dealt with are: Ideal Rankine cycle, Practical Rankine cycle with the isentropic efficiencies of turbine and pump considered, Reheat Rankine cycle (with both ideal and actual processes), Regenerative Rankine cycle and Reheat-Regenerative Rankine cycle.
9. Several useful Mathcad Functions are written for properties of steam in superheated and two-phase regions, since Mathcad does not have built-in Functions for steam, and are used in solving problems.
10. Also, many useful Functions/Procedures are written in EES for different variations of Rankine cycle.
11. Problems from University question papers and standard Text books are solved with Mathcad, EES and TEST.

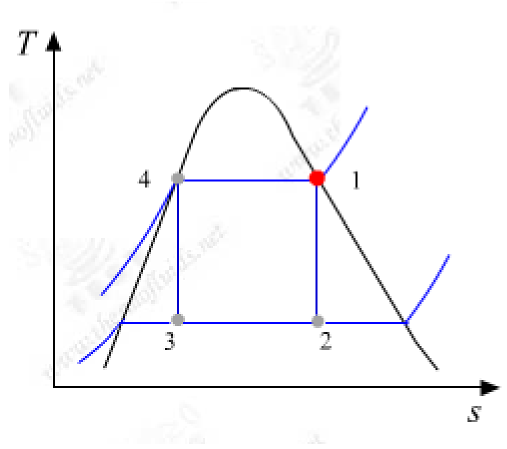
==

3.1 Definitions, Statements and Formulas used[1-7]:

While analyzing the following cycles, quantities of interest are: heat supplied in boiler (q_{in}, in kJ/kg), heat rejected in condenser (q_{out}, in kJ/kg), work output of turbine (w_t, in kJ/kg), work required by pump (w_{pump}, in kJ/kg), net work (w_{net}, in kJ/kg), thermal efficiency (η), Specific Steam consumption (SSC, in kg/kWh), and work ratio.

3.1.1 Carnot cycle for steam:





For Carnot cycle:

Process 1-2: Isentropic expansion in turbine

Process 2-3: Isothermal heat rejection in condenser

Process 3-4: Isentropic compression in pump

Process 4-1: Isothermal heat addition in boiler

Then, per unit mass of steam circulating, we have, in units of kJ/kg:

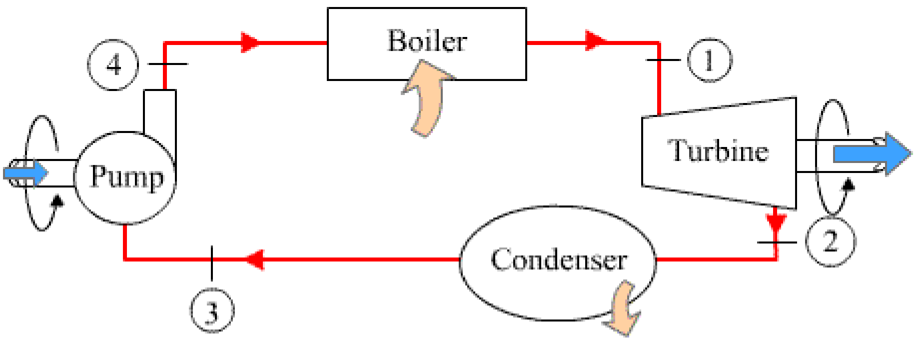
$q_{in} := h1 - h4$ $\qquad \eta_{carnot} = \frac{T1 - T2}{T1} = 1 - \frac{q_{out}}{q_{in}}$ With temp in Kelvin

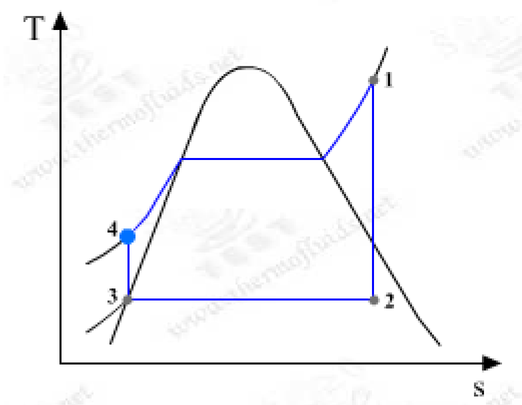
$q_{out} := h2 - h3$ $\qquad \eta := \frac{w_{net}}{q_{in}} \cdot 100$

$w_T := h1 - h2$ $\qquad SSC := \frac{3600}{w_{net}}$ Work Ratio: $WR := \frac{w_{net}}{w_T}$

$w_{net} := w_T - w_p$

3.1.2 Ideal Rankine cycle for steam:





Here, we have, per kg of steam circulating:

$q_{in} := h1 - h4$

$q_{out} := h2 - h3$

$w_T := h1 - h2$

$w_{net} := w_T - w_p$

$\eta := \frac{w_{net}}{q_{in}} \cdot 100$

Pump work: (with sp. vol = vf3 in m^3/kg, P1, P2 in bar):

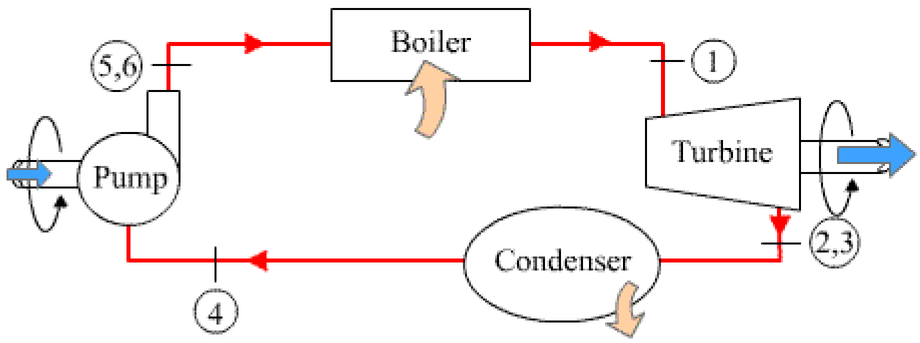
$w_p := vf3 \cdot (P1 - P2) \cdot 10^2$ kJ...pump work

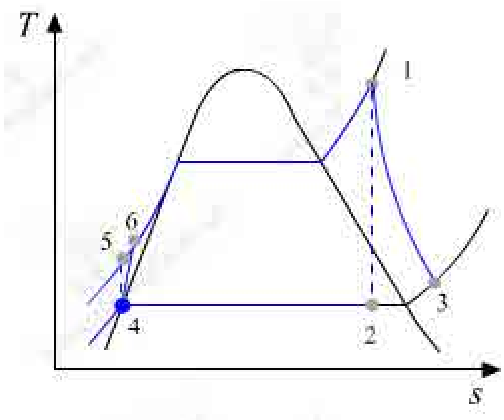
$h4 := h3 + w_p$

$SSC := \frac{3600}{w_{net}}$

Work Ratio: $WR := \frac{w_{net}}{w_T}$

3.1.3 Actual Rankine cycle for steam:





Here:

Process 1-2: Ideal isentropic expansion in turbine

Process 1-3: Actual expansion in turbine

Process 4-5: Ideal isentropic compression in pump

Process 4-6: Actual compression in pump

$$\eta_{turb} := \frac{h1 - h3}{h1 - h2}$$

$$\eta_{pump} = \frac{h5 - h4}{h6 - h4}$$

$$q_{in} = h1 - h6$$

$$q_{out} = h3 - h4$$

$$w_T = h1 - h3$$

Pump work, w_p_ideal (with sp. vol = vf3 in m^3/kg, P1, P2 in bar), in kJ/kg:

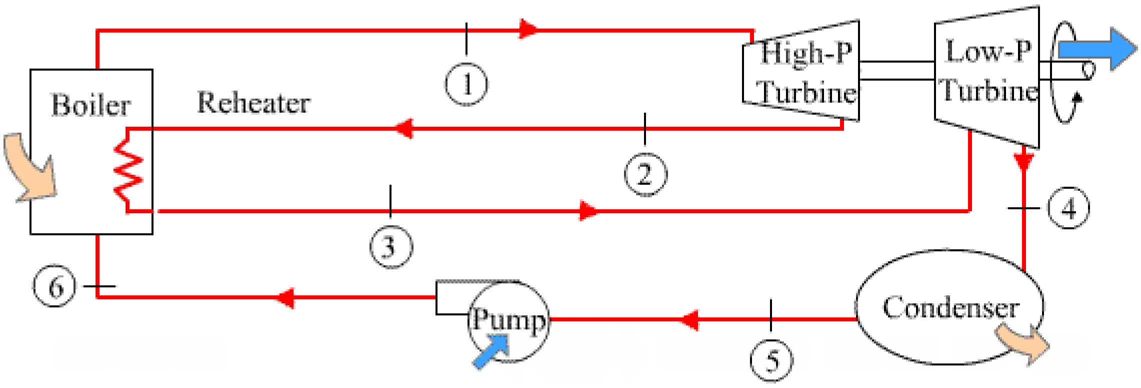
$$w_{p\_ideal} = vf4 \cdot (P1 - P2) \cdot 10^2 \quad \text{kJ/kg}$$

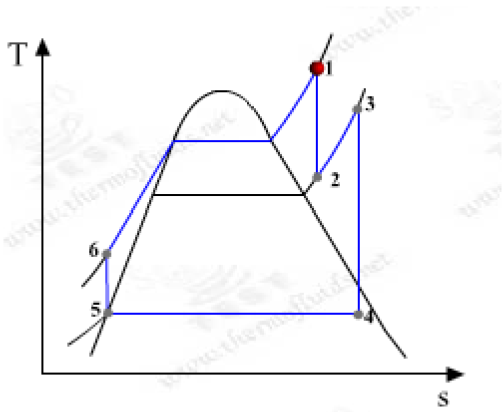
$$h5 = h4 + w_{p\_ideal} \qquad h6 = h4 + \frac{(h5 - h4)}{\eta_{pump}} \qquad w_{p\_actual} = h6 - h4$$

$$\eta = \frac{w_{net}}{q_{in}} \cdot 100$$

$$SSC = \frac{3600}{w_{net}} \quad \text{kg/kWh}$$

3.1.4 Reheat Rankine cycle, with ideal processes for steam:





For this case, we have:

$$Q_{in} := (h1 - h6) + (h3 - h2)$$

$$Q_{out} := h4 - h5$$

$$W_P := vf5 \cdot (P6 - P5) \cdot 10^2 \quad kJ/kg$$

$$h6 := h5 + W_P$$

$$W_T := (h1 - h2) + (h3 - h4)$$

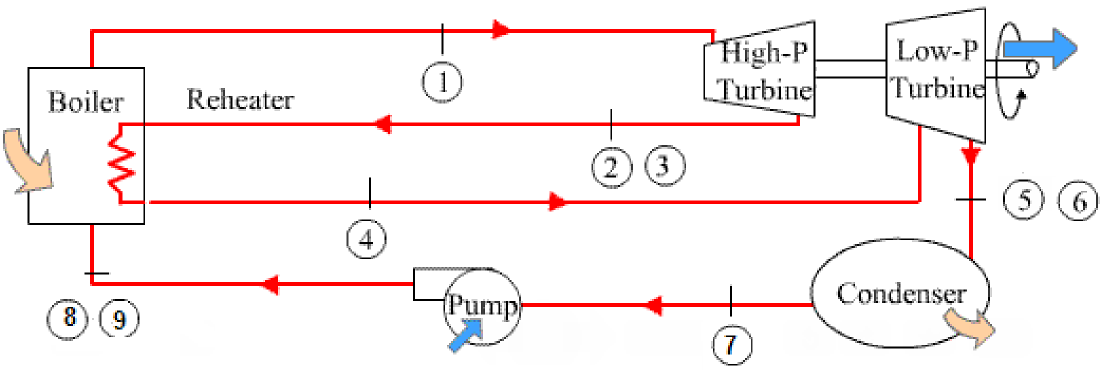
$$W_{net} := W_T - W_P$$

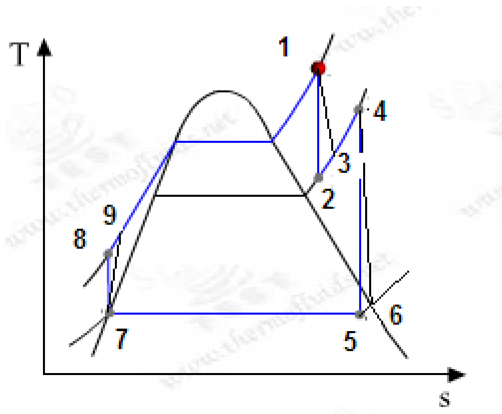
$$\eta := \frac{W_{net}}{Q_{in}} \cdot 100$$

$$SSC := \frac{3600}{W_{net}}$$

Work Ratio: $WR := \frac{W_{net}}{W_T}$

3.1.5 Actual, Reheat Rankine cycle for steam:





Various parameters are calculated as:

$$q_{in} = (h1 - h9) + (h4 - h3)$$

$$\eta_{pump} = \frac{h8 - h7}{h9 - h7}$$

$$q_{out} = h6 - h7$$

$$\eta_{turb1} = \frac{h1 - h3}{h1 - h2}$$

$$w_{turb} = (h1 - h3) + (h4 - h6)$$

$$\eta_{turb2} = \frac{h4 - h6}{h4 - h5}$$

$$h8 = h7 + vf7 \cdot (P1 - P5) \cdot 10^2$$

$$w_p = h9 - h7$$

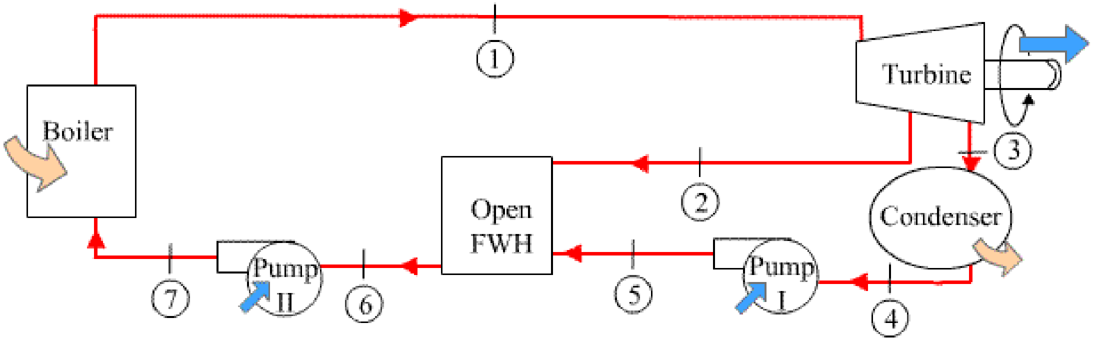
$$\eta = \frac{W_{net}}{Q_{in}} \cdot 100$$

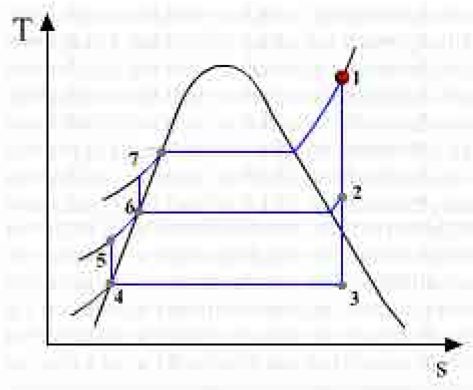
$$w_{net} = W_{turb} - w_p$$

$$SSC = \frac{3600}{W_{net}}$$

Work Ratio: $WR = \frac{w_{net}}{w_{turb}}$

3.1.6 Regenerative Rankine cycle, with ideal processes for steam:





Various parameters are calculated as:

$q_{in} = h1 - h7$

$q_{out} = (h3 - h4)\cdot(1 - y)$

$w_T = (h1 - h2) + (h2 - h3)\cdot(1 - y)$

$w_{P1} = (h5 - h4)\cdot(1 - y)$

$w_{P2} = h7 - h6$

$w_{net} = w_T - (w_{P1} + w_{P2})$

$y = \frac{h6 - h5}{h2 - h5}$

$h7 = h6 + vf6\cdot(P7 - P6)\cdot 10^2$

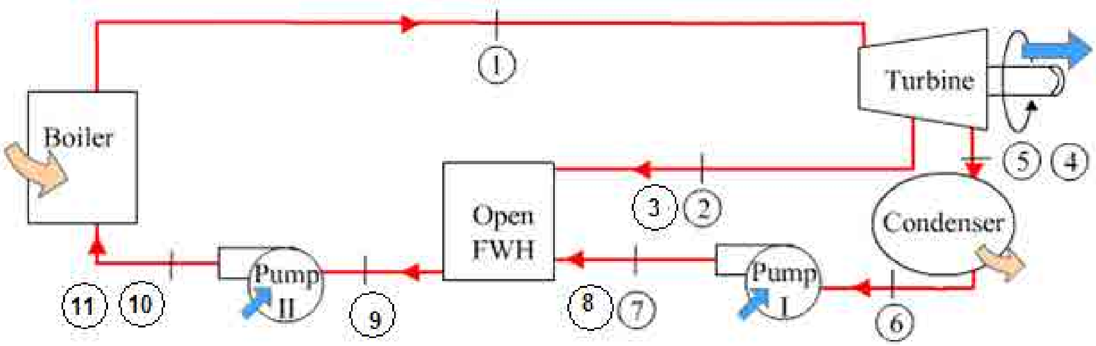
$h5 = h4 + vf4\cdot(P5 - P4)\cdot 10^2$

$\eta = \frac{w_{net}}{q_{in}}\cdot 100$

$SSC = \frac{3600}{w_{net}}$

Work Ratio: $WR = \frac{w_{net}}{w_T}$

3.1.7 Actual, Regenerative Rankine cycle for steam:



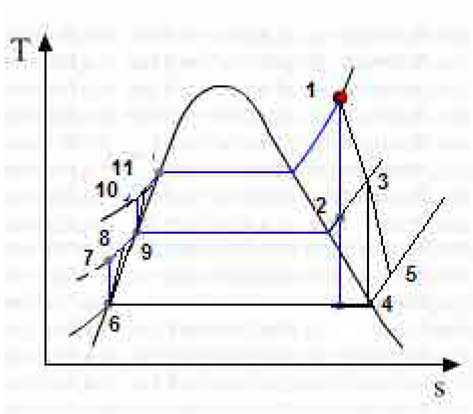


Fig.Prob.3.3.11 (a) Actual regenerative Rankine cycle with one open FWH, and (b) T-s diagram

Various quantities are calculated as:

$q_{in} = h1 - h11$

$y = \frac{h9 - h8}{h3 - h8}$

$q_{out} = (h5 - h6)\cdot(1 - y)$

$h7 = h6 + vf6\cdot(P7 - P6)\cdot 10^2$

$w_T = (h1 - h3) + (h3 - h5)\cdot(1 - y)$

$h10 = h9 + vf9\cdot(P10 - P9)\cdot 10^2$

$w_{P1} = (h8 - h6)\cdot(1 - y)$

$\eta = \frac{w_{net}}{q_{in}}\cdot 100$

$w_{P2} = h11 - h9$

$SSC = \frac{3600}{w_{net}}$

$w_{net} = w_T - (w_{P1} + w_{P2})$

Work Ratio: $WR = \frac{w_{net}}{w_T}$

==

3.2 Problems solved with Mathcad:

Note:

Mathcad does not have built-in functions for Water/Steam. So, generally, while solving problems on Rankine, cycle which uses Water/Steam as working substance, we have to refer to steam tables often to get properties of water/steam at various state points.

However, in our case, first, along with Mathcad, we shall use the *free* software SteamTab of M/s ChemicaLogic to get properties of water/steam.

For more information on SteamTab, see Chapter 1 of Part-I of the *free* e-book "**Basic Thermodynamics: Software Solutions**", by the same author, available from www.bookboon.com.

Next, we shall develop few simple Mathcad Functions based on published Steam Tables (Ref: TEST software, www.thermofluids.net). These Functions use the built-in linear interpolation function 'linterp' to get properties from the Tables.

Prob.3.2.1 A steam power plant works on Rankine cycle between pressure ratio 20 bar and 0.05 bar. Steam supplied to the turbine is dry, saturated. Find thermal effcy., work ratio and Specific Steam Consumption (SSC). What would be the efficiency and work ratio in case of Carnot cycle operating in the same pressure limits? [M.U.]

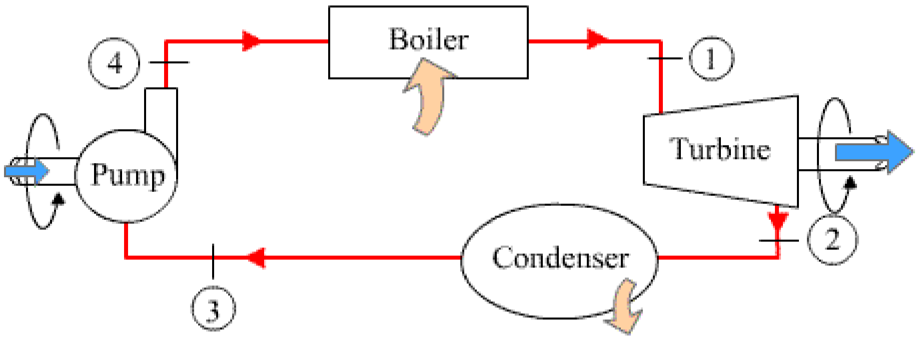


Fig.Prob.3.2.1 (a).Schematic diagram of simple, ideal Rankine cycle

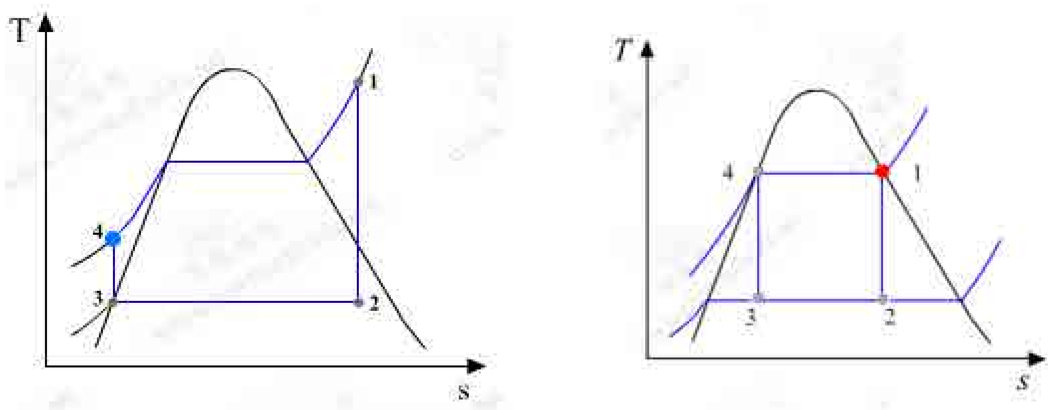


Fig.Prob.3.2.1 (b) and (c).T-s diagram of simple, ideal Rankine cycle, and of Carnot cycle

Mathcad Solution:

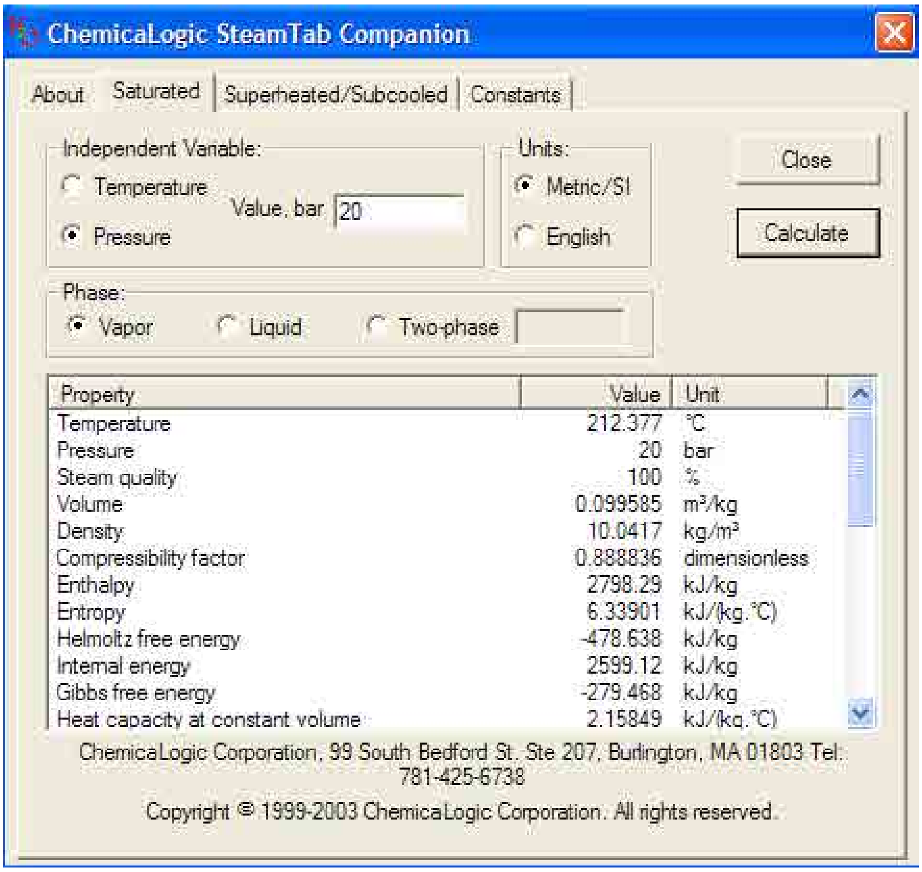
Fig.(a) above shows the schematic diagram, and fig. (b) shows the ideal Rankine cycle on the T-s diagram. (Ref. [7] for figures).

We need properties of Water/Steam at the salient points, and we shall use SteamTab of ChemicaLogic to get the properties.

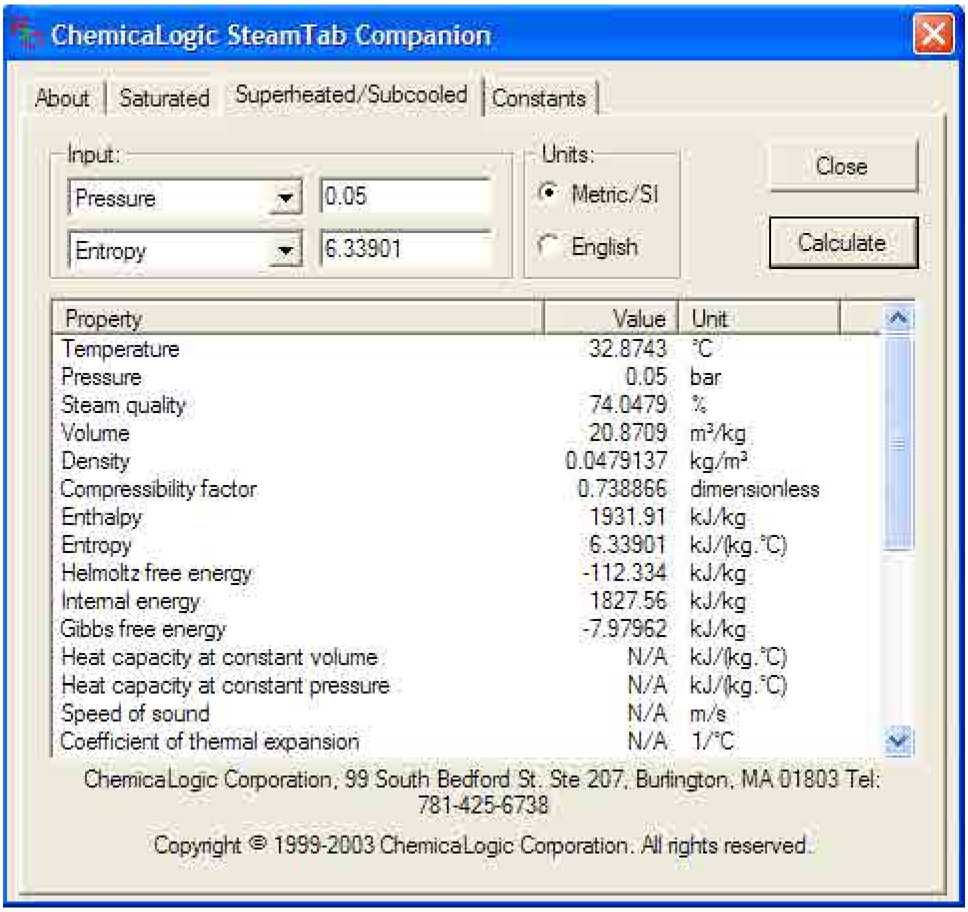
We have:

State 1: Inlet to turbine: P1 = 20 bar, T1 = Tsat, sat. vap.

From **'Saturated – vapor' Tab** of SteamTab, for sat. vap. **we get: T1 = 212.377 C, h1 = 2798.29 kJ/kg, s1 = 6.33901 kJ/kg.C**

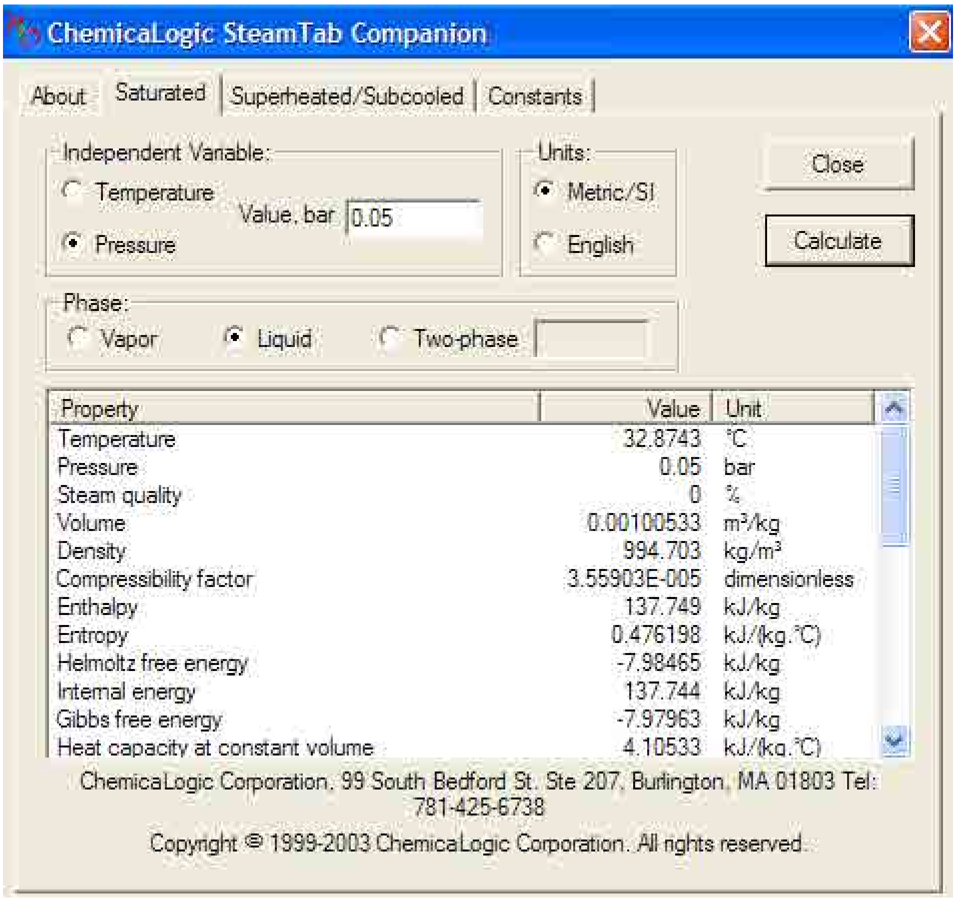

ChemicaLogic SteamTab Companion
About
Saturated
Superheated/Subcooled
Constants
Independent Variable:
Temperature
Pressure
Value, bar
20
Units:
Metric/SI
English
Close
Calculate
Phase:
Vapor
Liquid
Two-phase
Property | Value | Unit
Temperature 212.377 °C
Pressure 20 bar
Steam quality 100 %
Volume 0.099585 m³/kg
Density 10.0417 kg/m³
Compressibility factor 0.888836 dimensionless
Enthalpy 2798.29 kJ/kg
Entropy 6.33901 kJ/(kg.°C)
Helmoltz free energy -478.638 kJ/kg
Internal energy 2599.12 kJ/kg
Gibbs free energy -279.468 kJ/kg
Heat capacity at constant volume 2.15849 kJ/(kg.°C)
ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738
Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

State 2: Exit of turbine and inlet to condenser: P2 = 0.05 bar, s2 = s1 = 6.33901 kJ/kg.C. Entering these values, we get from **'Superheated/Subcooled' Tab** of SteamTab:



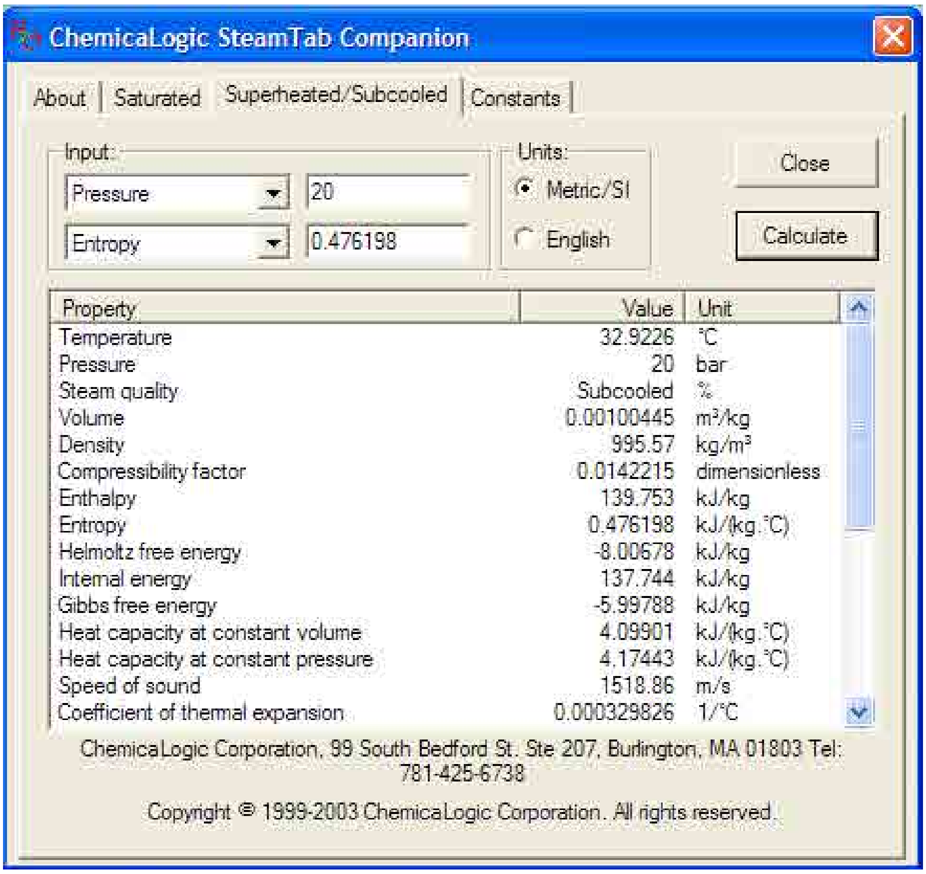
We get: we get: T2 = 32.8743 C, h2 = 1931.91 kJ/kg, s2 = 6.33901 kJ/kg.C, quality, x2 = 74.0479% = 0.7405.

State 3: Exit of condenser and inlet to Pump: P3 = 0.05 bar, sat.liq. Entering these values, we get from **'Saturated . liquid'** Tab of SteamTab:



We get: h3 = 137.749 kJ/kg, T3 = T2 = 32.8743C, vf3 = 0.00100533 m^3/kg

State 4: Exit of Pump and inlet to boiler: P4 = 20 bar, s4 = s3 = 0.476198 kJ/kg.C. Then, from **'Superheated/Subcooled' Tab** of SteamTab:



We get: h4 = 139.753 kJ/kg.

Now that we have got properties at the four salient points, we can complete the calculations:

Data:

$P1 := 20$ bar $P2 := 0.05$ bar $P3 := 0.05$ bar $P4 := P1$

Calculations:

From SteamTab:

$h1 := 2798.29$ kJ/kg $h2 := 1931.91$ kJ/kg $h3 := 137.749$ kJ/kg $h4 := 139.753$ kJ/kg

$x2 := 0.7405$ $vf3 := 0.00100533$ m^3/kg

Therefore:

$Q_{in} := h1 - h4$ i.e. $Q_{in} = 2.659 \times 10^3$ **kJ/kg .... heat supplied**

$Q_{out} := h2 - h3$ i.e. $Q_{out} = 1.794 \times 10^3$ **kJ/kg .... heat rejected**

$W_T := h1 - h2$ i.e. $W_T = 866.38$ kJ/kg.......Turbine work output

$W_P := h4 - h3$ i.e. $W_P = 2.004$ kJ/kg......Pump work required

Note: Pump work is also calculated as: $vf3 \cdot (P1 - P2) \cdot 100 = 2.006$ kJ...matches with the value already obtained.

$W_{net} := W_T - W_P$ i.e. $W_{net} = 864.376$ kJ/kg.... Net work output

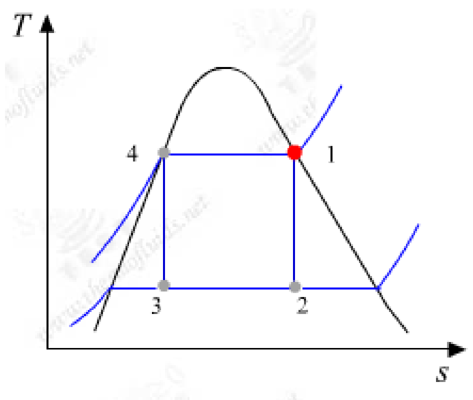
$\eta := \frac{W_{net}}{Q_{in}} \cdot 100$ i.e. $\eta = 32.513$ %, ...Thermal effcy....Ans.

$SSC := \frac{3600}{W_{net}}$ i.e. $SSC = 4.165$ kg/kWh... Specific steam consumption....Ans.

Work Ratio: $WR := \frac{W_{net}}{W_T}$ i.e. $WR = 0.998$ Work ratio.....Ans.

For Carnot cycle:

We have the T-s diagram:

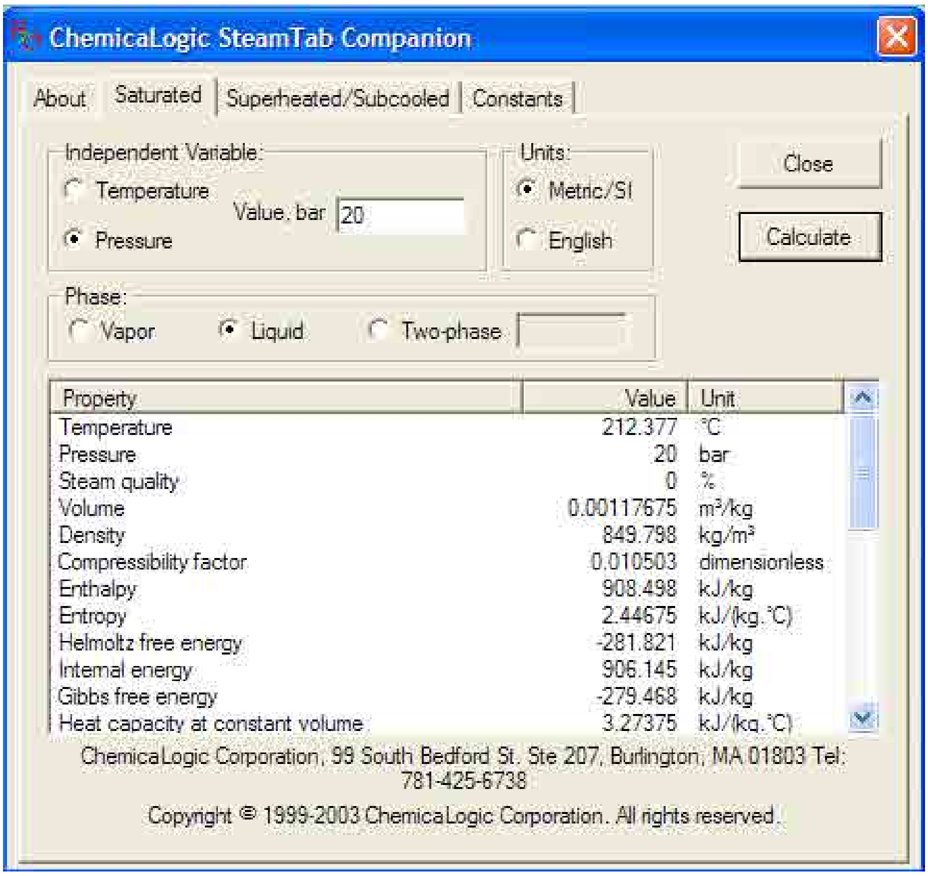


Properties at State points 1 and 2 are already obtained.

Get properties at State 4 and State 3:

State 4: P4 = P1 = 20 bar, sat. liquid state.

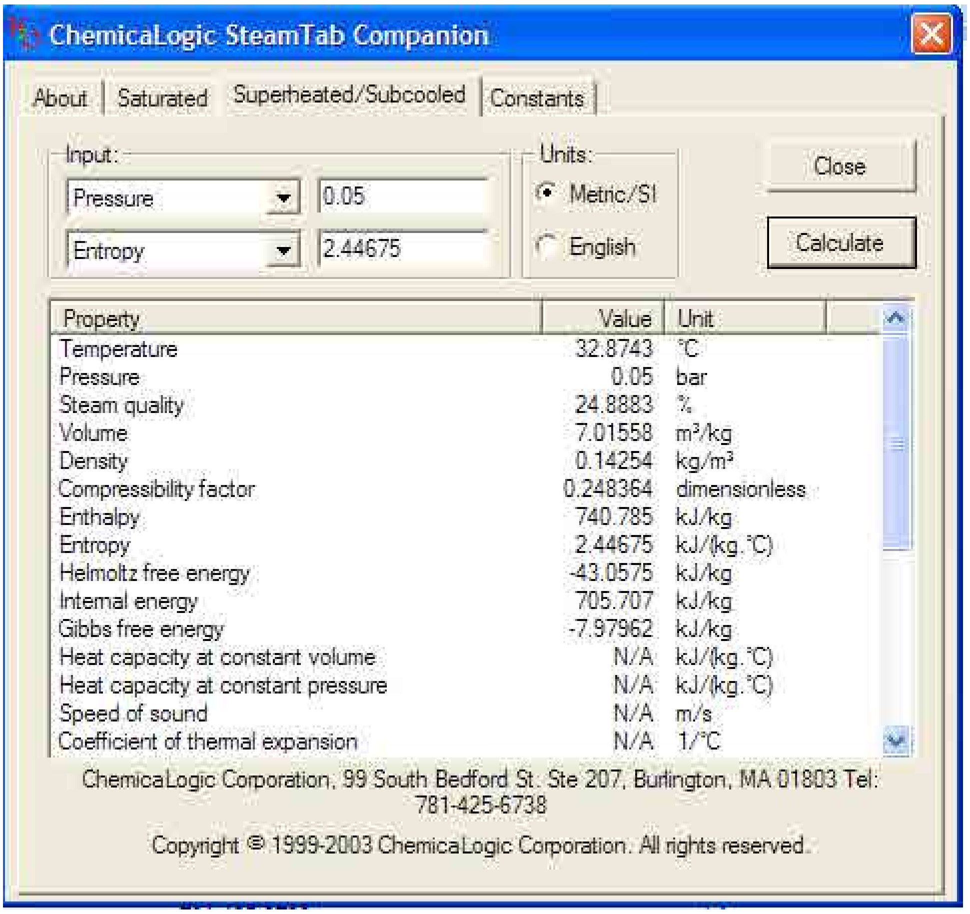
From 'Saturated – liquid' tab of SteamTab:


ChemicaLogic SteamTab Companion
About
Saturated
Superheated/Subcooled
Constants
Independent Variable:
Temperature
Pressure
Value, bar 20
Units:
Metric/SI
English
Close
Calculate
Phase:
Vapor
Liquid
Two-phase
Property | Value | Unit
Temperature 212.377 °C
Pressure 20 bar
Steam quality 0 %
Volume 0.00117675 m³/kg
Density 849.798 kg/m³
Compressibility factor 0.010503 dimensionless
Enthalpy 908.498 kJ/kg
Entropy 2.44675 kJ/(kg.°C)
Helmoltz free energy -281.821 kJ/kg
Internal energy 906.145 kJ/kg
Gibbs free energy -279.468 kJ/kg
Heat capacity at constant volume 3.27375 kJ/(kg.°C)
ChemicaLogic Corporation, 99 South Bedford St. Ste 207, Burlington, MA 01803 Tel: 781-425-6738
Copyright © 1999-2003 ChemicaLogic Corporation. All rights reserved.

We get: h4 = 908.498 kJ/kg, s4 = 2.44675 kJ/kg.C

State 3: P3 = 0.05 bar, s3 = s4.

Entering these values in **'Superheated/subcooled' tab of SteamTab**:



i.e. h3 = 740.785 kJ/kg.C, quality, x3 = 24.8883% = 0.2489

Now, complete the calculations in Mathcad:

For Carnot Cycle:
============

$T_h := 212.377 + 273$ K $T_c := 32.874 + 273$ K

$\eta_{carnot} := \frac{T_h - T_c}{T_h}$ i.e. $\eta_{carnot} = 0.37$ ...Thermal effcy...Ans.

Work of Turbine remains same. Now, compression is from point 3 to point 4.

From SteamTab:

$h3 := 740.785$ kJ/kg.... corresp. to 0.05 bar and s3 = s4

$h4 := 908.498$ kJ/kg

Therefore:

$W_P := h4 - h3$ i.e. $W_P = 167.713$ **kJ/kg.....New pump work.... Ans.**

Work Ratio: $WR_{carnot} := \frac{W_T - W_P}{W_T}$

i.e. $WR_{carnot} = 0.806$ **... ..Ans.**

===

Prob.3.2.2. Write Mathcad programs/Functions for properties of steam:

As mentioned earlier, our Mathcad Functions are based on published Steam Tables (Ref: TEST software, www.thermofluids.net).

There are separate Tables for Superheated steam and for Saturated steam.

First, for Superheated steam:

For each pressure, the Table is copied as a matrix in Mathcad, each column is extracted as a vector, and linear interpolation is done for intermediate values.

Functions are written for the following pressures: 0.1, 0.5, 1.0, 5, 10, 14, 16, 20, 25, 30, 40, 60, 70, 80, 100, 150, 200 and 250 bar.

A sample set of Functions written for a pressure of 5 bar are shown below:

Steam at 5 bar:

T.....deg. C
v....m^3/kg
u, h....kJ/kg;
s...kJ/kg.K.....deg. C

S5 :=

T	v	u	h	s
151.86	0.3749	2561.2	2748.7	6.8213
200	0.4249	2642.9	2855.4	7.0592
250	0.4744	2723.5	2960.7	7.2709
300	0.5226	2802.9	3064.2	7.4599
350	0.5701	2882.6	3167.7	7.6329
400	0.6173	2963.2	3271.9	7.7938
500	0.7109	3128.4	3483.9	8.0873
600	0.8041	3299.6	3701.7	8.3522
700	0.8969	3477.5	3925.9	8.5952
800	0.9896	3662.1	4156.9	8.8211
900	1.0822	3853.6	4394.7	9.0329
1000	1.1747	4051.8	4639.1	9.2328
1100	1.2672	4256.3	4889.9	9.4224
1200	1.3956	4466.8	5146.6	9.6029
1300	1.4521	4682.5	5408.6	9.7749

$temp5 := S5^{\langle 0 \rangle}$ $\quad$ $length(temp5) = 15$

$spvol5 := S5^{\langle 1 \rangle}$ $\quad$ $enth5 := S5^{\langle 3 \rangle}$ $\quad$ $entrop5 := S5^{\langle 4 \rangle}$

$HSTEAM5B(T) := linterp(temp5, enth5, T)$ $\quad$ ex: $\quad$ $HSTEAM5B(250) = 2.961 \times 10^3$

$SSTEAM5B(T) := linterp(temp5, entrop5, T)$ $\quad$ ex: $\quad$ $SSTEAM5B(250) = 7.271$

Then, all the Functions written for the different pressures are combined into a single program with linear interpolation applied for any desired pressure:

This Function returns enthalpy (h, kJ/kg) and entropy (s, kJ/kg.C) when pressure (P, in bar) and temp (T, in C) are input.

```
h_and_s_SuperheatSteam(P,T) := | return "P should be between 0.01 bar and 250 bar"  if P < 0.01 ∨ P > 250
                               | return "T should be between 45.81 C and 1300 C"  if T < 45.81 ∨ T > 1300
                               | if P ≥ 0.1 ∧ P < 0.5
                               |   h ← HSTEAM01B(T) + (P − 0.1)/(0.5 − 0.1)·(HSTEAM05B(T) − HSTEAM01B(T))
                               |   s ← SSTEAM01B(T) + (P − 0.1)/(0.5 − 0.1)·(SSTEAM05B(T) − SSTEAM01B(T))
                               | if P ≥ 0.5 ∧ P < 1
                               |   h ← HSTEAM05B(T) + (P − 0.5)/(1 − 0.5)·(HSTEAM1B(T) − HSTEAM05B(T))
                               |   s ← SSTEAM05B(T) + (P − 0.5)/(1 − 0.5)·(SSTEAM1B(T) − SSTEAM05B(T))
                               | if P ≥ 1 ∧ P < 5
                               |   h ← HSTEAM1B(T) + (P − 1)/(5 − 1)·(HSTEAM5B(T) − HSTEAM1B(T))
                               |   s ← SSTEAM1B(T) + (P − 1)/(5 − 1)·(SSTEAM5B(T) − SSTEAM1B(T))
                               | if P ≥ 5 ∧ P < 10
                               |   h ← HSTEAM5B(T) + (P − 5)/(10 − 5)·(HSTEAM10B(T) − HSTEAM5B(T))
                               |   s ← SSTEAM5B(T) + (P − 5)/(10 − 5)·(SSTEAM10B(T) − SSTEAM5B(T))
                               | if P ≥ 10 ∧ P < 14
                               |   h ← HSTEAM10B(T) + (P − 10)/(14 − 10)·(HSTEAM14B(T) − HSTEAM10B(T))
                               |   s ← SSTEAM10B(T) + (P − 10)/(14 − 10)·(SSTEAM14B(T) − SSTEAM10B(T))
```

$$\text{if } P \geq 14 \wedge P < 16$$

$$h \leftarrow HSTEAM14B(T) + \frac{(P-14)}{(16-14)} \cdot (HSTEAM16B(T) - HSTEAM14B(T))$$

$$s \leftarrow SSTEAM14B(T) + \frac{(P-14)}{(16-14)} \cdot (SSTEAM16B(T) - SSTEAM14B(T))$$

$$\text{if } P \geq 16 \wedge P < 20$$

$$h \leftarrow HSTEAM16B(T) + \frac{(P-16)}{(20-16)} \cdot (HSTEAM20B(T) - HSTEAM16B(T))$$

$$s \leftarrow SSTEAM16B(T) + \frac{(P-16)}{(20-16)} \cdot (SSTEAM20B(T) - SSTEAM16B(T))$$

$$\text{if } P \geq 20 \wedge P < 25$$

$$h \leftarrow HSTEAM20B(T) + \frac{(P-20)}{(25-20)} \cdot (HSTEAM25B(T) - HSTEAM20B(T))$$

$$s \leftarrow SSTEAM20B(T) + \frac{(P-20)}{(25-20)} \cdot (SSTEAM25B(T) - SSTEAM20B(T))$$

$$\text{if } P \geq 25 \wedge P < 30$$

$$h \leftarrow HSTEAM25B(T) + \frac{(P-25)}{(30-25)} \cdot (HSTEAM30B(T) - HSTEAM25B(T))$$

$$s \leftarrow SSTEAM25B(T) + \frac{(P-25)}{(30-25)} \cdot (SSTEAM30B(T) - SSTEAM25B(T))$$

$$\text{if } P \geq 30 \wedge P < 40$$

$$h \leftarrow HSTEAM30B(T) + \frac{(P-30)}{(40-30)} \cdot (HSTEAM40B(T) - HSTEAM30B(T))$$

$$s \leftarrow SSTEAM30B(T) + \frac{(P-30)}{(40-30)} \cdot (SSTEAM40B(T) - SSTEAM30B(T))$$

$$
\begin{aligned}
&\text{if } P \ge 40 \wedge P < 60\\
&\quad h \leftarrow HSTEAM40B(T) + \frac{(P-40)}{(60-40)}\cdot(HSTEAM60B(T) - HSTEAM40B(T))\\
&\quad s \leftarrow SSTEAM40B(T) + \frac{(P-40)}{(60-40)}\cdot(SSTEAM60B(T) - SSTEAM40B(T))\\
&\text{if } P \ge 60 \wedge P < 70\\
&\quad h \leftarrow HSTEAM60B(T) + \frac{(P-60)}{(70-60)}\cdot(HSTEAM70B(T) - HSTEAM60B(T))\\
&\quad s \leftarrow SSTEAM60B(T) + \frac{(P-60)}{(70-60)}\cdot(SSTEAM70B(T) - SSTEAM60B(T))\\
&\text{if } P \ge 70 \wedge P < 80\\
&\quad h \leftarrow HSTEAM70B(T) + \frac{(P-70)}{(80-70)}\cdot(HSTEAM80B(T) - HSTEAM70B(T))\\
&\quad s \leftarrow SSTEAM70B(T) + \frac{(P-70)}{(80-70)}\cdot(SSTEAM80B(T) - SSTEAM70B(T))\\
&\text{if } P \ge 80 \wedge P < 100\\
&\quad h \leftarrow HSTEAM80B(T) + \frac{(P-80)}{(100-80)}\cdot(HSTEAM100B(T) - HSTEAM80B(T))\\
&\quad s \leftarrow SSTEAM80B(T) + \frac{(P-80)}{(100-80)}\cdot(SSTEAM100B(T) - SSTEAM80B(T))\\
&\text{if } P \ge 100 \wedge P < 150\\
&\quad h \leftarrow HSTEAM100B(T) + \frac{(P-100)}{(150-100)}\cdot(HSTEAM150B(T) - HSTEAM100B(T))\\
&\quad s \leftarrow SSTEAM100B(T) + \frac{(P-100)}{(150-100)}\cdot(SSTEAM150B(T) - SSTEAM100B(T))
\end{aligned}
$$

$$
\begin{aligned}
&\text{if } P \ge 150 \wedge P < 200\\
&\quad h \leftarrow HSTEAM150B(T) + \frac{(P-150)}{(200-150)}\cdot(HSTEAM200B(T) - HSTEAM150B(T))\\
&\quad s \leftarrow SSTEAM150B(T) + \frac{(P-150)}{(200-150)}\cdot(SSTEAM200B(T) - SSTEAM150B(T))\\
&\text{if } P \ge 200 \wedge P \le 250\\
&\quad h \leftarrow HSTEAM200B(T) + \frac{(P-200)}{(250-200)}\cdot(HSTEAM250B(T) - HSTEAM200B(T))\\
&\quad s \leftarrow SSTEAM200B(T) + \frac{(P-200)}{(250-200)}\cdot(SSTEAM250B(T) - SSTEAM200B(T))\\
&(h \;\; s)
\end{aligned}
$$

Next, we write Functions for properties of steam in the two-phase region:

Here, the Sat. pressure Table is used. Since the Table is rather large, we write it separately as a simple text file in Notepad and name it as satprop.prn, and read it from Mathcad with the built-in Function READPRN, i.e. we enter: READPRN("satprop.prn").

A part of the Sat. Table is shown below:

PROPERTIES OF SAT. STEAM ...PRESSURE TABLE (Ref: TEST)

PRESS. (MPa)	TEMP (C)	hf (kJ/kg)	hg (kJ/kg)	sf (kJ/kg.K)	sg (kJ/kg.K)	vf (cc/g)	vg (cu.m/kg)
0.0006113	0.01	0.01	2501.4	0.000	9.1562	1.000	206.14
0.001	6.98	29.3	2514.2	0.1059	8.9756	1.000	129.21
0.0015	13.03	54.71	2525.3	0.1957	8.8279	1.001	87.98
0.002	17.50	73.48	2533.5	0.2607	8.7237	1.001	67.00
0.0025	21.08	88.49	2540.0	0.3120	8.6432	1.002	54.25

....

10.00	311.06	1407.65	2724.7	3.3596	5.6141	1.452	0.018026
11.00	318.15	1450.10	2705.6	3.4295	5.5527	1.489	0.015987
12.00	324.75	1491.30	2684.9	3.4962	5.4924	1.527	0.014263
13.00	330.93	1531.5	2662.2	3.5606	5.4323	1.567	0.012780
14.00	336.75	1571.1	2637.6	3.6232	5.3717	1.611	0.011485
15.00	342.24	1610.5	2610.5	3.6848	5.3098	1.658	0.010337
16.00	347.44	1650.1	2580.6	3.7461	5.2455	1.711	0.009306
18.00	357.06	1732.0	2509.1	3.8715	5.1044	1.840	0.007489
20.00	365.81	1826.3	2409.7	4.0139	4.9269	2.036	0.005834
22.09	374.14	2099.3	2099.3	4.4298	4.4298	3.155	0.003155

....

To write the Functions, we extract each column as a vector and use them to get interpolated values, in conjunction with the interpolation function 'linterp' in Mathcad.

SAT := READPRN("satprop.prn")

Psat.....Mpa, Tsat.....deg. C
hfsat, hgsat....kJ/kg;
sfsat, sgsat....kJ/kg.K
vfsat..............cm^3/g
vgsat..............m^3/kg

$psat := SAT^{\langle 0 \rangle}$ $\quad$ $length(psat) = 54$

$tsat := SAT^{\langle 1 \rangle}$ $\quad$ $hfsat := SAT^{\langle 2 \rangle}$

$hgsat := SAT^{\langle 3 \rangle}$ $\quad$ $sfsat := SAT^{\langle 4 \rangle}$ $\quad$ $sgsat := SAT^{\langle 5 \rangle}$ $\quad$ $vfsat := SAT^{\langle 6 \rangle}$ $\quad$ $vgsat := SAT^{\langle 7 \rangle}$

Following *very useful* Functions are written to find out enthalpy, entropy, sp. volume of both the sat. liquid and sat. vapor conditions, as functions of sat. temp and sat. pressures. Note that pressure is in MPa in these Functions:

$TSAT(P) := linterp(psat, tsat, P)$

$PSAT(T) := linterp(tsat, psat, T)$

$HFSATP(P) := linterp(psat, hfsat, P)$

$HFSATT(T) := linterp(tsat, hfsat, T)$

$HGSATP(P) := linterp(psat, hgsat, P)$

$HGSATT(T) := linterp(tsat, hgsat, T)$

$HFGSATP(P) := HGSATP(P) - HFSATP(P)$

$HFGSATT(T) := HGSATT(T) - HFSATT(T)$

$SFSATP(P) := linterp(psat, sfsat, P)$

$SFSATT(T) := linterp(tsat, sfsat, T)$

$SGSATP(P) := linterp(psat, sgsat, P)$

$SGSATT(T) := linterp(tsat, sgsat, T)$

$SFGSATP(P) := SGSATP(P) - SFSATP(P)$

$SFGSATT(T) := SGSATT(T) - SFSATT(T)$

$VGSATP(P) := linterp(psat, vgsat, P)$

$VGSATT(T) := linterp(tsat, vgsat, T)$

$VFSATP(P) := linterp(psat, vfsat, P) \cdot 10^{-3}$

$VFSATT(T) := linterp(tsat, vfsat, T) \cdot 10^{-3}$

$VFGSATP(P) := VGSATP(P) - VFSATP(P)$

$VFGSATT(T) := VGSATT(T) - VFSATT(T)$

$UGSATP(P) := HGSATP(P) - P \cdot 10^{3} \cdot VGSATP(P)$

$UFSATP(P) := HFSATP(P) - P \cdot VFSATP(P) \cdot 10^{3}$

$UFGSATP(P) := UGSATP(P) - UFSATP(P)$

$UGSATT(T) := HGSATT(T) - PSAT(T) \cdot 10^{3} \cdot VGSATT(T)$

$UFSATT(T) := HFSATT(T) - PSAT(T) \cdot 10^{3} \cdot VFSATT(T)$

$UFGSATT(T) := UGSATT(T) - UFSATT(T)$

Further, following *additional functions* for finding out the entropy, enthalpy, quality etc in the two-phase region are written. They are very useful in calculations related to Rankine cycle.

In the following program: psat = sat. pr.(bar), tsat = sat. temp (C), s = entropy (kJ/kg.C), h = enthalpy (kJ/kg), x = quality:

```
quality_Ps(psat, s) := | (return "psat should be between 0.006113 bar and 220.9 bar ! ") if psat < 0.006113 ∧ psat > 220.9
                       | PSAT ← psat/10
                       | sf ← SFSATP(PSAT)
                       | sfg ← SFGSATP(PSAT)
                       | x ← (s − sf)/sfg
```

```
quality_Ts(tsat, s) := | return "tsat should be between 0.01 C and 374.14 C ! "  if  tsat < 0.01 ∧ tsat > 374.14
                       | sf ← SFSATT(tsat)
                       | sfg ← SFGSATT(tsat)
                       | x ← (s − sf)/sfg
```

```
quality_Th(tsat, h) := | return "tsat should be between 0.01 C and 374.14 C ! "  if  tsat < 0.01 ∧ tsat > 374.14
                       | hf ← HFSATT(tsat)
                       | hfg ← HFGSATT(tsat)
                       | x ← (h − hf)/hfg
```

```
entropy_2phase_Px(psat, x) := | (return "psat should be between 0.006113 bar and 220.9 bar ! ")  if  psat < 0.006113 ∧ psat > 220.9
                              | PSAT ← psat/10
                              | sf ← SFSATP(PSAT)
                              | sfg ← SFGSATP(PSAT)
                              | s ← sf + x·sfg
```

```
entropy_2phase_Tx(tsat,x) := | return "tsat should be between 0.01 C and 374.14 C ! "  if  tsat < 0.01 ∧ tsat > 374.14
                             | sf ← SFSATT(tsat)
                             | sfg ← SFGSATT(tsat)
                             | s ← sf + x·sfg

entropy_2phase_Th(tsat,h) := | return "tsat should be between 0.01 C and 374.14 C ! "  if  tsat < 0.01 ∧ tsat > 374.14
                             | sf ← SFSATT(tsat)
                             | sfg ← SFGSATT(tsat)
                             | x ← quality_Th(tsat,h)
                             | s ← sf + x·sfg

enthalpy_2phase_Px(psat,x) := | (return "psat should be between 0.006113 bar and 220.9 bar ! ")  if  psat < 0.006113 ∧ psat > 220.9
                              | PSAT ← psat/10
                              | hf ← HFSATP(PSAT)
                              | hfg ← HFGSATP(PSAT)
                              | h ← hf + x·hfg

enthalpy_2phase_Tx(tsat,x) := | return "tsat should be between 0.01 C and 374.14 C ! "  if  tsat < 0.01 ∧ tsat > 374.14
                              | hf ← HFSATT(tsat)
                              | hfg ← HFGSATT(tsat)
                              | h ← hf + x·hfg

enthalpy_2phase_Ts(tsat,s) := | return "tsat should be between 0.01 C and 374.14 C ! "  if  tsat < 0.01 ∧ tsat > 374.14
                              | x ← quality_Ts(tsat,s)
                              | hf ← HFSATT(tsat)
                              | hfg ← HFGSATT(tsat)
                              | h ← hf + x·hfg

enthalpy_2phase_Ps(psat,s) := | (return "psat should be between 0.006113 bar and 220.9 bar ! ")  if  psat < 0.006113 ∧ psat > 220.9
                              | x ← quality_Ps(psat,s)
                              | PSAT ← psat/10
                              | hf ← HFSATP(PSAT)
                              | hfg ← HFGSATP(PSAT)
                              | h ← hf + x·hfg
```

Further, for convenience and uniformity, we write the following program to get enthalpy and entropy when P and T are given in bar and deg.C respectively:

```
enthalpy(P, T) := | tsat ← TSAT(P/10)
                  | h ← h_and_s_SuperheatSteam(P, T)_{0,0}  if  T ≥ tsat
                  | (return  "State point in two phase region--- use 2 phase Functions")   otherwise
```

```
entropy(P, T) := | tsat ← TSAT(P/10)
                 | s ← h_and_s_SuperheatSteam(P, T)_{0,1}  if  T ≥ tsat
                 | (return  "State point in two phase region--- use 2 phase Functions")   otherwise
```

===

Now, let us solve the above Problem on Simple, Ideal Rankine cycle, using these Functions:

Problem statement is repeated below:

Prob.3.2.1 A steam power plant works on Rankine cycle between pressure ratio 20 bar and 0.05 bar. Steam supplied to the turbine is dry, saturated. Find thermal effcy., work ratio and Specific Steam Consumption (SSC). What would be the efficiency and work ratio in case of Carnot cycle operating in the same pressure limits? [M.U.]

(b) For the ideal Rankine cycle above, plot the thermal effcy and net work output as the condenser pressure varies from 6 kPa to 15 kPa (i.e. from 0.06 bar to 0.15 bar):

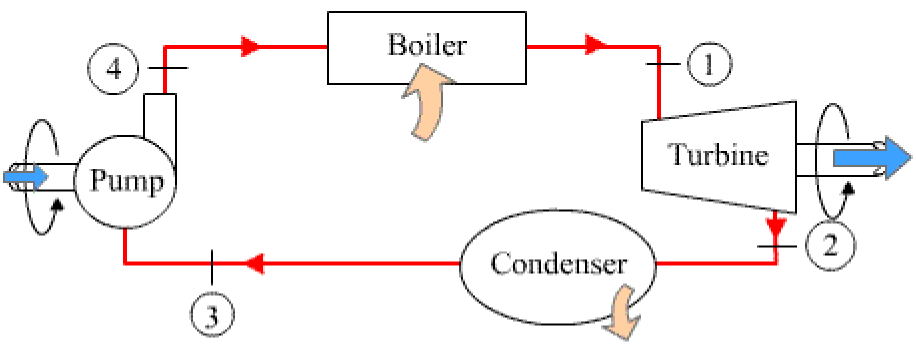


Fig.Prob.3.2.1 (a) Schematic diagram of simple, ideal Rankine cycle

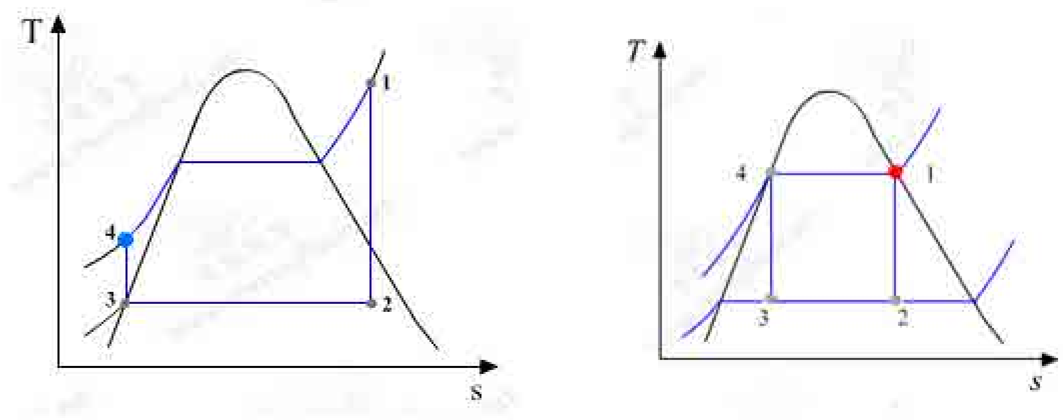


Fig.Prob.3.2.1 (b) and (c) T-s diagram of simple, ideal Rankine cycle, and of Carnot cycle

Solution using Mathcad Functions:

Since we have to plot the thermal effcy and net work output as against condenser pressure (P2) later, we shall write the relevant quantities as functions of P2:

Calculations:

To find h1 and s1:

$h1 := \text{enthalpy\_2phase\_Px}(P1, x1)$ kJ/kg..... using the Function written above, with pressure in MPa

i.e. $h1 = 2.7995 \times 10^{3}$ **kJ/kg... at inlet to turbine**

$s1 := \text{SGSATP}\left(\frac{P1}{10}\right)$ kJ/kg.C..... using the Function written above, with pressure in MPa

i.e. $s1 = 6.3409$ kJ/kg.C

Data:

$P1 := 20$ bar $P2 := 0.05$ bar $P3 := 0.05$ bar $P4 := P1$ $x1 := 1$ $x3 := 0$

$h1 = 2.8 \times 10^{3}$ **kJ/kg....this value remains the same.**

$s1 = 6.341$ **kJ/kg.C ....this value remains the same.**

$s2 = 6.341$ **kJ/kg.C ....this value remains the same.**

Now, write the relevant quantities as functions of condenser pressure P2:

$h2(P2) := \text{enthalpy\_2phase\_Ps}(P2, s2)$ i.e. $h2(P2) = 1.933 \times 10^{3}$ **kJ/kg..at exit of turbine**

Also: $x2(P2) := \text{quality\_Ps}(P2, s2)$

i.e. $x2(P2) = 0.741$ **...quality of steam at point 2, after expn. in turbine**

To find h3: i.e. at entry to pump:

$h3(P2) := \text{enthalpy\_2phase\_Px}(P2, 0)$ i.e. $h3(P2) = 137.82$ **= 137.82 kJ/kg**

To find h4: i.e. at exit of pump:

$vf3(P2) := VFSATP\left(\frac{P2}{10}\right)$ i.e. $vf3(P2) = 1.005 \times 10^{-3}$ **m^3/kg..sp. vol. of sat. liq. at 2**

Therefore: $w_p(P2) := vf3(P2)\cdot(P1 - P2)\cdot 10^2$ kJ...pump work

i.e. $w_p(P2) = 2.005$ **kJ...pump work**

Then: $h4(P2) := h3(P2) + w_p(P2)$

i.e. $h4(P2) = 139.825$ **kJ/kg..at exit of pump, and inlet to boiler**

Therefore:

$q_{in}(P2) := h1 - h4(P2)$ i.e. $q_{in}(P2) = 2.66 \times 10^3$ **kJ/kg .... heat supplied**

$q_{out}(P2) := h2(P2) - h3(P2)$ i.e. $q_{out}(P2) = 1.795 \times 10^3$ **kJ/kg .... heat rejected**

$w_T(P2) := h1 - h2(P2)$ i.e. $w_T(P2) = 866.73$ **kJ/kg.......Turbine work output**

$w_{net}(P2) := w_T(P2) - w_p(P2)$ i.e. $w_{net}(P2) = 864.725$ **kJ/kg.... Net work output**

$\eta(P2) := \frac{w_{net}(P2)}{q_{in}(P2)}\cdot 100$ i.e. $\eta(P2) = 32.512$ **, ...Thermal effcy....Ans.**

$SSC(P2) := \frac{3600}{w_{net}(P2)}$ i.e. $SSC(P2) = 4.163$ **kg/kWh... Specific steam consumption....Ans.**

Work Ratio: $WR(P2) := \frac{w_{net}(P2)}{w_T(P2)}$ $WR(P2) = 0.998$ **Work ratio.....Ans.**

For Carnot Cycle:
============

$T_h := TSAT(2)$ i.e. $T_h = 212.42$ C $T_c := TSAT(0.005)$ i.e. $T_c = 32.88$ C

$\eta_{carnot} := \frac{(T_h + 273) - (T_c + 273)}{T_h + 273}$ i.e. $\eta_{carnot} = 0.37$ **...Thermal effcy...Ans.**

Work of Turbine remains same. Now, compression is from point 3 to point 4.

From Mathcad Functions written above:

$s4 := SFSATP\left(\frac{P4}{10}\right)$ i.e. $s4 = 2.447$ kJ/kg.C

$h4 := HFSATP\left(\frac{P4}{10}\right)$ i.e. $h4 = 908.79$ **kJ/kg**

Work of Turbine remains same. Now, compression is from point 3 to point 4.

From Mathcad Functions written above:

$s4 := SFSATP\left(\frac{P4}{10}\right)$ i.e. $s4 = 2.447$ kJ/kg.C.... note that pressure is in MPa

$h4 := HFSATP\left(\frac{P4}{10}\right)$ i.e. $h4 = 908.79$ **kJ/kg..** note that pressure is in MPa

To find h3:

We have: $s3 := s4$ ...for isentropi compression in pump

Then:

$h3 := enthalpy\_2phase\_Ps(P3, s3)$ i.e. $h3 = 741.085$ **kJ/kg.... corresp. to 0.05 bar and s3 = s4**

Also: $x3 := quality\_Ps(P3, s3)$

i.e. $x3 = 0.249$ **...quality at point 3**

Therefore:

$wp := h4 - h3$ i.e. $wp = 167.705$ **kJ/kg.....New pump work.... Ans.**

Work Ratio: $WR_{carnot} := \frac{w_T - wp}{w_T}$

i.e. $WR_{carnot} = 0.807$ **... ..Ans.**

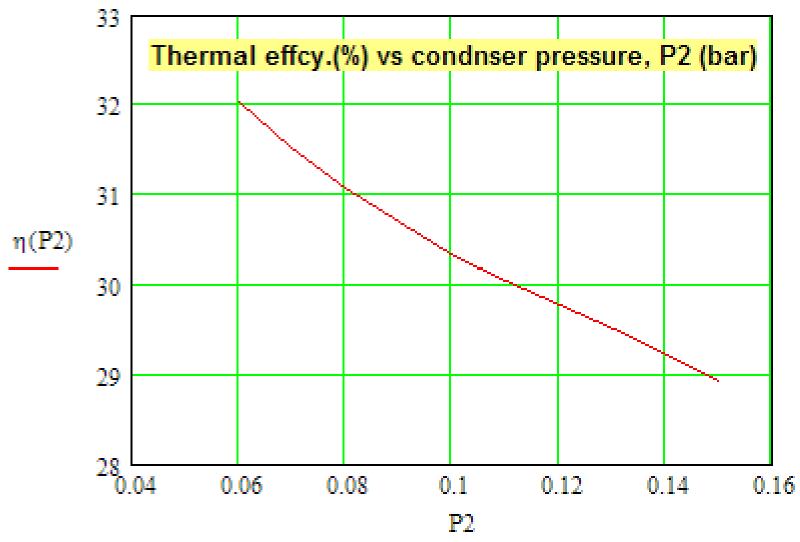
(b) For the ideal Rankine cycle above, plot the thermal effcy and net work output as the condenser pressure varies from 6 kPa to 15 kPa (i.e. from 0.06 bar to 0.15 bar):

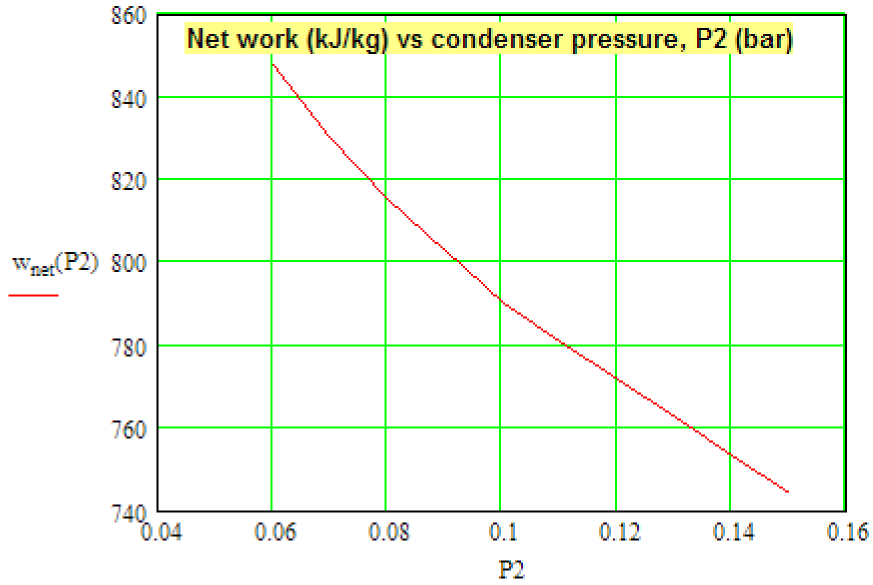
We have already the relevant quantities as functions of condenser pressure P2:

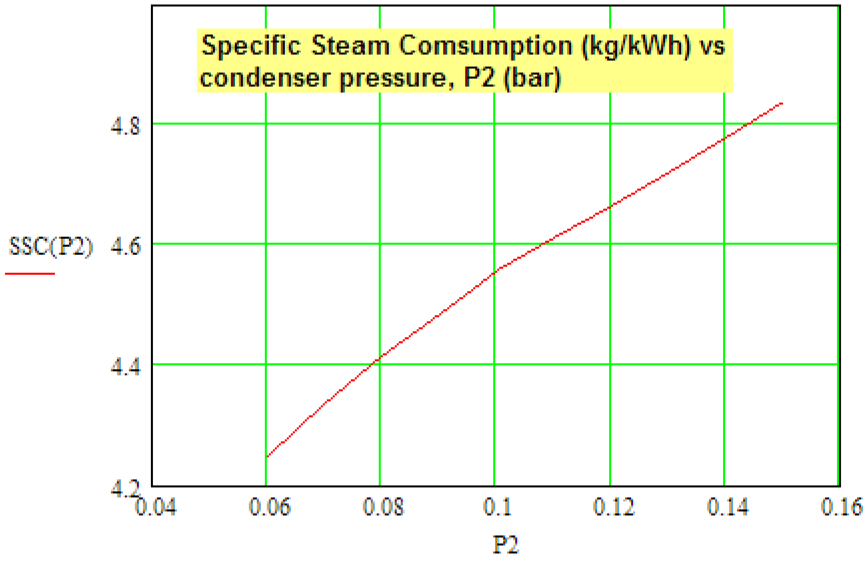
Now, plot the results:

$P2 := 0.06, 0.07..0.15$ bar.....define a range variable

P2 =	$w_{net}(P2)$ =	$\eta(P2)$ =	SSC(P2) =	WR(P2) =	x2(P2) =
0.06	847.632	32.019	4.247	0.998	0.745
0.07	830.348	31.513	4.336	0.998	0.749
0.08	815.352	31.072	4.415	0.998	0.753
0.09	802.717	30.698	4.485	0.998	0.756
0.1	789.977	30.318	4.557	0.997	0.759
0.11	780.884	30.047	4.61	0.997	0.761
0.12	771.739	29.774	4.665	0.997	0.763
0.13	762.54	29.496	4.721	0.997	0.765
0.14	753.286	29.216	4.779	0.997	0.768
0.15	743.976	28.931	4.839	0.997	0.77


Thermal effcy.(%) vs condnser pressure, P2 (bar)
η(P2)
33
32
31
30
29
28
0.04
0.06
0.08
0.1
0.12
0.14
0.16
P2


Net work (kJ/kg) vs condenser pressure, P2 (bar)
w_net(P2)
860
840
820
800
780
760
740
0.04
0.06
0.08
0.1
0.12
0.14
0.16
P2


Specific Steam Comsumption (kg/kWh) vs
condenser pressure, P2 (bar)
SSC(P2)
4.8
4.6
4.4
4.2
0.04
0.06
0.08
0.1
0.12
0.14
0.16
P2

==

Prob.3.2.2 In a reheat Rankine cycle, steam at 500 C expands in a HP turbine till it is saturated vap. It is then reheated at constant pressure to 400 C and then expanded in a LP turbine to 40 C. If the max. moisture content at the turbine exhaust is limited to 15%, find: (i) the reheat pressure, (ii) pressure of steam at the inlet to HP turbine, (iii) net specific work output, (iv) cycle efficiency, and (v) steam rate. Assume all ideal processes. [VTU-ATD-Dec. 2011]

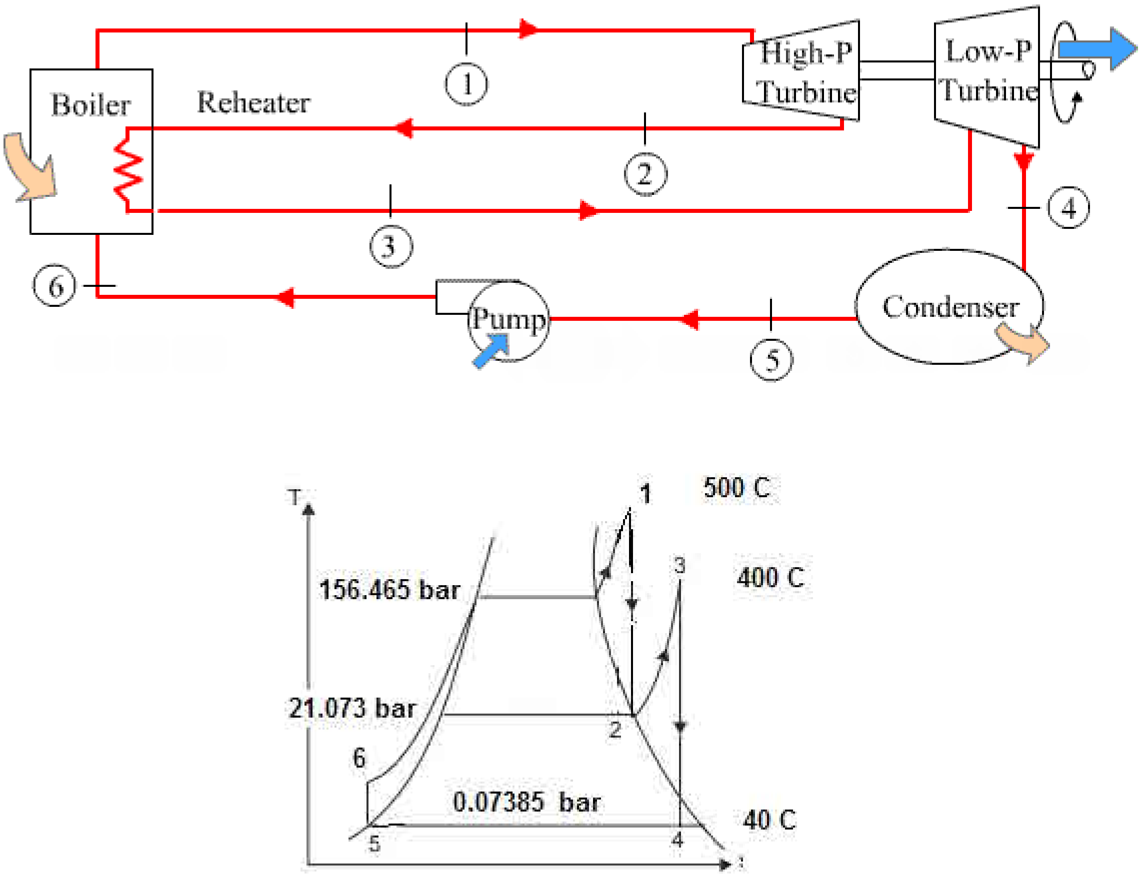


Fig.Prob.3.2.2 (a) Ideal Reheat, Rankine cycle, and (b) T-s diagram

Mathcad Solution:

Essentially, we have to find out the enthalpies at all the state points.

We shall use the Mathcad Functions written above, and start with State 4, since the temperature and quality are known at point 4.

Data:

T1 := 500 C   x2 := 1   T3 := 400 C   x4 := 0.85   T4 := 40 C   T5 := T4

P5 := P4   P6 := P1   P3 := P2

Calculations:

$P4 := PSAT(T4)$ i.e. $P4 = 7.402 \times 10^{-3}$ MPa = 7402 Pa = 0.07402 bar

i.e. $P4 := 0.07402$ bar $P5 := P4$

To find s4: use the Mathcad Function already written above.

$s4 := entropy\_2phase\_Tx(T4, x4)$ i.e, $s4 = 7.104$ kJ/kg.C

To find h4:

$h4 := enthalpy\_2phase\_Tx(T4, x4)$ i.e. $h4 = 2.213 \times 10^{3}$ **kJ/kg.C**

To find P3:

Now: $s3 := s4$ ...for isentropic expn. in turbine-2

Using the 'Solve block' of Mathcad:

Let: $P3 := 15$ bar....guess value

Given

$s3 = entropy(P3, T3)$

$P3 := Find(P3)$

$P3 = 21.01$ **bar....Ans..... Reheat pressure**

Then find s2 at this reheat pressure:

$P2 := P3$

$s2 := SGSATP\left(\frac{P2}{10}\right)$ ...Note: Pressure is in MPa

i.e. $s2 = 6.324$ kJ/kg.C

And: $s1 := s2$ ....for isentropic expn. in turbine-1

Now, find P1:

Using the 'Solve block' of Mathcad:

$P1 := 200$ bar... guess value

Given

$s1 = \text{entropy}(P1, T1)$

$P1 := \text{Find}(P1)$

$P1 = 154.956$ **bar....Ans..... Turbine-1 inlet pressure**

Now:

$P5 := P4 \quad P6 := P1$

$T2 := \text{TSAT}\left(\frac{P2}{10}\right)$ i.e. $T2 = 214.756$ C

$P4 := 0.07402$ bar $\quad T4 = 40$ C

To find enthalpies at all points:

$h1 := enthalpy(P1, T1)$ i.e. $h1 = 3.302 \times 10^3$ **kJ/kg**

$h2 := enthalpy(P2, T2)$ i.e. $h2 = 2.8 \times 10^3$ **kJ/kg**

$h3 := enthalpy(P3, T3)$ i.e. $h3 = 3.246 \times 10^3$ **kJ/kg**

$h4 = 2.213 \times 10^3$ **kJ/kg**

$h5 := enthalpy\_2phase\_Tx(T5, 0)$ i.e. $h5 = 167.578$ **kJ/kg**

For h6:

$vf5 := VFSATT(T5)$ i.e. $vf5 = 1.008 \times 10^{-3}$ m^3/kg...sp. vol. of liq. at inlet to pump

Therefore: $W_P := vf5 \cdot (P6 - P5) \cdot 10^5$ i.e. $W_P = 1.561 \times 10^4$ **J = 15.61 kJ/kg ... pump work**

i.e. $W_P := 15.61$ **kJ/kg...pump work**

And: $h6 := h5 + W_P$ i.e. $h6 = 183.188$ **kJ/kg**

Therefore:

$Q_{in} := (h1 - h6) + (h3 - h2)$ i.e. $Q_{in} = 3.565 \times 10^3$ **kJ/kg .... heat supplied**

$Q_{out} := h4 - h5$ i.e. $Q_{out} = 2.046 \times 10^3$ **kJ/kg .... heat rejected**

$W_T := (h1 - h2) + (h3 - h4)$ i.e. $W_T = 1.535 \times 10^3$ **kJ/kg.......Turbine work output**

$W_{net} := W_T - W_P$ i.e. $W_{net} = 1.519 \times 10^3$ **kJ/kg.... Net work output**

$\eta := \frac{W_{net}}{Q_{in}} \cdot 100$ i.e. $\eta = 42.612$ **%, ...Thermal effcy....Ans.**

$SSC := \frac{3600}{W_{net}}$ i.e. $SSC = 2.37$ i.e. **kg/kWh... Specific steam consumption....Ans.**

Work Ratio: $WR := \frac{W_{net}}{W_T}$ i.e. $WR = 0.99$ **Work ratio.....Ans.**

Note: In the above analysis, Pump work is considered. But, many times, the pump work can be neglected since it is quite small compared to net work.

==

Prob.3.2.3 Steam at 30 bar, 350 C is supplied to a steam turbine in a practical regenerative Rankine cycle and the steam is bled at 4 bar. The bled steam comes out as dry, saturated steam and heats the feed water in an open type feed water heater to its sat. liquid state. The rest of the steam in the turbine expands to a condenser pressure of 0.1bar. Assuming the turbine efficiency to be same before and after bleeding, determine: (i) the turbine effcy. (ii) steam quality at inlet to condenser, (iii) mass flow rate of bled steam per unit mass flow rate at turbine inlet, and (iv) the cycle efficiency. [VTU-ATD-Jan.–Feb. 2005]

(b) For this Regenerative Rankine cycle, plot the thermal effcy., net work output and SSC as the turbine inlet pressure, P1 varies from 15 bar to 100 bar:

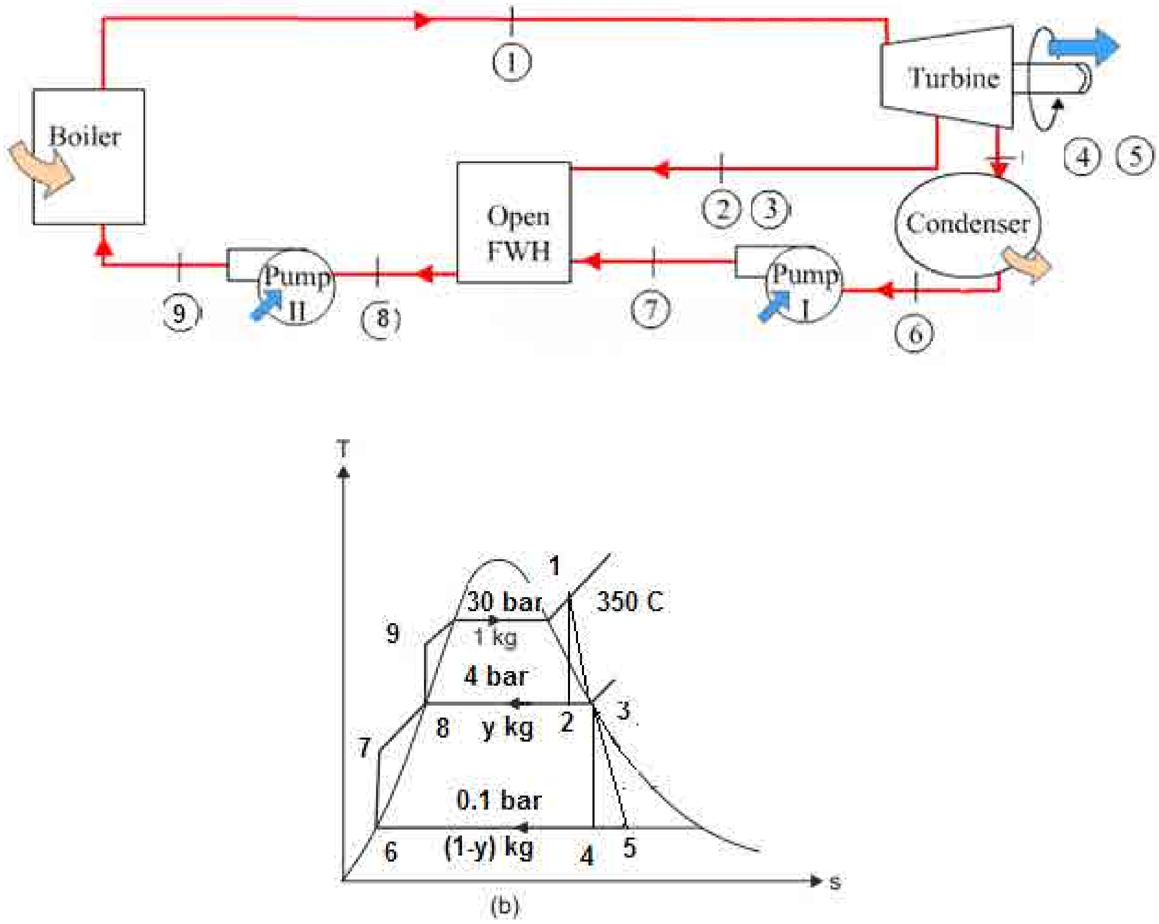


Fig.Prob.3.2.3 (a) Regenerative Rankine cycle, and (b) T-s diagram

Solution using Mathcad Functions:

Refer to the schematic diagram given above.

Since we have to plot the thermal effcy. and net work output against turbine input pressure (P1) later, we shall write the relevant quantities as functions of P1:

Data:

$T1 := 350$ C $P1 := 30$ bar $P2 := 4$ bar $P3 := P2$ $P4 := 0.1$ bar $P5 := P4$ $P6 := P4$

$P7 := P2$ $P8 := P2$ $P9 := P1$ $x3 := 1$ $x6 := 0$ $x8 := 0$

Calculations:

To find enthalpies at salient points:

$h1(P1) := \text{enthalpy}(P1, T1)$ i.e. $h1(P1) = 3.115 \times 10^3$ kJ/kg

$s1(P1) := \text{entropy}(P1, T1)$ i.e. $s1(P1) = 6.743$ kJ/kg.C

And: $s2(P1) := s1(P1)$ ...for isentropic expn. in turbine-1

Therefore: $h2(P1) := \text{enthalpy\_2phase\_Ps}(P2, s2(P1))$

i.e. $h2(P1) = 2.675 \times 10^3$ kJ/kg

And: at point 3, it is sat. vap., i.e. x3 = 1. Therefore:

$h3 := enthalpy\_2phase\_Px(P3, x3)$ i.e. $h3 = 2.739 \times 10^{3}$ **kJ/kg**

Therefore, turbine effcy: $\eta_{turb}(P1) := \dfrac{h1(P1) - h3}{h1(P1) - h2(P1)}$

i.e. $\eta_{turb}(P1) = 0.855$ **= 85.5 %....turbine effcy....Ans.**

$s3 := entropy\_2phase\_Px(P3, x3)$ i.e. $s3 = 6.896$ kJ/kg.C

And: $s4 := s3$ ...for isentropic expn. in turbine-2

Therefore: $h4 := enthalpy\_2phase\_Ps(P4, s4)$

i.e. $h4 = 2.185 \times 10^{3}$ **kJ/kg**

And: $h5(P1) := h3 - \eta_{turb}(P1) \cdot (h3 - h4)$ i.e. $h5(P1) = 2.265 \times 10^{3}$ **kJ/kg**

Also: $h6 := enthalpy\_2phase\_Px(P6, x6)$ i.e. $h6 = 191.83$ **kJ/kg**

To find h7:

$vf6 := VFSATP(P6)$ i.e. $vf6 = 1.043 \times 10^{-3}$ m^3/kg...sp. vol. of liq. at inlet to pump

Therefore: $W_P := vf6 \cdot (P7 - P6) \cdot 10^{5}$ i.e. $W_P = 406.77$ **J = 0.406 kJ/kg ... pump-1 work**

i.e. $W_P := 0.406$ **kJ/kg...pump work**

And: $h7 := h6 + W_P$ i.e. $h7 = 192.236$ **kJ/kg**

Now: $h8 := enthalpy\_2phase\_Px(P8, x8)$ i.e. $h8 = 604.74$ **kJ/kg**

To find h9:

$vf8 := VFSATP(P8)$

i.e. $vf8 = 1.252 \times 10^{-3}$ m^3/kg...sp. vol. of liq. at inlet to pump

Therefore: $W_P(P1) := vf8 \cdot (P1 - P8) \cdot 10^{5}$ i.e. $W_P(P1) = 3.255 \times 10^{3}$ **J = 3.255 kJ/kg ... pump-2 work**

i.e. $W_P(P1) := 3.255$ **kJ/kg...pump-2 work**

And: $h9(P1) := h8 + W_P(P1)$ i.e. $h9(P1) = 607.995$ **kJ/kg**

Therefore:

Amount of steam bled from turbine: Let this fraction be y.

Then applying an energy balance to the open heater:

$$y \cdot h3 + (1 - y) \cdot h7 = 1 \cdot h8$$

i.e. $y := \dfrac{h8 - h7}{h3 - h7}$ i.e. $y = 0.162$ **....fraction bled from turbine ... Ans.**

$Q_{in}(P1) := (h1(P1) - h9(P1))$ i.e. $Q_{in}(P1) = 2.507 \times 10^{3}$ **kJ/kg .... heat supplied**

$Q_{out}(P1) := (h5(P1) - h6) \cdot (1 - y)$ i.e. $Q_{out}(P1) = 1.737 \times 10^{3}$ **kJ/kg .... heat rejected**

$W_T(P1) := (h1(P1) - h3) + (h3 - h5(P1)) \cdot (1 - y)$ i.e. $W_T(P1) = 773.724$ **kJ/kg.......Turbine work output**

$W_{P1} := (h7 - h6) \cdot (1 - y)$ i.e. $W_{P1} = 0.34$ **kJ/kg......work required for Pump-1**

$W_{P2}(P1) := (h9(P1) - h8)$ i.e. $W_{P2}(P1) = 3.255$ **kJ/kg......work required for Pump-2**

$W_{net}(P1) := W_T(P1) - (W_{P1} + W_{P2}(P1))$ i.e. $W_{net}(P1) = 770.129$ **kJ/kg.... Net work output**

$\eta(P1) := \dfrac{W_{net}(P1)}{Q_{in}(P1)} \cdot 100$ i.e. $\eta(P1) = 30.715$ **%, ...Thermal effcy....Ans.**

$SSC(P1) := \dfrac{3600}{W_{net}(P1)}$ i.e. $SSC(P1) = 4.675$ **kg/kWh... Specific steam consumption....Ans.**

Work Ratio: $WR(P1) := \dfrac{W_{net}(P1)}{W_T(P1)}$ i.e. $WR(P1) = 0.995$ **Work ratio.....Ans.**

Note: In the above analysis, Pump work is considered. But, many times, the pump work can be neglected since it is quite small compared to net work.

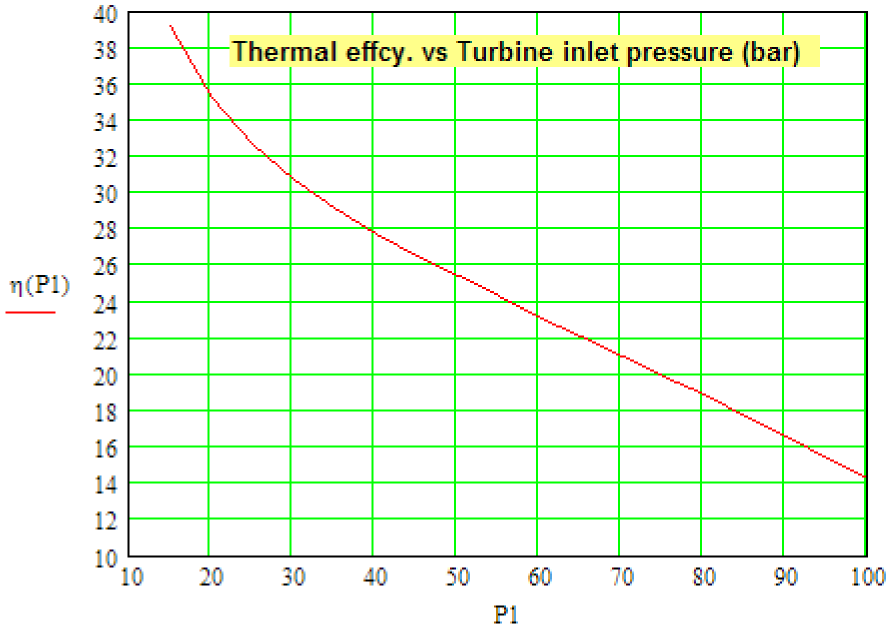
(b) For the Regenerative Rankine cycle solved above, plot the thermal effcy., net work output and SSC as the turbine inlet pressure, P1 varies from 15 bar to 100 bar:

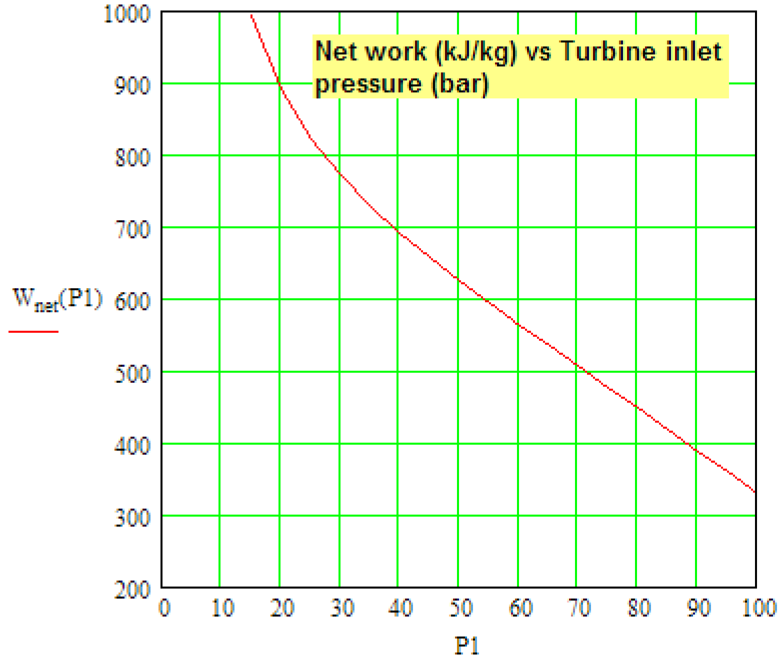
We have already written the relevant quantities as functions of pressure P1:

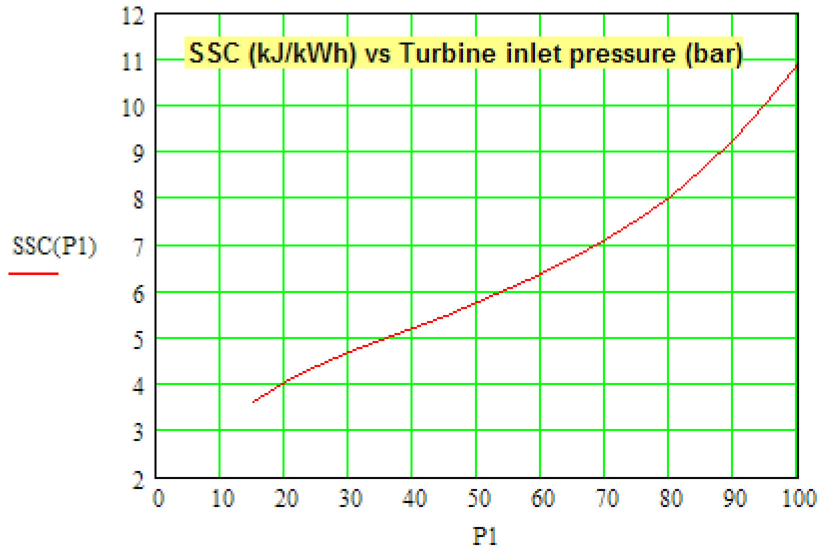
Now, to plot the results:

P1 := 15, 20 .. 100   bar.... define a range variable

P1 =	η(P1) =	W_{net}(P1) =	SSC(P1) =
15	39.126	993.577	3.623
20	35.208	890.407	4.043
25	32.649	822.2	4.378
30	30.715	770.129	4.675
35	29.181	728.328	4.943
40	27.744	689.298	5.223
45	26.543	656.185	5.486
50	25.375	624.168	5.768
55	24.237	593.164	6.069
60	23.125	563.095	6.393
65	22.057	534.103	6.74
70	20.996	505.582	7.121
75	19.921	476.849	7.55
80	18.847	448.426	8.028
85	17.698	418.263	8.607
90	16.541	388.267	9.272
95	15.374	358.436	10.044
100	14.199	328.766	10.95


Thermal effcy. vs Turbine inlet pressure (bar)
η(P1)
P1
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
10
20
30
40
50
60
70
80
90
100





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3.3 Problems solved with EES

i. It has built-in functions for properties of steam and several other fluids.
ii. Also, the cycle can be 'overlaid' on the built-in property diagrams.
iii. In EES, there is also a facility to enter data and perform calculations from a single window, called 'the diagram window'.

Prob.3.3.1 Superheated steam enters the turbine of an ideal Rankine cycle at 8 MPa, 480 C. The condenser pressure is 8 kPa. The net power output of the cycle is 100 MW. Determine: (i) rate of heat transfer in the steam generator, (ii) thermal efficiency, (iii) mass flow rate of condenser cooling water in kg/s, if water enters the condenser at 15 C and exits at 35 C.

b) Plot each of the quantities mentioned above for condenser pressures ranging from 6 kPa to 100 kPa.
c) Plot each of the quantities in (a) as steam generator pressure varies from 4 MPa to 24 MPa, maintaining the turbine inlet temp at 480 C. [Ref: 3]

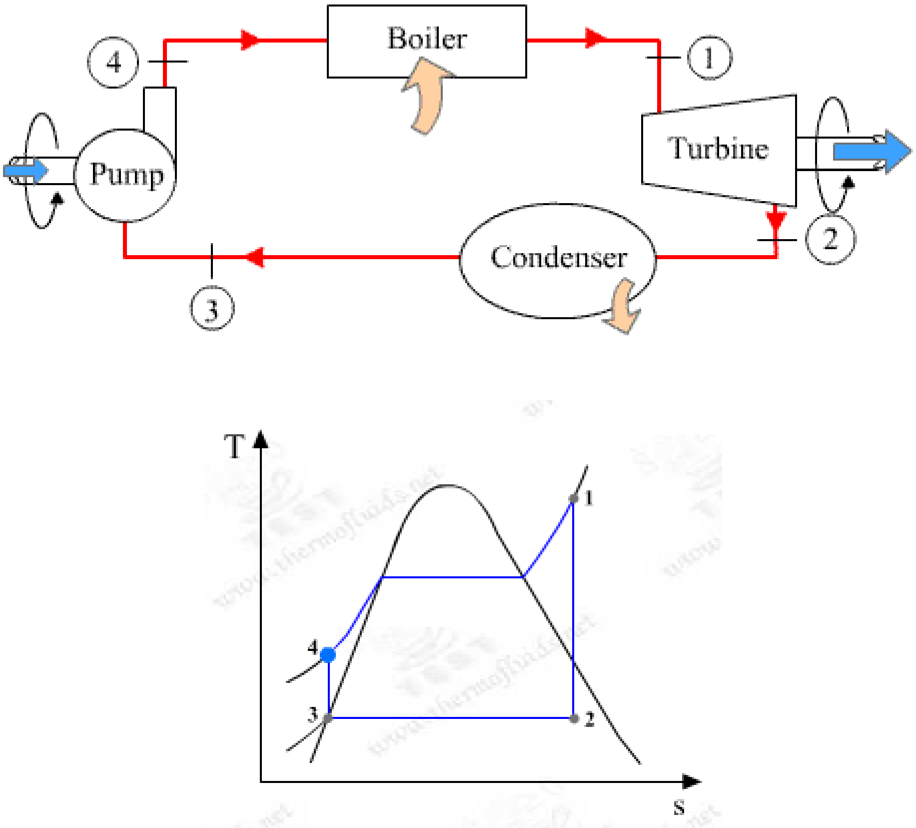


Fig.Prob.3.3.1 (a) Schematic diagram of simple, ideal Rankine cycle, and (b) T-s diagram

EES Solution:

"Data:"

Fluid$ = 'Steam_IAPWS'

P[1]=8000[kPa]"…at entry to turbine"

P[2]=8[kPa]"…at exit of turbine"

```
P[3]=P[2]"….at entry to pump"

P[4]=P[1]"…at exit of pump"

x[3]=0.0 "…sat. liq. at entry to pump"

T[1]=480[C]

Power = 1E05[kW] "…power developed"

T_cw1 = 15 [C] "..inlet temp of cooling water"

T_cw2 = 35 [C] "..exit temp of cooling water"

cp_w = 4.18 "kJ/kg.C … sp. heat of cooling water"

"Calculations:"

h[1]=ENTHALPY(Fluid$,T=T[1],P=P[1])"kJ/kg…enthalpy of fluid at entry to turbine"

s[1]=ENTROPY(Fluid$,T=T[1],P=P[1]) "kJ/kg.C…entropy of fluid at entry to turbine"

s[2]=s[1] "…for isentropic expn. in turbine"

h[2]=ENTHALPY(Fluid$,s=s[2],P=P[2])"kJ/kg…enthalpy of fluid at exit of turbine"

T[2]=TEMPERATURE(Fluid$,s=s[2],h=h[2])"C…temp at exit of turbine"

x[2]=Quality(Fluid$,T=T[2],s=s[2])"….quality of steam at exit of turbine"

v_f=VOLUME(Fluid$,P=P[3],x=x[3]) "m^3/kg … sp. vol. of fluid entering the pump"

T[3]=T_SAT(Fluid$,P=P[3]) "…sat. temp. at condenser pressure"

h[3]=ENTHALPY(Fluid$,T=T[3],x=x[3])"kJ/kg … enthalpy at entry to pump"

w_p = v_f * (P[4]-P[3]) ".kJ..pump work"

h[4]=h[3]+w_p "kJ/kg … enthalpy at the exit of pump"

q_in=h[1]-h[4]"kJ/kg"
```

q_out=h[2]-h[3]"kJ/kg"

w_turb = h[1] – h[2] "kJ/kg …. turbine work output"

w_net = w_turb – w_p "kJ/kg … net work output"

eta_th=1- q_out/q_in

s[3]=ENTROPY(Fluid$,P=P[3],h=h[3]) "kJ/kg.C … entropy of fluid at entry to pump"

s[4] = s[3]"…isentropic compression in pump"

T[4]=TEMPERATURE(Fluid$,P=P[4],s=s[4])"C…temp at exit of pump"

m_steam = Power / w_net "kg/s …. mass flow rate of steam"

m_cw * cp_w * (T_cw2 – T_cw1) = m_steam * q_out "…kg/s … finds mass flow rate of cooling water, by energy balance in the condenser"

Qtot_in = q_in * m_steam "kW …. total heat input in steam generator"

Results:

Unit Settings: SI C kPa kJ mass deg

cp_w = 4.18	η_{th} = 0.3972	Fluid$ = 'Steam_IAPWS'	m_{cw} = 1816 [kg/s]
m_{steam} = 79.48 [kg/s]	Power = 100000 [kW]	$Qtot_{in}$ = 251778 [kW]	q_{in} = 3168 [kJ/kg]
q_{out} = 1910 [kJ/kg]	T_{cw1} = 15 [C]	T_{cw2} = 35 [C]	v_f = 0.001008 [m^3/kg]
w_{net} = 1258 [kJ/kg]	w_p = 8.06 [kJ/kg]	w_{turb} = 1266 [kJ/kg]	

Sort	h_i [kJ/kg]	P_i [kPa]	s_i [kJ/kg-C]	T_i [C]	x_i
[1]	3350	8000	6.661	480	
[2]	2083	8	6.661	41.51	0.7949
[3]	173.8	8	0.5925	41.51	0
[4]	181.9	8000	0.5925	41.75	

Thus:

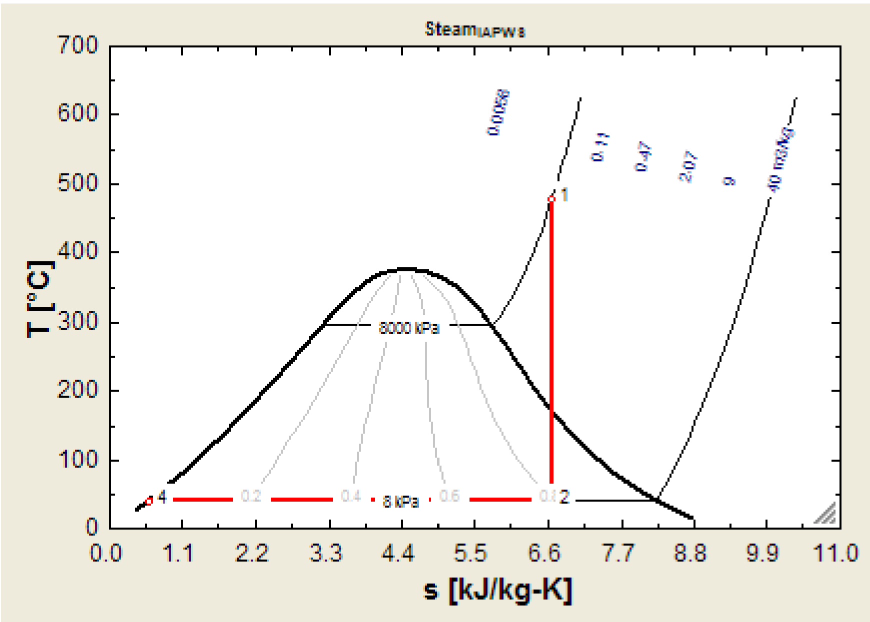
Heat input in the steam generator = Qtot_in = 250175 kW….Ans.

Mass flow rate of steam = m_steam = 78.98 kg/s …. Ans.

Mass flow rate of cooling water = m_cw = 1804 kg/s … Ans.

Thermal efficiency = eta_th = 0.3972 = 39.72% … Ans.

T-s plot of cycle:

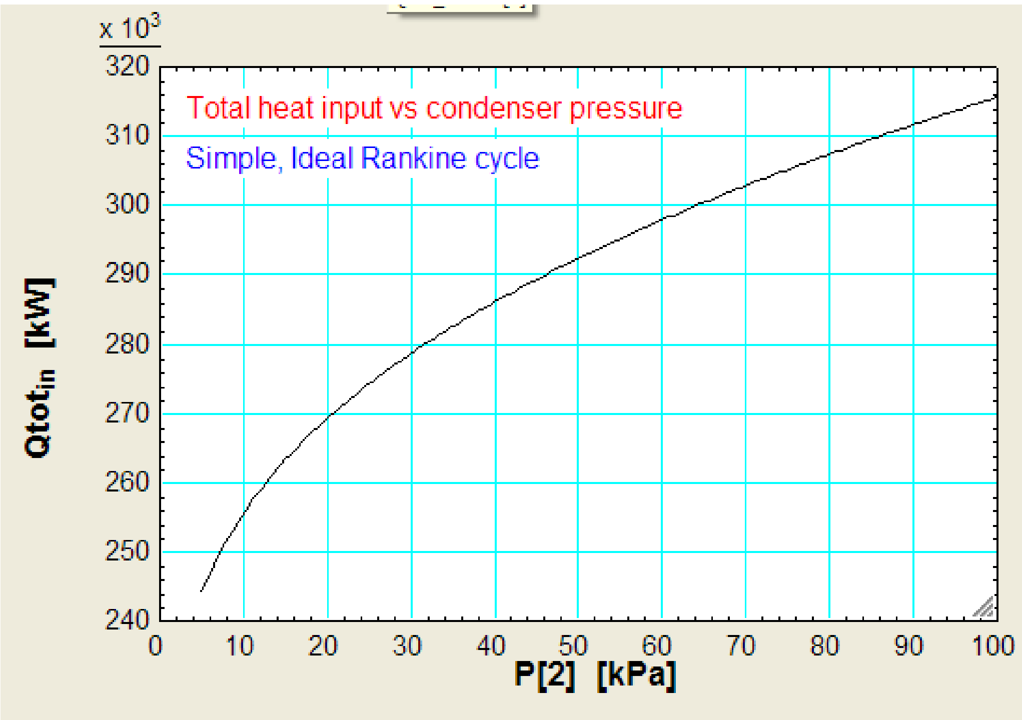


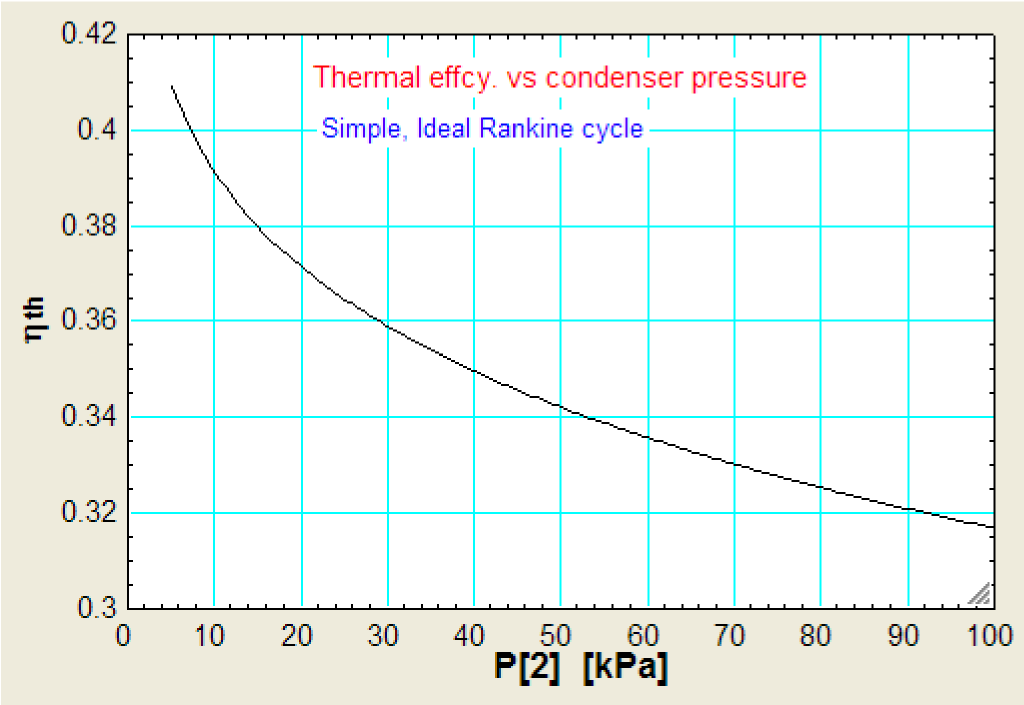
(b) Plot each of the quantities mentioned above for condenser pressure (P2) ranging from 6 kPa to 100 kPa.

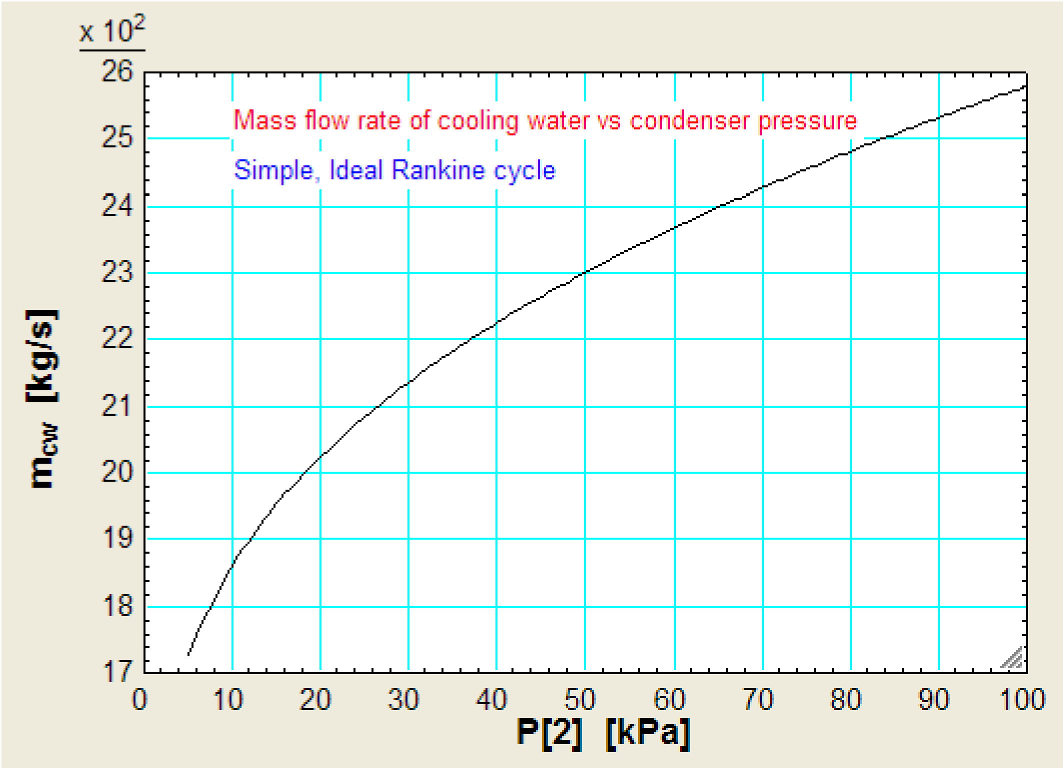
First, compute the Parametric Table:

1..15	P_2 [kPa]	$Qtot_{in}$ [kW]	η_{th}	m_{cw} [kg/s]
Run 1	5	244368	0.4092	1727
Run 2	11.79	258612	0.3867	1897
Run 3	18.57	267641	0.3736	2005
Run 4	25.36	274571	0.3642	2088
Run 5	32.14	280324	0.3567	2157
Run 6	38.93	285310	0.3505	2217
Run 7	45.71	289752	0.3451	2270
Run 8	52.5	293786	0.3404	2318
Run 9	59.29	297499	0.3361	2362
Run 10	66.07	300953	0.3323	2404
Run 11	72.86	304194	0.3287	2443
Run 12	79.64	307255	0.3255	2479
Run 13	86.43	310161	0.3224	2514
Run 14	93.21	312934	0.3196	2547
Run 15	100	315590	0.3169	2579

Now, plot the results:




Thermal effcy. vs condenser pressure
Simple, Ideal Rankine cycle
ηth
0.42
0.4
0.38
0.36
0.34
0.32
0.3
0
10
20
30
40
50
60
70
80
90
100
P[2] [kPa]

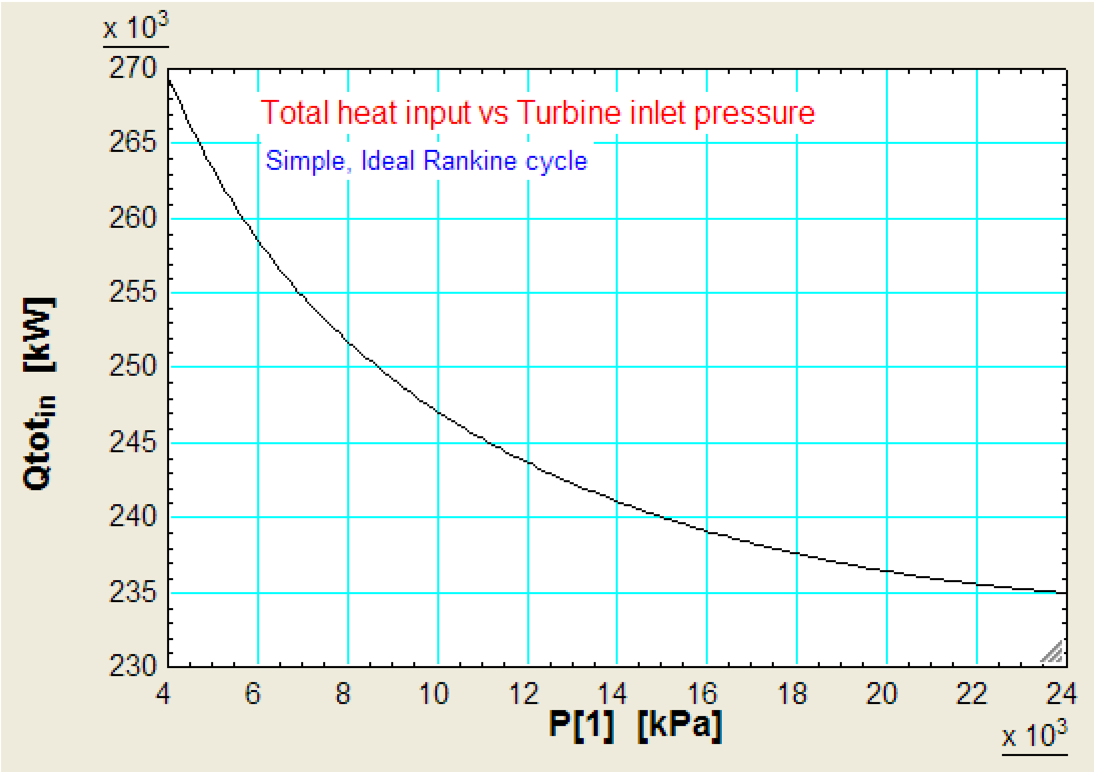


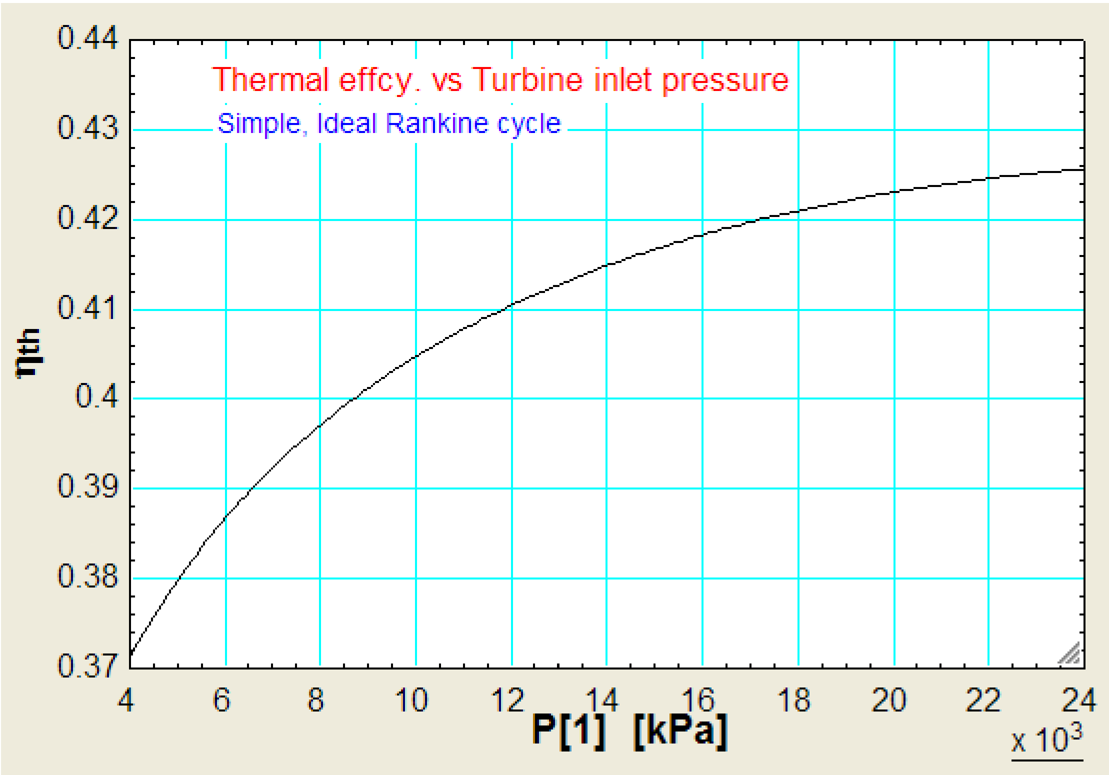
(c) Plot each of the quantities in (a) as steam generator pressure (P1) varies from 4 MPa to 24 MPa, maintaining T1 at 480 C.

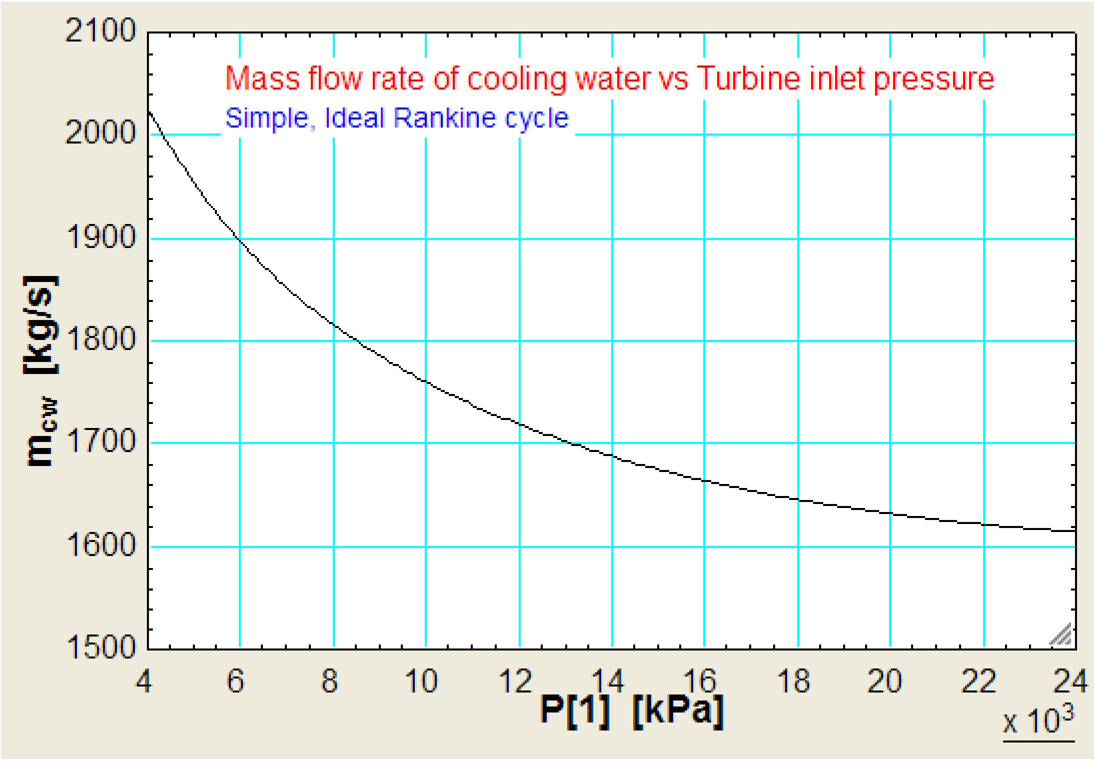
First, compute the Parametric Table:

1..11	P_1 [kPa]	$Qtot_{in}$ [kW]	η_{th}	m_{cw} [kg/s]
Run 1	4000	269416	0.3712	2027
Run 2	6000	258549	0.3868	1897
Run 3	8000	251778	0.3972	1816
Run 4	10000	247090	0.4047	1759
Run 5	12000	243657	0.4104	1718
Run 6	14000	241065	0.4148	1687
Run 7	16000	239079	0.4183	1664
Run 8	18000	237554	0.421	1645
Run 9	20000	236396	0.423	1632
Run 10	22000	235543	0.4246	1621
Run 11	24000	234952	0.4256	1614

Now, plot the results:







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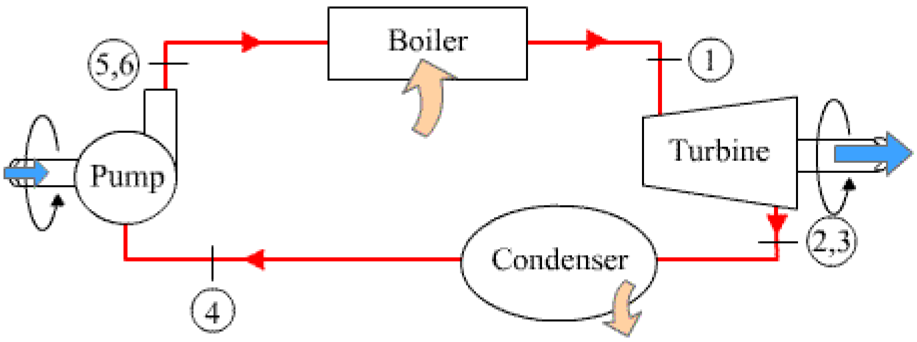
"**Prob.3.3.2** Write an EES Procedure to calculate thermal effcy etc of a Simple, actual, Rankine cycle, i.e. considering the isentropic efficiencies of turbine and pump:"



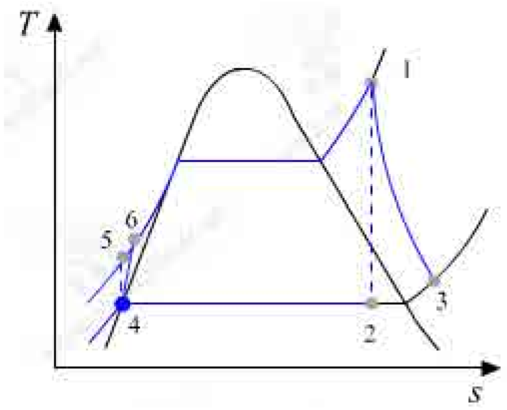


Fig.Prob.3.3.2 (a) Schematic diagram of simple, actual Rankine cycle, and (b) T-s diagram [Ref: 7]

EES Solution:

$UnitSystem kPa C kJ

PROCEDURE Simple_actual_Rankine(P[1], T[1], P[2], eta_turb, eta_pump: T[3], w_turb_act, w_p_act, w_net, eta_th,q_in, q_out)

"**Inputs**:P1(kPa), T1 (C), P2 (kPa), eta_turb, eta_comp

Outputs: T3 (C…actual turbine outlet temp), w_turb_act (kJ/kg), w_comp_act (kJ/kg), w_net (kJ/kg), eta_th, q_in (kJ/kg), q_out (kJ/kg)"

```
Fluid$ := 'Steam_IAPWS'

P[3]:=P[2]"....pressure at actual exit from turbine"

P[4]:=P[2]"...pressure at inlet of pump"

P[5] := P[1] "...pressure at exit of pump"

P[6] := P[5]

x[4]=0.0 "...sat. liq. at entry to pump"

"Calculations:"

h[1] :=ENTHALPY(Fluid$,T=T[1],P=P[1])"kJ/kg...enthalpy of fluid at entry to turbine"

s[1] :=ENTROPY(Fluid$,T=T[1],P=P[1]) "kJ/kg.C...entropy of fluid at entry to turbine"

s[2] :=s[1] "...for isentropic expn. in turbine"

T[2] :=TEMPERATURE(Fluid$,P=P[2],s=s[2])"C...temp at isentr. exit of turbine"

h[2] :=ENTHALPY(Fluid$,s=s[2],P=P[2])"kJ/kg...enthalpy of fluid at exit of turbine"

w_turb_isentr := h[1] – h[2] "kJ/kg .... turbine work output, isentropic"

w_turb_act := eta_turb * w_turb_isentr "kJ/kg ... actual turbine output"

h[3] := h[1] – w_turb_act "kJ/kg ... enthalpy at actual turbine outlet"

T[3] :=TEMPERATURE(Fluid$,P=P[3],h=h[3])"C...temp at actual exit of turbine"

x[2] :=Quality(Fluid$,T=T[2],s=s[2])"....quality of steam at isentropic exit of turbine"

v_f :=VOLUME(Fluid$,P=P[4],x=x[4]) "m^3/kg ... sp. vol. of fluid entering the pump"

T[4] :=T_SAT(Fluid$,P=P[4]) "...sat. temp. at condenser pressure"

h[4] :=ENTHALPY(Fluid$,T=T[4],x=x[4])"kJ/kg ... enthalpy at entry to pump"
```

w_p_isentr := v_f * (P[5]-P[4]) ".kJ..isentr. pump work"

w_p_act := w_p_isentr / eta_pump "kJ/kg …. actual pump work required"

h[5] :=h[4]+w_p_isentr "kJ/kg … enthalpy at the isentropic exit of pump"

h[6] := h[4] + w_p_act "kJ/kg … enthalpy at actual exit of pump"

q_in :=h[1]-h[6]"kJ/kg"

q_out :=h[3]-h[4]"kJ/kg"

w_net := w_turb_act – w_p_act "kJ/kg …. net work output"

eta_th :=1- q_out/q_in "…thermal effcy."

s[3] :=ENTROPY(Fluid$,P=P[3],h=h[3]) "kJ/kg.C … entropy of fluid at actual exit of turbine"

s[4] := ENTROPY(Fluid$,P=P[4],x=x[4]) "kJ/kg.C … entropy of fluid at inlet of pump"

s[5] := s[4]"…isentropic compression in pump"

T[5] :=TEMPERATURE(Fluid$,P=P[5],s=s[5])"C…temp at isentropic exit of pump"

s[6] :=ENTROPY(Fluid$,P=P[6],h=h[6]) "kJ/kg.C … entropy of fluid at actual exit of pump"

T[6] :=TEMPERATURE(Fluid$,P=P[6],s=s[6])"C…temp at actual exit of pump"

END

"==="

"**Example:** Verify the results obtained in Prob.3.3.1"

We have:

P[1]=8000 "kPa"
T[1] = 480"C"
P[2] = 8"kPa"

eta_turb = 1"…isentropic effcy. of turbine "
eta_pump = 1"…isentropic effcy. of pump"

CALL Simple_actual_Rankine(P[1], T[1],P[2], eta_turb, eta_pump: T[3], w_turb_act, w_p_act, w_net, eta_th,q_in,q_out)

Results:

Main | Simple_actual_Rankine

Unit Settings: SI C kPa kJ mass deg

η_{pump} = 1	η_{th} = 0.3972	η_{turb} = 1
q_{in} = 3168 [kJ/kg]	q_{out} = 1910 [kJ/kg]	w_{net} = 1258 [kJ/kg]
$w_{p,act}$ = 8.06 [kJ/kg]	$w_{turb,act}$ = 1266 [kJ/kg]	

We see that the results match.

Auxiliary results calculated are obtained from the 'Simple_actual_Rankine' tab in the Results:

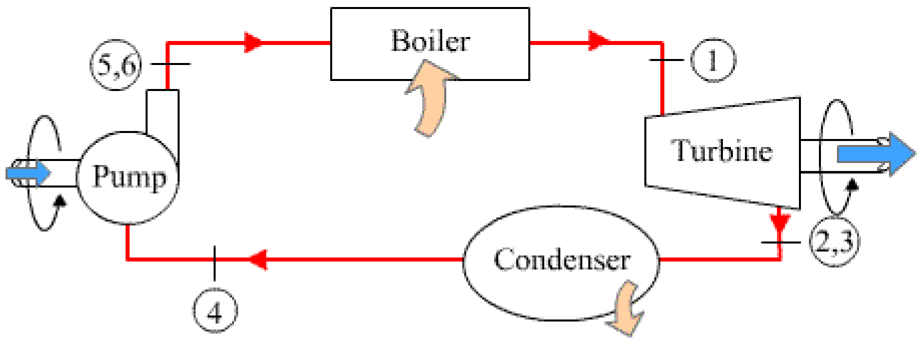
Local variables in Procedure Simple_actual_Rankine (1 call, 0.02 sec)

η_{pump}=1	η_{th}=0.3972	η_{turb}=1
Fluid$='Steam_IAPWS'	h_1=3350 [kJ/kg]	h_2=2083 [kJ/kg]
h_3=2083 [kJ/kg]	h_4=173.8 [kJ/kg]	h_5=181.9 [kJ/kg]
h_6=181.9 [kJ/kg]	P_1=8000 [kPa]	P_2=8 [kPa]
P_3=8 [kPa]	P_4=8 [kPa]	P_5=8000 [kPa]
P_6=8000 [kPa]	q_{in} =3168 [kJ/kg]	q_{out} =1910 [kJ/kg]
s_1=6.661 [kJ/kg-C]	s_2=6.661 [kJ/kg-C]	s_3=6.661 [kJ/kg-C]
s_4=0.5925 [kJ/kg-C]	s_5=0.5925 [kJ/kg-C]	s_6=0.5925 [kJ/kg-C]
T_1=480 [C]	T_2=41.51 [C]	T_3=41.51 [C]
T_4=41.51 [C]	T_5=41.75 [C]	T_6=41.75 [C]
v_f =0.001008 [m^3/kg]	w_{net} =1258 [kJ/kg]	$w_{p,act}$ =8.06 [kJ/kg]
$w_{p,isentr}$=8.06 [kJ/kg]	$w_{turb,act}$ =1266 [kJ/kg]	$w_{turb,isentr}$=1266 [kJ/kg]
x_2 =0.7949	x_4 =0	

===

Prob.3.3.3 Superheated steam enters the turbine of an actual, simple Rankine cycle at 8 MPa, 480 C. The condenser pressure is 8 kPa. The net power output of the cycle is 100 MW. Isentropic effcy of turbine = 85%, and that of the pump is 70%. Determine: (i) thermal effcy., (ii) mass flow rate of steam, (iii) mass flow rate of condenser cooling water in kg/s, if water enters the condenser at 15 C and exits at 35 C.

b) Plot each of the quantities mentioned above for condenser pressures ranging from 6 kPa to 100 kPa.
c) Plot each of the quantities in (a) as steam generator pressure varies from 4 MPa to 24 MPa, maintaining the turbine inlet temp at 480 C. [Ref: 3]



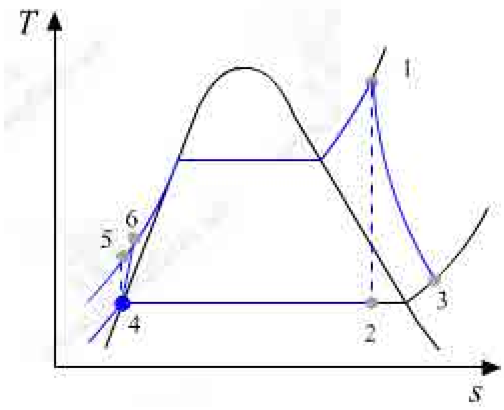


Fig.Prob.3.3.3 (a) Schematic diagram of simple, actual Rankine cycle, and (b) T-s diagram [Ref: 7]

EES Solution:

We shall use the EES Procedure written above:

"Data:"

P[1]=8000"kPa"

T[1] = 480"C"

P[2] = 8"kPa"

eta_turb = 0.85

eta_pump = 0.7

cp_w = 4.18"kJ/kg.C…sp. heat of condenser cooling water"

T_cw1 = 15 "C… inlet temp of cooling water"

T_cw2 = 35 "C … exit temp of cooling water"

"Calculations:"

CALL Simple_actual_Rankine(P[1], T[1],P[2], eta_turb, eta_pump: T[3], w_turb_act, w_p_act, w_net, eta_th,q_in,q_out)

Power = 100000 "kW"

"Therefore:"

m_steam = Power / w_net "kg/s….mass flow rate of steam required to produce net power of 100 MW"

m_w * cp_w * (T_cw2 – T_cw1) = m_steam * q_out "…finds mass flow rate of cooling water required, m_w, by an energy balance in the condenser"

Results:

Unit Settings: SI C kPa kJ mass deg

cp_w = 4.18 [kJ/kg-C]	η_{pump} = 0.7	η_{th} = 0.3365	η_{turb} = 0.85
m_{steam} = 93.92 [kg/s]	m_w = 2359 [kg/s]	Power = 100000 [kW]	q_{in} = 3164 [kJ/kg]
q_{out} = 2100 [kJ/kg]	T_{cw1} = 15 [C]	T_{cw2} = 35 [C]	w_{net} = 1065 [kJ/kg]
$w_{p,act}$ = 11.51 [kJ/kg]	$w_{turb,act}$ = 1076 [kJ/kg]		

Thus:

Thermal effcy. = eta_th = 0.3365 = 33.65%…Ans.

Mass flow rate of steam = m_steam = 93.92 kg/s …. Ans.

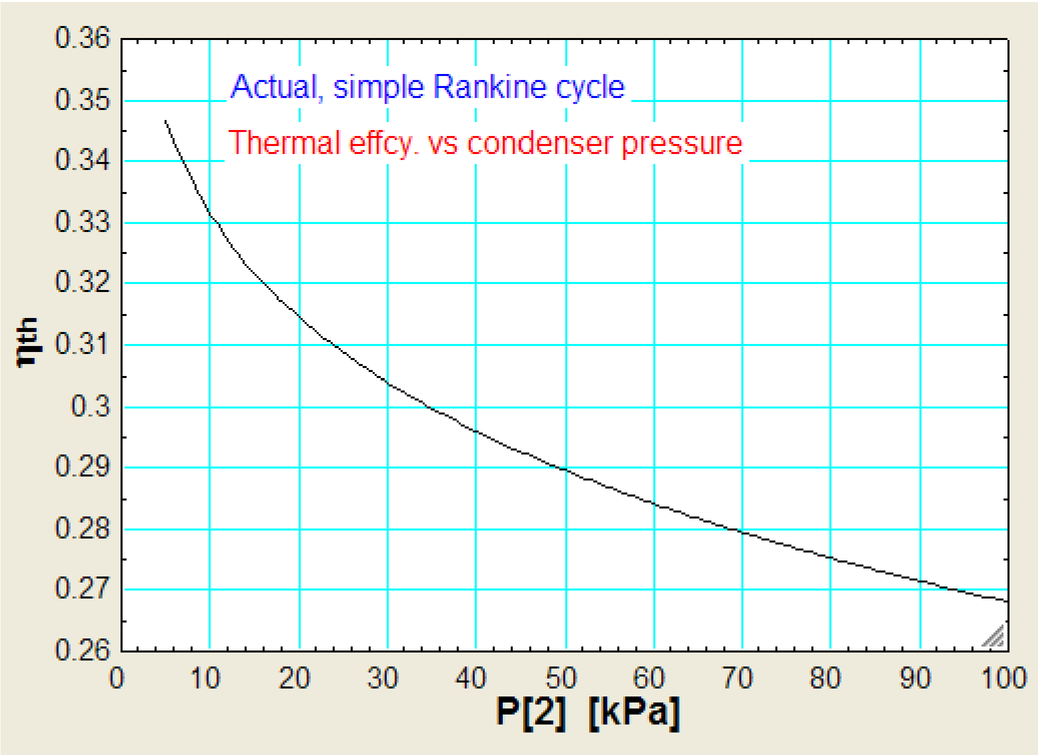
Mass flow rate of cooling water = m_w = 2359 kg/s …. Ans.

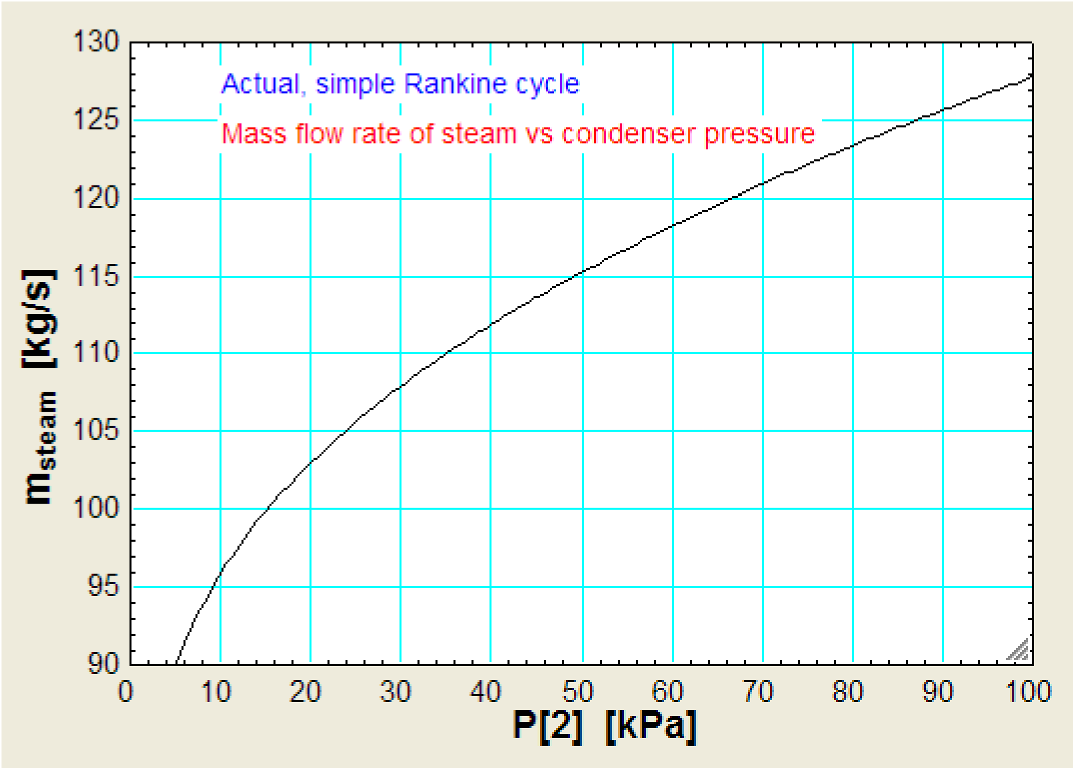
(b) Plot each of the quantities mentioned above for condenser pressures (P2) ranging from 6 kPa to 100 kPa:

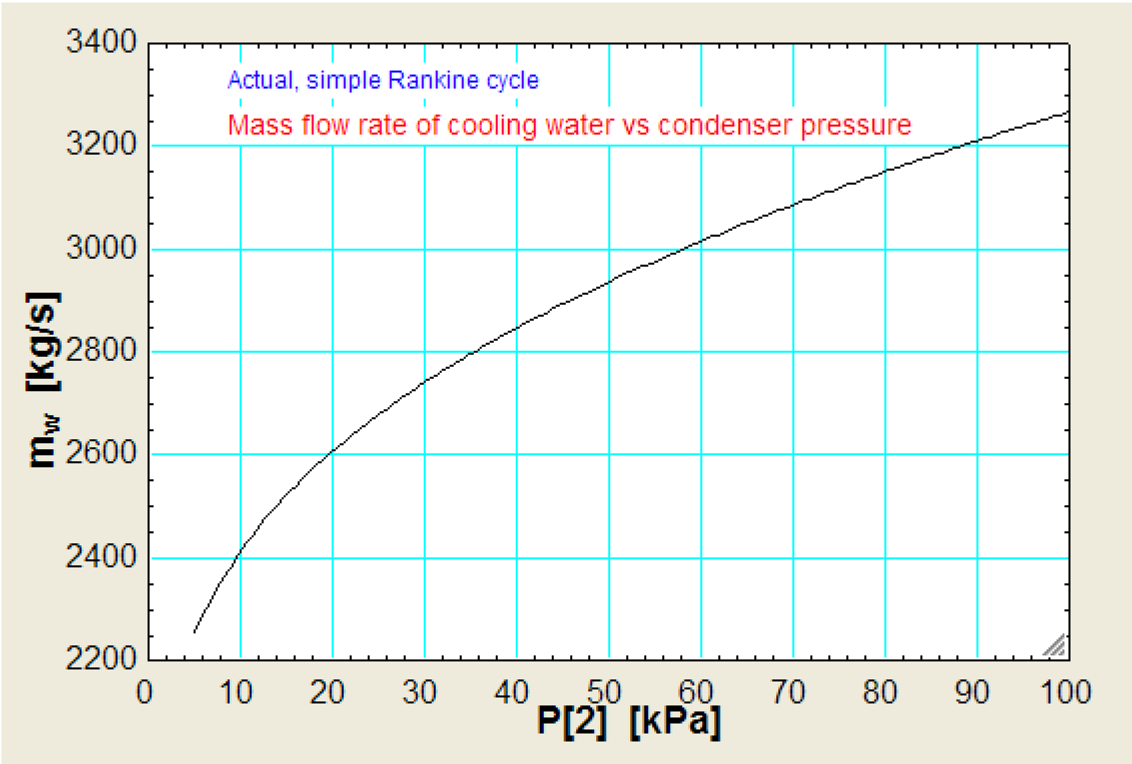
First, compute the Parametric Table:

1..15	1 P_2 [kPa]	2 η_{th}	3 m_{steam} [kg/s]	4 m_w [kg/s]
Run 1	5	0.3468	90.11	2253
Run 2	11.79	0.3275	97.45	2456
Run 3	18.57	0.3164	102.2	2584
Run 4	25.36	0.3084	105.8	2683
Run 5	32.14	0.302	108.8	2764
Run 6	38.93	0.2967	111.5	2835
Run 7	45.71	0.2921	113.9	2899
Run 8	52.5	0.2881	116	2956
Run 9	59.29	0.2845	118	3009
Run 10	66.07	0.2812	119.8	3058
Run 11	72.86	0.2782	121.6	3104
Run 12	79.64	0.2754	123.2	3148
Run 13	86.43	0.2728	124.8	3189
Run 14	93.21	0.2703	126.3	3229
Run 15	100	0.268	127.8	3267

Now, plot the results:




Actual, simple Rankine cycle
Mass flow rate of steam vs condenser pressure
m_{steam} [kg/s]
P[2] [kPa]
130
125
120
115
110
105
100
95
90
0
10
20
30
40
50
60
70
80
90
100

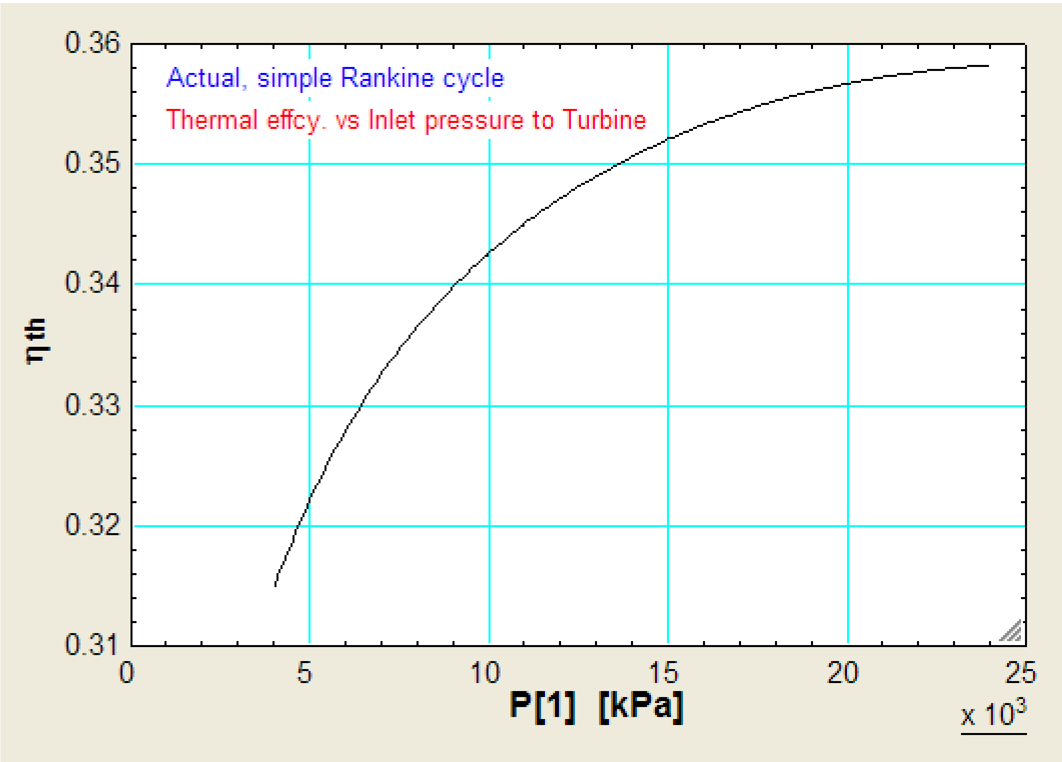

Actual, simple Rankine cycle
Mass flow rate of cooling water vs condenser pressure
m_w [kg/s]
P[2] [kPa]
3400
3200
3000
2800
2600
2400
2200
0
10
20
30
40
50
60
70
80
90
100

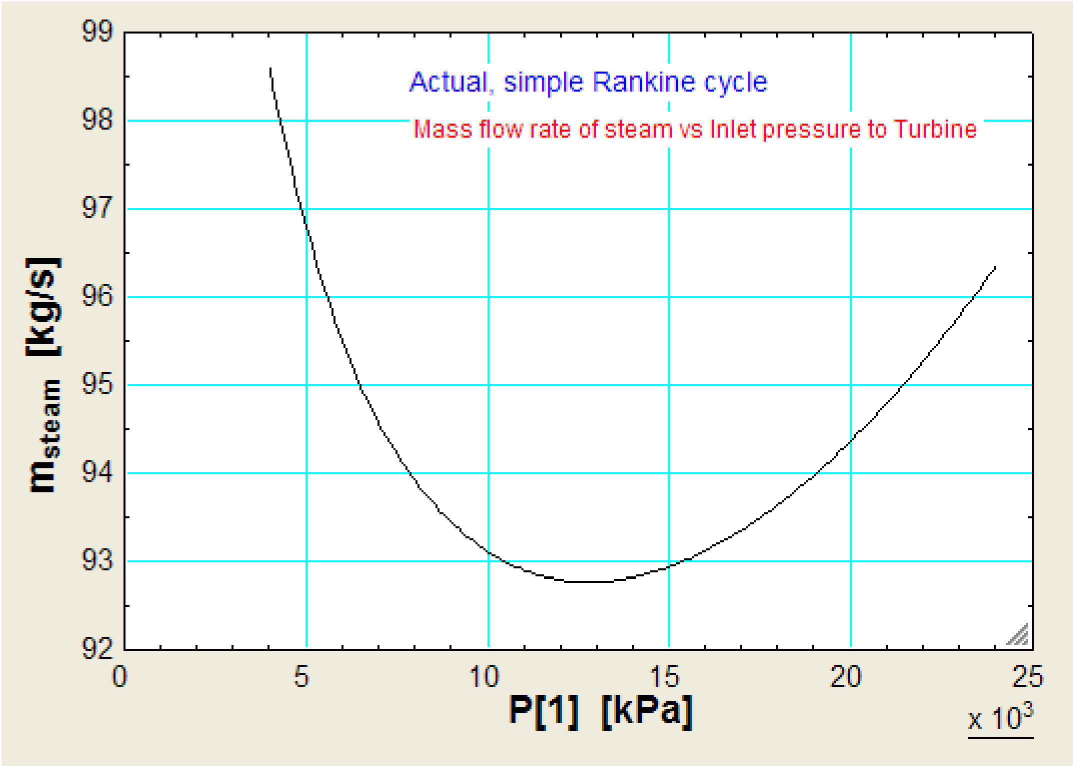
(c) Plot each of the quantities in (a) as steam generator pressure (P1) varies from 4 MPa to 24 MPa, maintaining the turbine inlet temp at 480 C:

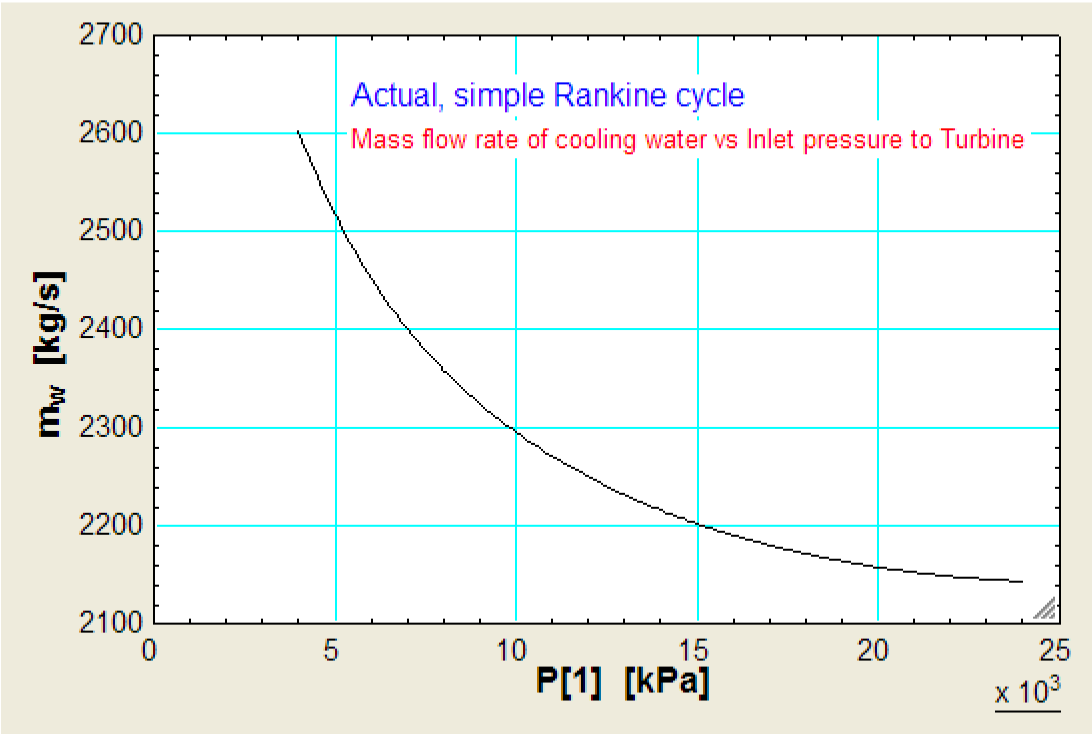
First, compute the Parametric Table:

1..11	P_1 [kPa]	η_{th}	m_{steam} [kg/s]	m_w [kg/s]
Run 1	4000	0.3149	98.59	2602
Run 2	6000	0.3279	95.51	2451
Run 3	8000	0.3365	93.92	2359
Run 4	10000	0.3426	93.11	2295
Run 5	12000	0.3472	92.79	2249
Run 6	14000	0.3506	92.82	2215
Run 7	16000	0.3533	93.12	2190
Run 8	18000	0.3552	93.65	2171
Run 9	20000	0.3567	94.37	2157
Run 10	22000	0.3577	95.28	2148
Run 11	24000	0.3582	96.37	2143

Now, plot the results:




Actual, simple Rankine cycle
Mass flow rate of steam vs Inlet pressure to Turbine
msteam [kg/s]
99
98
97
96
95
94
93
92
0
5
10
15
20
25
P[1] [kPa]
x 10³


Actual, simple Rankine cycle
Mass flow rate of cooling water vs Inlet pressure to Turbine
mw [kg/s]
2700
2600
2500
2400
2300
2200
2100
0
5
10
15
20
25
P[1] [kPa]
x 10³

(d) Use the Diagram Window in EES to input data and make calculations:

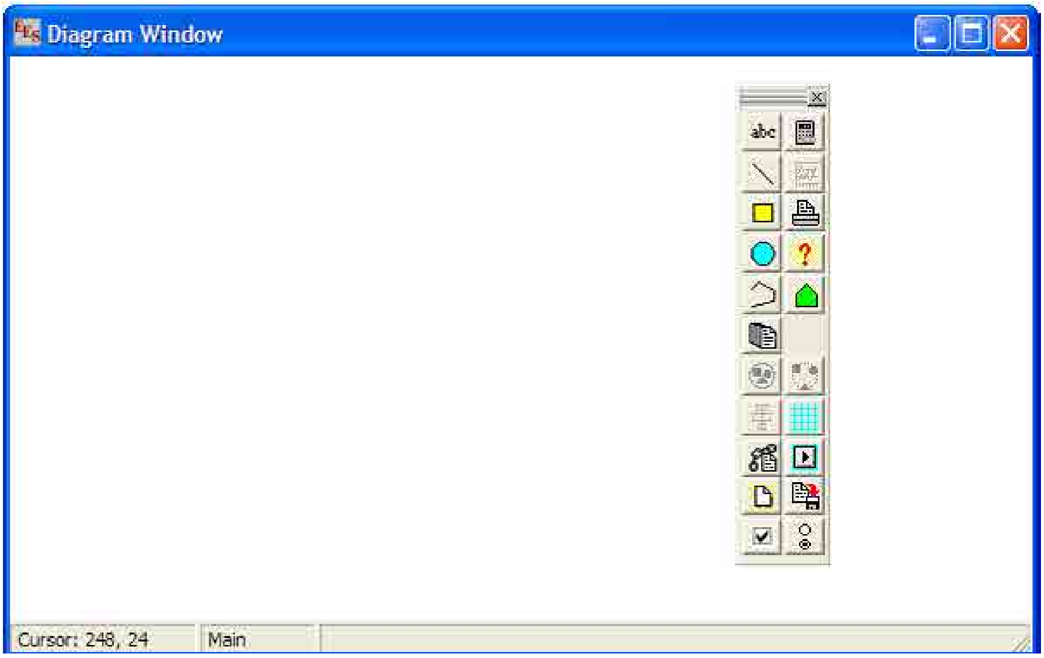
Diagram Window in EES can be used to input data. Simple diagrams can be made with the tool bar provided, or diagrams made in your favorite software can be copied in to the diagram window.

Advantages of using the diagram window are:

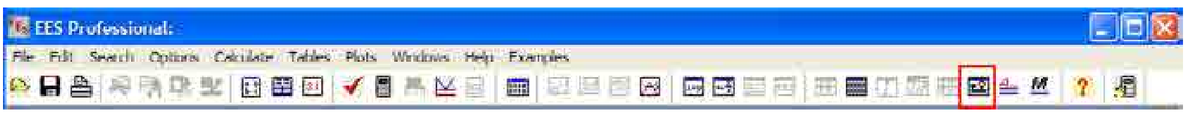
1. Drawings, plots and data and results cal all be shown in a single window, thus adding to the clarity of solution
2. Changing the data and doing the calculations to observe the results are done from a single window
3. Since the user need not know the details of calculations and has to o0nly input the data, press 'Calculate' button and observe the results, he need not be conversant with the software nor the details of calculations.
4. Can be distributed to those in the team who may not know details of EES.

Following is the procedure to use the diagram window:

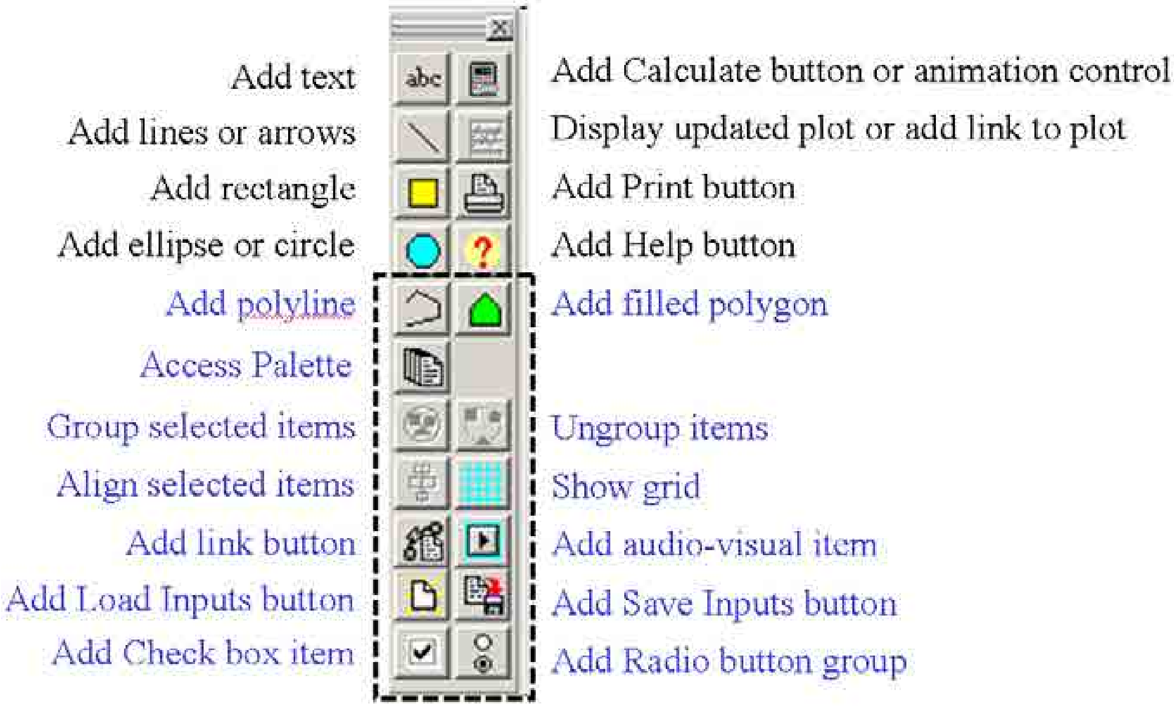
a) From the equations window, press ^D (i.e. control + D). We get:



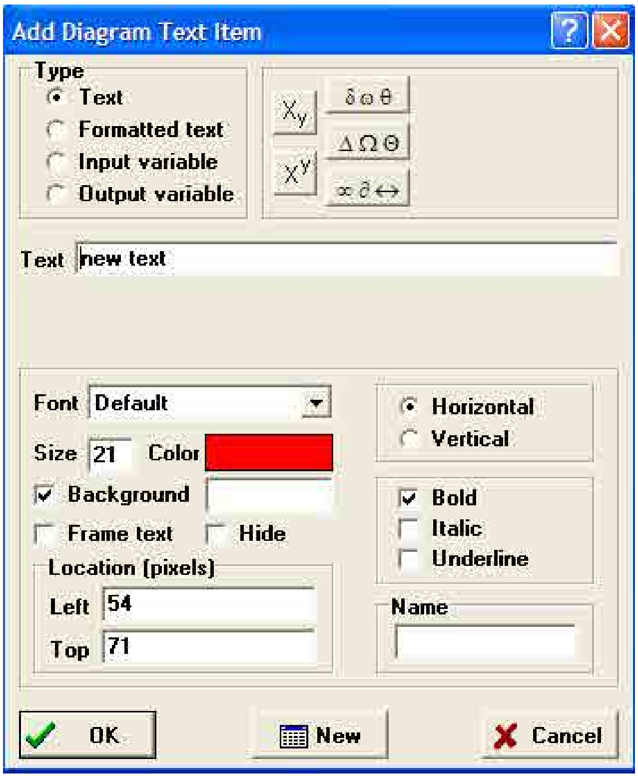
On the right, you see the vertical, diagram window tool bar.
You can also get the diagram window by clicking on the 'speed button' in the tool bar of eqn. window, as shown below:



Explanation of each button in the diagram window tool bar is given below (Ref: EES Manual):

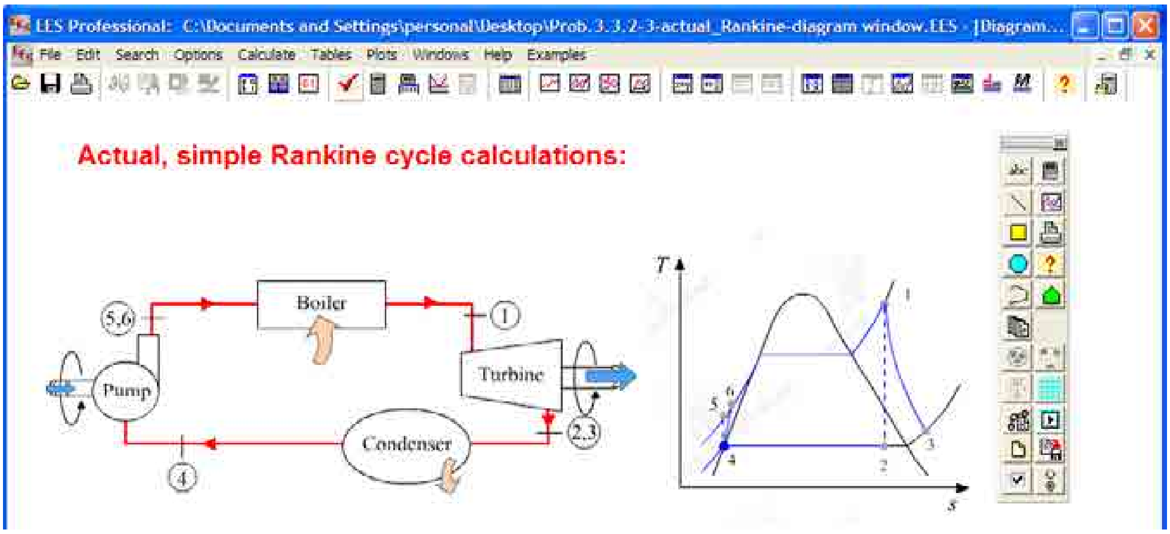


b) After copying the schematic diagram and T-s diagram, press on the top, left button (i.e. Add text) on the tool bar:

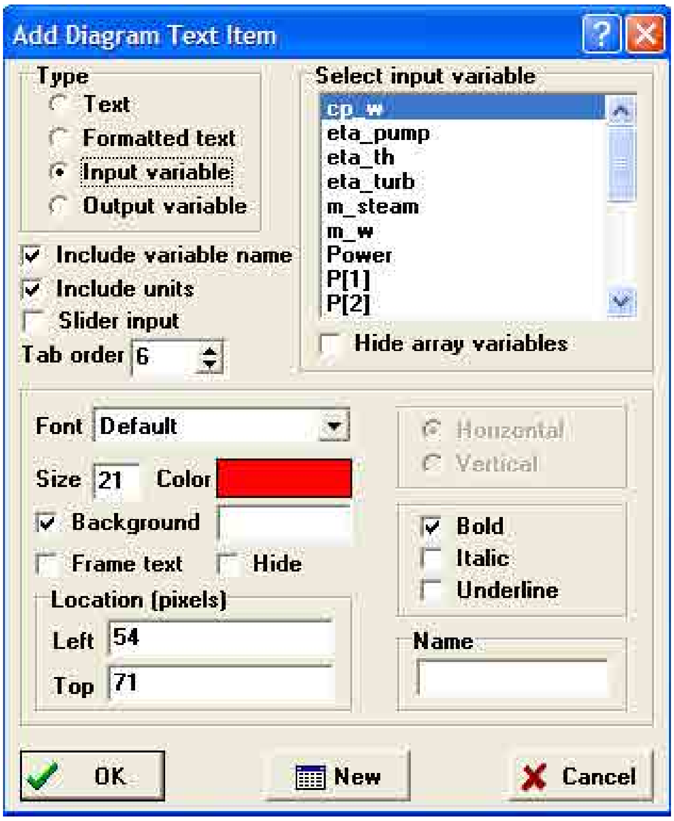


Here, by choosing the radio buttons, we can enter text, formatted text, input variable or output variables.

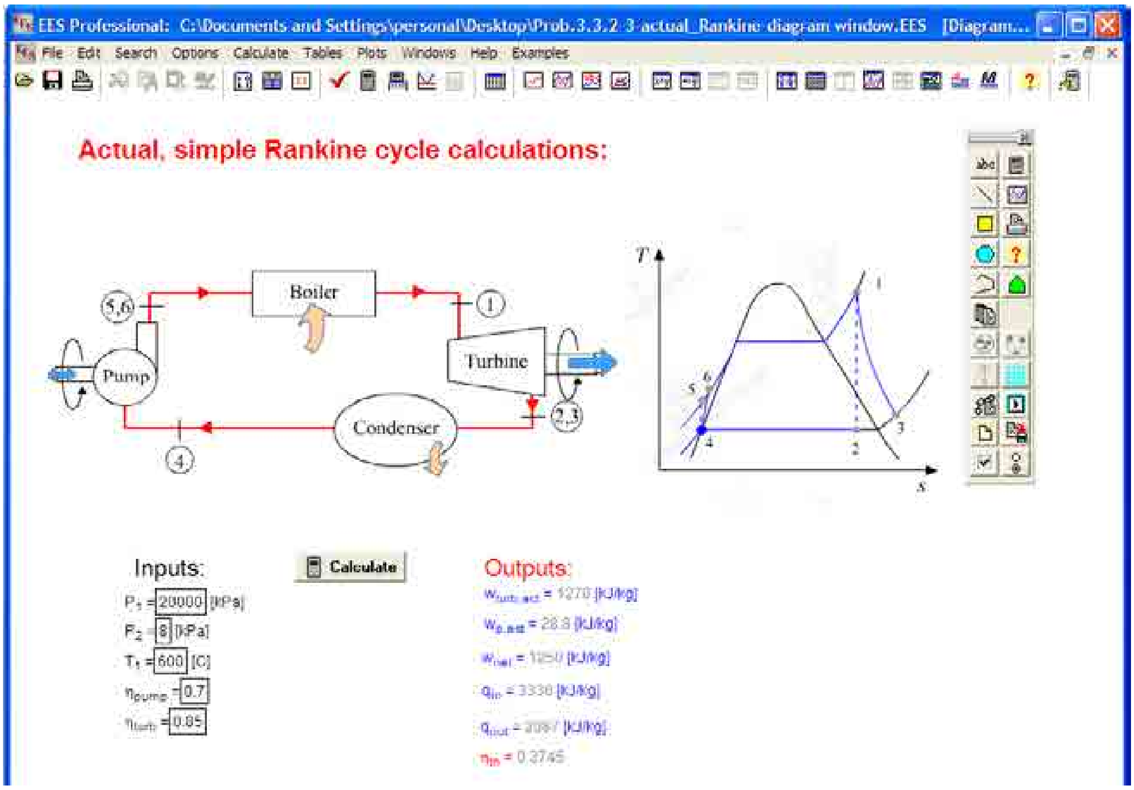
Partly completed diagram window is shown below:



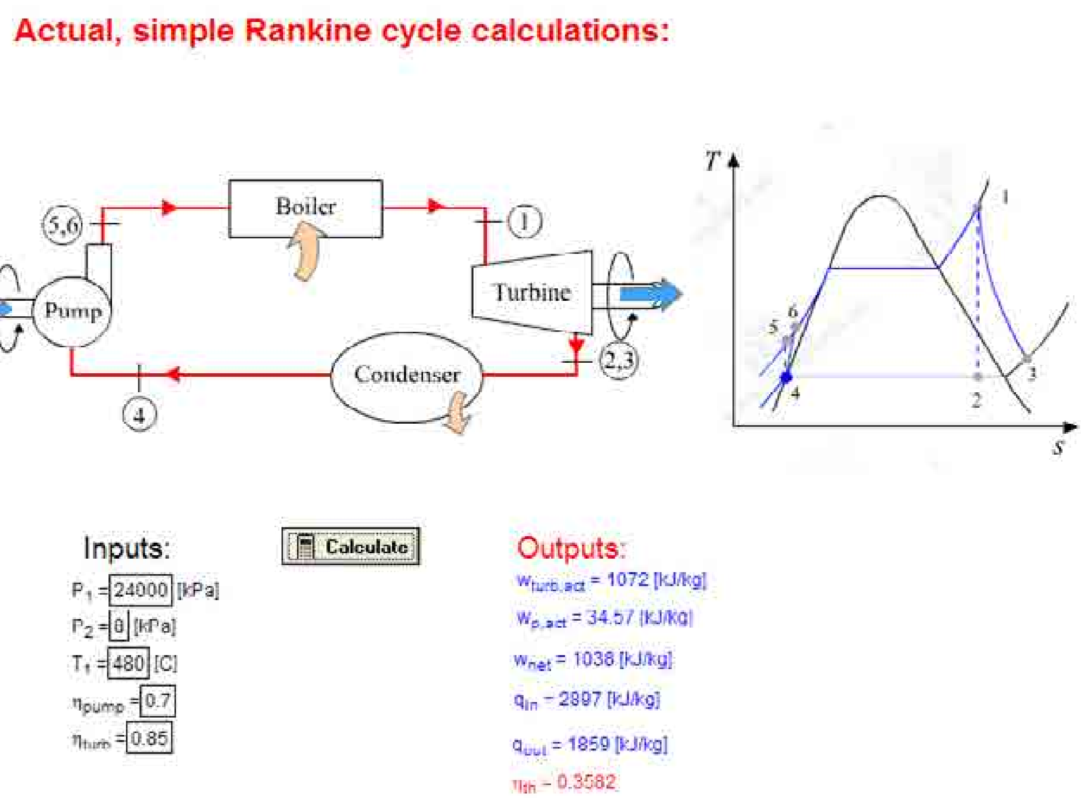
c) Now, select the Input variable radio button, and we get:



d) Choose the required Input variables and click OK one by one. They appear neatly on the Diagram window. You can drag them and position wherever you feel like. Do the same thing with Output variables too. And add a **'Calculate'** button also, from the tool bar on the right. Final arrangement of Diagram window is shown below:

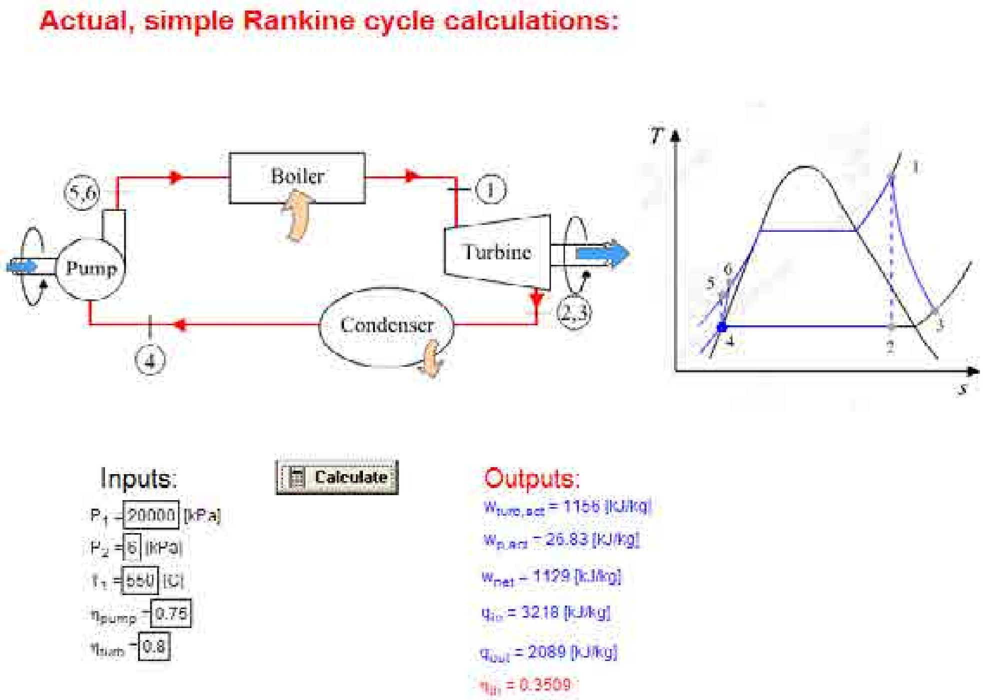


e) **To make calculations:** When the tool bar is visible in the diagram window, it is said to be in the *'Development mode'*, i.e. you can add diagrams, text etc. To do calculations, you have to change to the *'Application mode'*. To do this, press (control+ D) again. The tool bar disappears and you are in the Applications mode. Thus, by pressing (control + D) you can alternate between these two modes easily. In Applications mode, now, we have:



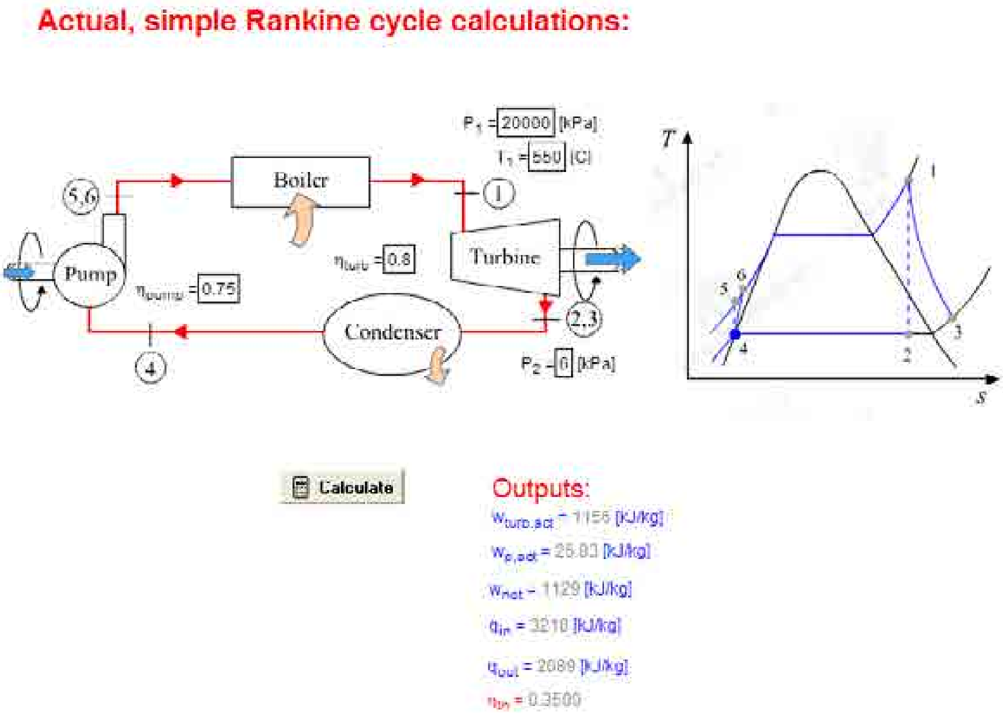
In Applications mode, we can input any new values we desire for the Input variables, and press **'Calculate'** button, and immediately the output variables update themselves.

As an example, make following entries for Input variables: P1 = 20 MPa, P2 = 6 kPa, T1 = 550 C, eta_pump = 0.75 and eta_turb = 0.8. And, click on **Calculate** button. We get:



In the above screen shot, see how the results have changed.

f) In addition, you can position the Input variables, by the side of respective components in the schematic diagram itself for clarity. For example, eta_turb can be placed by the side of the turbine, P1, T1 over the Turbine, eta_pump near the pump etc. See below:



There are many other buttons in the tool bar, and many more possibilities of using the diagram window; Refer to the User Manual in EES to get more information.

Thus, Diagram window is a very convenient, useful facility in EES.

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Prob.3.3.4 An ideal Rankine cycle with reheat uses water as the working fluid. The conditions at the inlet to the first stage turbine are 14 MPa, 600 C and the steam is reheated between the turbine stages to 600 C. For a condenser pressure of 6 kPa, plot the cycle thermal efficiency versus reheat pressure for pressures ranging from 2 to 12 MPa. [Ref: 3]

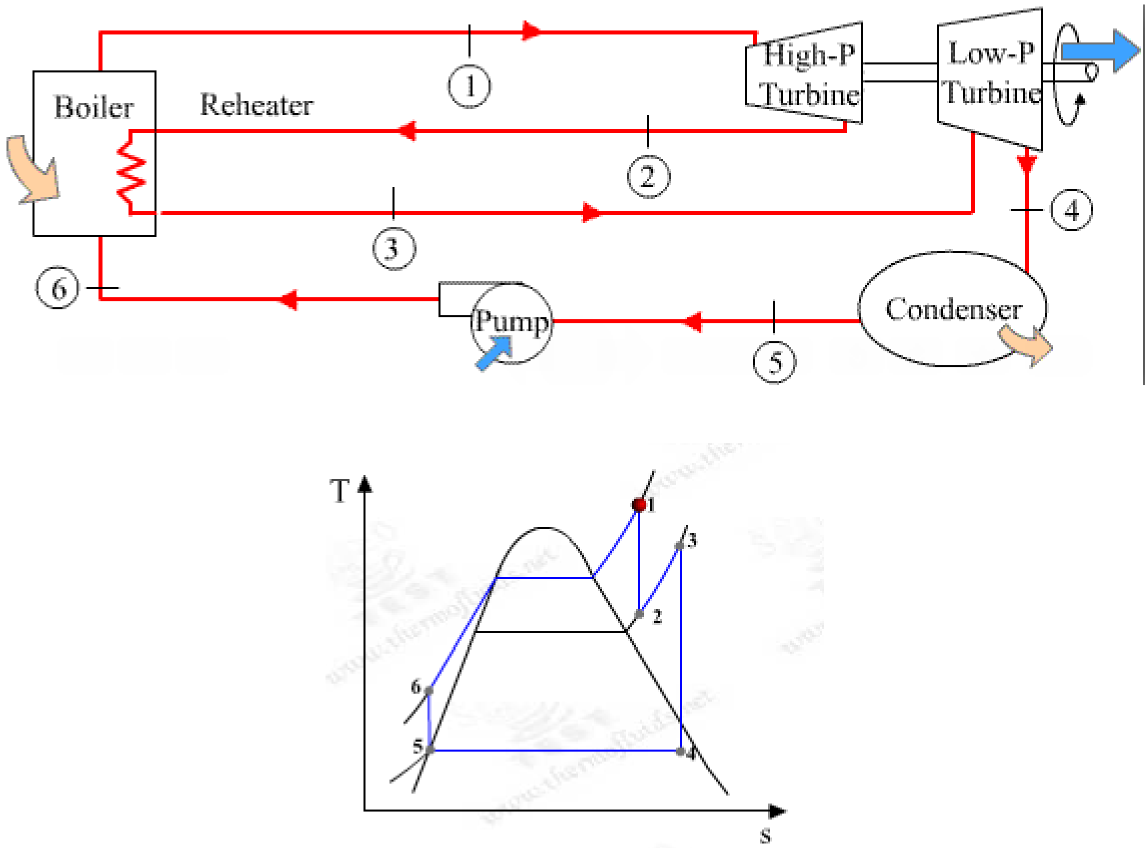


Fig.Prob.3.3.4 (a) Ideal Rankine cycle with reheat, and (b) T-s diagram

EES Solution:

"Data:"

Fluid$ = 'Steam_IAPWS'

P[1]=14000[kPa]"…at entry to HP turbine"

T[1]= 600[C] "…HP turbine inlet temp."

T[3] = 600[C] "..reheat temp"

P[2]=2000[kPa]"…reheat pressure…. at exit of HP turbine"

P[3] = P[2]"…at inlet to LP turbine"

P[4]=6 [kPa]"….at exit of LP turbine"

P[5]=P[4]"…at inlet of pump"

P[6] = P[1] "..at exit of pump, i.e. inlet to boiler"

x[5] = 0 "…sat. liq. at entry to pump"

```
"Calculations:"

h[1]=ENTHALPY(Fluid$,T=T[1],P=P[1])"kJ/kg…enthalpy of fluid at entry to HP turbine"

s[1]=ENTROPY(Fluid$,T=T[1],P=P[1]) "kJ/kg.C…entropy of fluid at entry to HP turbine"

s[2]=s[1] "…for isentropic expn. in HP turbine"

h[2]=ENTHALPY(Fluid$,s=s[2],P=P[2])"kJ/kg…enthalpy of fluid at exit of HP turbine"

T[2]=TEMPERATURE(Fluid$,s=s[2],h=h[2])"C…temp at exit of HP turbine"

h[3]=ENTHALPY(Fluid$,T=T[3],P=P[3])"kJ/kg…enthalpy of fluid at entry to LP turbine"

s[3]=ENTROPY(Fluid$,T=T[3],P=P[3]) "kJ/kg.C…entropy of fluid at entry to LP turbine"

s[4] = s[3] "…for isentropic expn. in LP turbine"

h[4]=ENTHALPY(Fluid$,s=s[4],P=P[4])"kJ/kg…enthalpy of fluid at exit of LP turbine"

T[4]=TEMPERATURE(Fluid$,s=s[4],h=h[4])"C…temp at exit of LP turbine"

x[2]=Quality(Fluid$,T=T[2],s=s[2])"….quality of steam at exit of HP turbine"

x[4]=Quality(Fluid$,T=T[4],s=s[4])"….quality of steam at exit of LP turbine"

v_f=VOLUME(Fluid$,P=P[5],x=x[5]) "m^3/kg … sp. vol. of fluid entering the pump"

T[5]=T_SAT(Fluid$,P=P[5]) "…sat. temp. at condenser pressure"

h[5]=ENTHALPY(Fluid$,T=T[5],x=x[5])"kJ/kg … enthalpy at entry to pump"

w_p = v_f * (P[6]-P[5]) ".kJ..pump work"

h[6] = h[5]+w_p "kJ/kg … enthalpy at the exit of pump"

q_boiler = h[1]-h[6]"kJ/kg …. heat input in boiler"

q_reheat = h[3]-h[2]"kJ/kg … heat input in reheater"
```

q_in = q_boiler + q_reheat "kJ/kg …. total heat input to cycle"

q_out=h[4]-h[5]"kJ/kg"

w_turb1 = h[1] – h[2] "kJ/kg …. HP turbine work output"

w_turb2 = h[3] – h[4] "kJ/kg …. LP turbine work output"

w_turb_tot = w_turb1 + w_turb2 "kJ/kg … total turbine work output"

w_net = w_turb_tot – w_p "kJ/kg …. net work output"

eta_th=1- q_out/q_in "….thermal efficiency of cycle"

s[5]=ENTROPY(Fluid$,P=P[5],h=h[5]) "kJ/kg.C … entropy of fluid at entry to pump"

s[6] = s[5]"…isentropic compression in pump"

T[6]=TEMPERATURE(Fluid$,P=P[6],s=s[6])"C…temp at exit of pump"

Results (with reheat pressure P2 = 2000 kPa):

Unit Settings: SI C kPa kJ mass deg

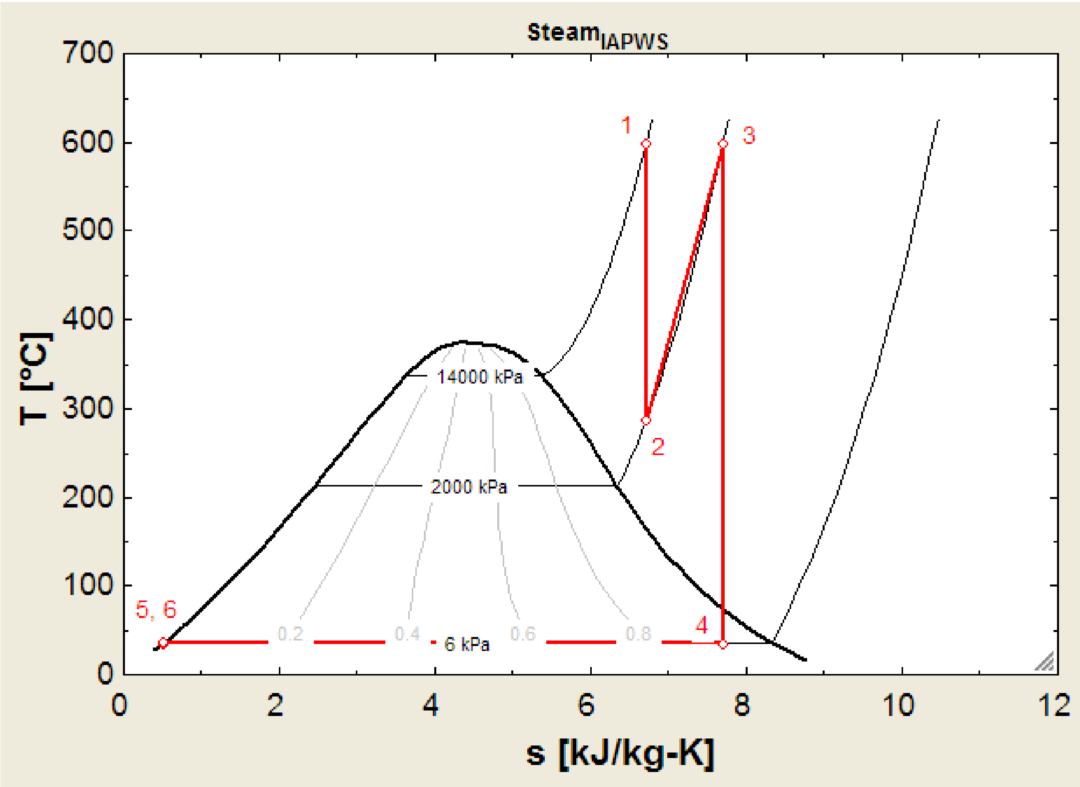
η_{th} = 0.4608
q_{in} = 4121 [kJ/kg]
v_f = 0.001006 [m^3/kg]
w_{turb1} = 595.6 [kJ/kg]
Fluid$ = 'Steam_IAPWS'
q_{out} = 2222 [kJ/kg]
w_{net} = 1899 [kJ/kg]
w_{turb2} = 1317 [kJ/kg]
q_{boiler} = 3426 [kJ/kg]
q_{reheat} = 694.5 [kJ/kg]
w_p = 14.08 [kJ/kg]
$w_{turb,tot}$ = 1913 [kJ/kg]

Sort	h_i	P_i [kPa]	s_i	T_i [C]	x_i
[1]	3592	14000	6.719	600	
[2]	2996	2000	6.719	288	100
[3]	3691	2000	7.704	600	
[4]	2373	6	7.704	36.16	0.92
[5]	151.5	6	0.5208	36.16	0
[6]	165.6	14000	0.5208	36.53	

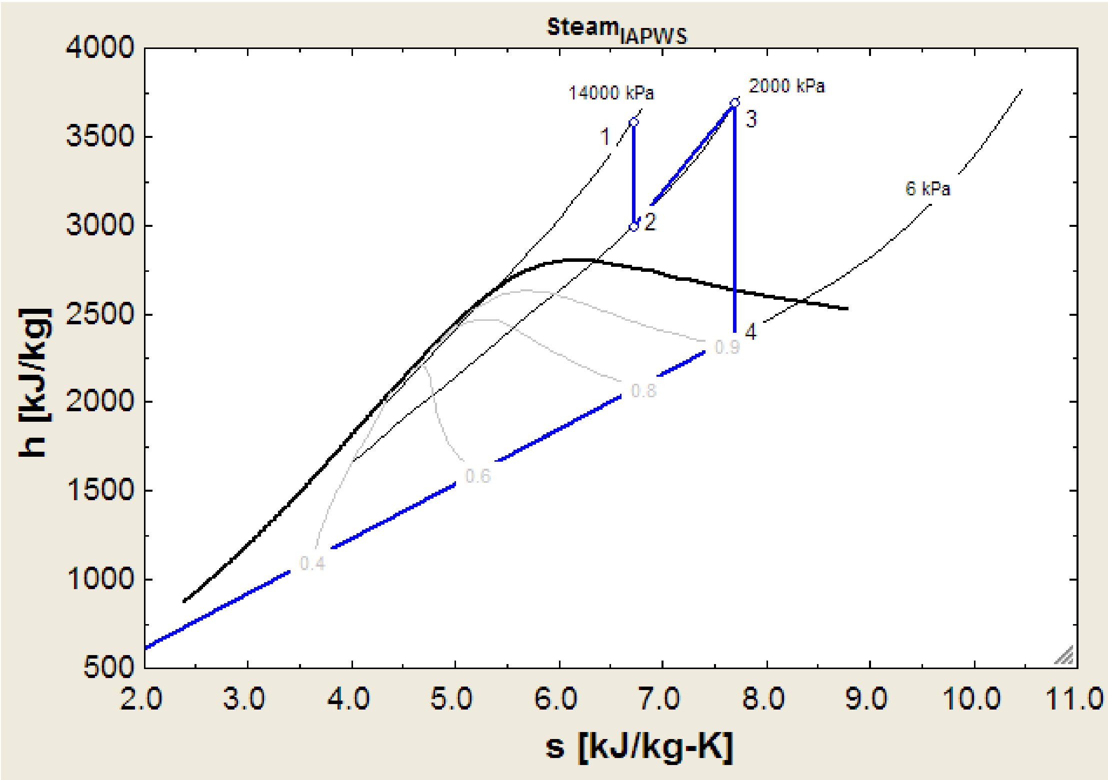
Thus, for a reheat pressure of 2 MPa, we have:

Thermal efcy of cycle = eta_th = 0.4608 = 46.08% …. Ans.

Cycle on the T-s plot, using Property plot of EES:



Cycle on the h-s plot, using Property plot of EES:

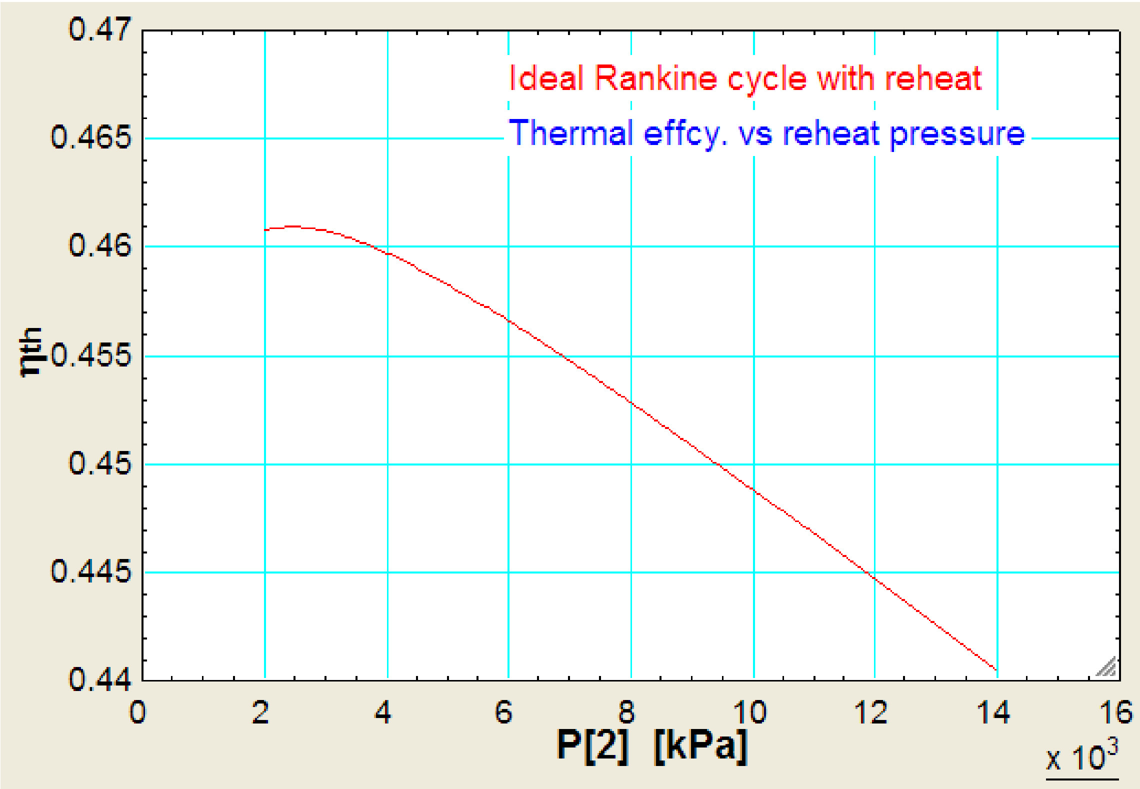


(b) Plot Thermal effcy. vs reheat pressure (P2):

First, compute the Parametric Table:

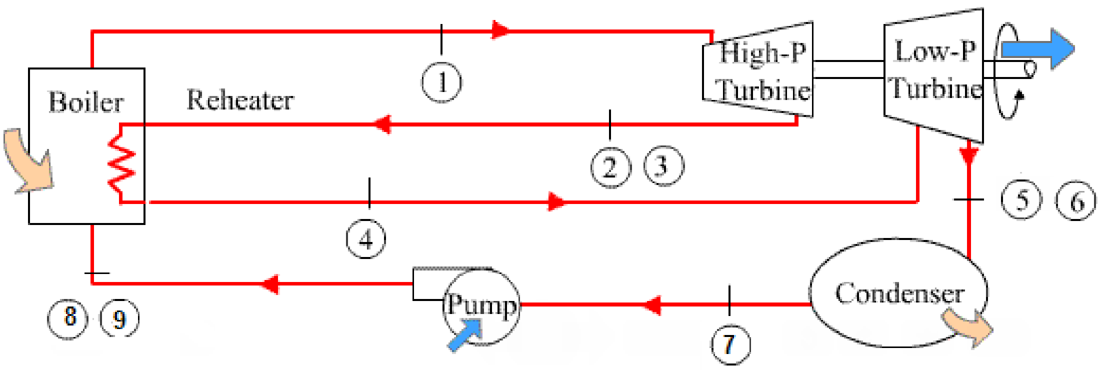
1..13	P_2 [kPa]	w_{net} [kJ/kg]	q_{in} [kJ/kg]	η_{th}
Run 1	2000	1899	4121	0.4608
Run 2	3000	1847	4009	0.4607
Run 3	4000	1803	3921	0.4597
Run 4	5000	1763	3848	0.4583
Run 5	6000	1728	3784	0.4566
Run 6	7000	1695	3727	0.4547
Run 7	8000	1664	3675	0.4528
Run 8	9000	1635	3627	0.4508
Run 9	10000	1608	3582	0.4488
Run 10	11000	1581	3540	0.4467
Run 11	12000	1556	3500	0.4447
Run 12	13000	1532	3462	0.4426
Run 13	14000	1509	3426	0.4404

Now, plot the results:



===

Prob.3.3.5 An actual Rankine cycle with reheat uses water as the working fluid. The conditions at the inlet to the first stage turbine are 14 MPa, 600 C and the steam is reheated between the turbine stages to 600 C. For a condenser pressure of 6 kPa, plot the cycle thermal efficiency versus reheat pressure for pressures ranging from 2 to 12 MPa. Assume the isentropic efficiencies of both the turbines, and the pump as 0.8. [Ref: 3]



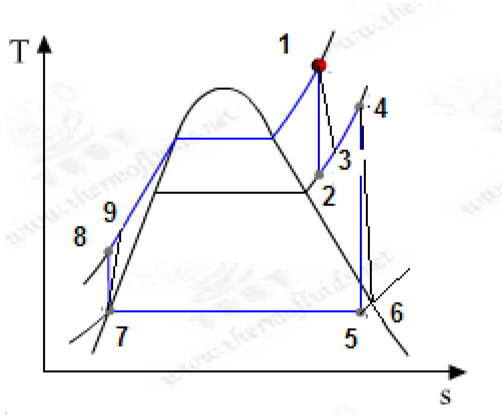


Fig.Prob.3.3.5 (a) Actual Rankine cycle with reheat, and (b) T-s diagram

EES Solution:

Let us first write an EES Procedure for Actual Rankine cycle with reheat:

$UnitSystem kPa C kJ

PROCEDURE Reheat_Rankine_actual(P[1],P[2], P[5], T[1],T[4],eta_turb1,eta_turb2,eta_pump:w_turb1,w_turb2,w_p,w_net,q_boiler,q_reheat,q_in,q_out,eta_th)

```
{Reheat_Rankine_actual finds eta_th etc for an actual, reheat Rankine cycle.

Pressures in kPa, Temps in C, Work in kJ/kg

Inputs: P[1], T[1] … at inlet of HP Turbine, , P[2], T[4],… at inlet of LP Turbine, P[5] at incondenser (or inlet to pump)

eta_turb1,eta_turb2,eta_pump …isentropic efficiencies of HP turb, LP turb and pump

Outputs: w_turb1,w_turb2,w_p …. actual wors of HP turb, LP turb and pump
w_net …. net work output,
q_boiler,q_reheat,…. heat transferred in boiler and reheater
q_in,… total heat supplied, q_out … heat rej. in condenser
 eta_th …. thermal effcy.
}

Fluid$ := 'Steam_IAPWS'

P[3] := P[2]"…at actual exit of HP turbine"

P[4]:=P[2]"….at inlet of LP turbine"

P[6] :=P[5]"…at inlet of pump"

P[6] := P[5] "..at exit of LP Turbine, inlet of condenser"

P[7] := P[6] "..at inlet to pump"

P[8] := P[1]"at isentropic exit of pump"

P[9] := P[8]

x[7] := 0 "…sat. liq. at entry to pump"
```

"Calculations:"

h[1]:=ENTHALPY(Fluid$,T=T[1],P=P[1])"kJ/kg…enthalpy of fluid at entry to HP turbine"

s[1]:=ENTROPY(Fluid$,T=T[1],P=P[1]) "kJ/kg.C…entropy of fluid at entry to HP turbine"

s[2]:=s[1] "…for isentropic expn. in HP turbine"

h[2]:=ENTHALPY(Fluid$,s=s[2],P=P[2])"kJ/kg…enthalpy of fluid at isentropic exit of HP turbine"

T[2]:=TEMPERATURE(Fluid$,s=s[2],h=h[2])"C…temp at isentropic exit of HP turbine"

w_turb1_isentr := h[1] – h[2] "kJ/kg …. HP turbine isentr. work output"

w_turb1 := eta_turb1 * w_turb1_isentr "kJ/kg …. HP turbine actual work output"

h[3] :=h[1] – w_turb1"kJ/kg… enthalpy of fluid at iactual exit of HP turbine"

s[3] :=ENTROPY(Fluid$,h=h[3],P=P[3]) "kJ/kg.C…entropy of fluid at actual exit of HP turbine"

T[3] := TEMPERATURE(Fluid$,s=s[3],h=h[3])"C…temp at actual exit ofHP turbine"

h[4] :=ENTHALPY(Fluid$,T=T[4],P=P[4])"kJ/kg…enthalpy of fluid at inlet of LP turbine"

s[4] :=ENTROPY(Fluid$,T=T[4],h=h[4]) "kJ/kg.C…entropy of fluid at inlet of LP turbine"

s[5] := s[4] "…for isentropic expn. in LP turbine"

h[5]=ENTHALPY(Fluid$,s=s[5],P=P[5])"kJ/kg…enthalpy of fluid at isentropic exit of LP turbine"

w_turb2_isentr := h[4] – h[5] "kJ/kg …. LP turbine isentr. work output"

w_turb2 := eta_turb2 * w_turb2_isentr "kJ/kg …. LP turbine actual work output"

h[6] :=h[4] – w_turb2"kJ/kg… enthalpy of fluid at iactual exit of LP turbine"

s[6] :=ENTROPY(Fluid$,P=P[6],h=h[6]) "kJ/kg.C…entropy of fluid at actual exit of LP turbine"

T[6] := TEMPERATURE(Fluid$,s=s[6],h=h[6])"C…temp at actual exit ofHP turbine"

T[7] :=T_SAT(Fluid$,P=P[7]) "…sat. temp. at condenser pressure"

s[7] :=ENTROPY(Fluid$,T=T[7],x=x[7]) "kJ/kg.C…entropy of fluid at entry to pump"

```
h[7] :=ENTHALPY(Fluid$,T=T[7],x=x[7])"kJ/kg … enthalpy at entry to pump"

s[8] := s[7]"..for isentropic comprn. in pump"

v_f=VOLUME(Fluid$,P=P[7],x=x[7]) "m^3/kg … sp. vol. of fluid entering the pump"

w_p_isentr := v_f * (P[8] – P[7]) "kJ/kg … isentr. pump work"

w_p := w_p_isentr/eta_pump "kJ/kg …. actual pu,p work"

h[8] :=h[7] + w_p_isentr"kJ/kg … enthalpy at isentr. exit of pump"

h[9] := h[7] + w_p "kJ/kg … enthalpy at actual exit of pump"

T[8] := TEMPERATURE(Fluid$,s=s[8],P=P[8])"C…temp at isentr. exit of pump"

s[9] := ENTROPY(Fluid$,P=P[9],h=h[9]) "kJ/kg.C…entropy of fluid at actual exit of pump"

T[9] := TEMPERATURE(Fluid$,s=s[9],P=P[9])"C…temp at actual exit of pump"

x[3] :=Quality(Fluid$,T=T[3],s=s[3])"….quality of steam at actual exit of HP turbine"

x[6] :=Quality(Fluid$,T=T[6],s=s[6])"….quality of steam at actual exit of LP turbine"

q_boiler := h[1]-h[9]"kJ/kg"

q_reheat := h[4]-h[3]"kJ/kg"

q_in := q_boiler + q_reheat "kJ/kg …. total heat input to cycle"

q_out :=h[6]-h[7]"kJ/kg"

w_turb_tot := w_turb1 + w_turb2 "kJ/kg … total turbine work output"

w_net := w_turb_tot – w_p "kJ/kg …. net work output"

eta_th :=1- q_out/q_in "….thermal efficiency of cycle"

END

"=================================================================="
```

"Ex: Verify results of Prob.3.3.4"

We have:

"Data:"

P[1]=14000"kPa"

P[2] = 2000 "kPa … reheat pressure"

P[5] = 6 "kPa"

T[1] = 600 "C"

T[4] = 600 "C"

eta_turb1 = 1

eta_turb2 = 1

eta_pump= 1

"Calculations:"

CALL Reheat_Rankine_actual(P[1],P[2], P[5], T[1],T[4],eta_turb1,eta_turb2,eta_pump:w_turb1,w_turb2,w_p,w_net,q_boiler,q_reheat,q_in,q_out,eta_th)

Results (for a reheat pressure of 2 MPa):

Main | Reheat_Rankine_actual

Unit Settings: SI C kPa kJ mass deg

η_{pump} = 1	η_{th} = 0.4608	η_{turb1} = 1
η_{turb2} = 1	q_{boiler} = 3426 [kJ/kg]	q_{in} = 4121 [kJ/kg]
q_{out} = 2222 [kJ/kg]	q_{reheat} = 694.5 [kJ/kg]	w_{net} = 1899 [kJ/kg]
w_p = 14.08 [kJ/kg]	w_{turb1} = 595.6 [kJ/kg]	w_{turb2} = 1317 [kJ/kg]

Click on this line to see the array variables in the Arrays Table window

Main | Reheat_Rankine_actual

Local variables in Procedure Reheat_Rankine_actual (1 call, 0.02 sec)

η_{pump}=1	η_{th} =0.4608	η_{turb1} =1
Fluid$='Steam_IAPWS'	h_1=3592 [kJ/kg]	h_2=2996 [kJ/kg]
h_4=3691 [kJ/kg]	h_5=2373 [kJ/kg]	h_6=2373 [kJ/kg]
h_8=165.5628 [kJ/kg]	h_9=165.5628 [kJ/kg]	P_1=14000 [kPa]
P_3=2000 [kPa]	P_4=2000 [kPa]	P_5=6 [kPa]
P_7=6 [kPa]	P_8=14000 [kPa]	P_9=14000 [kPa]
q_{in} =4121 [kJ/kg]	q_{out} =2222 [kJ/kg]	q_{reheat} =694.5 [kJ/kg]
s_2=6.719 [kJ/kg-C]	s_3=6.719 [kJ/kg-C]	s_4=7.704 [kJ/kg-C]
s_6=7.704 [kJ/kg-C]	s_7=0.5208 [kJ/kg-C]	s_8=0.5208 [kJ/kg-C]
T_1=600 [C]	T_2=288 [C]	T_3=288 [C]
T_6=36.16 [C]	T_7=36.16 [C]	T_8=36.53 [C]
v_f =0.001006 [m^3/kg]	w_{net} =1899 [kJ/kg]	w_p=14.08 [kJ/kg]
w_{turb1} =595.6 [kJ/kg]	$w_{turb1,isentr}$ =595.6 [kJ/kg]	w_{turb2} =1317 [kJ/kg]
$w_{turb,tot}$=1913 [kJ/kg]	x_3=100	x_6=0.92

Thus, we see that the results match very well with the results obtained earlier in Prob. 3.3.4.

Now, let us solve the prob. 3.3.5 using this EES Procedure:

"Data:"

P[1]=14000"kPa"

P[2] = 2000 "kPa….reheat pressure"

P[5] = 6 "kPa"

T[1] = 600 "C"

T[4] = 600 "C"

eta_turb1 = 0.8

eta_turb2 = 0.8

eta_pump= 0.8

"Calculations:"

CALL Reheat_Rankine_actual(P[1],P[2], P[5], T[1],T[4],eta_turb1,eta_turb2,eta_pump:w_turb1,w_turb2,w_p,w_net,q_boiler,q_reheat,q_in,q_out,eta_th)

Results:

Main | Reheat_Rankine_actual

Unit Settings: SI C kPa kJ mass deg

η_{pump} = 0.8

η_{th} = 0.3784

η_{turb1} = 0.8

η_{turb2} = 0.8

q_{boiler} = 3423 [kJ/kg]

q_{in} = 3998 [kJ/kg]

q_{out} = 2485 [kJ/kg]

q_{reheat} = 575.4 [kJ/kg]

w_{net} = 1513 [kJ/kg]

w_p = 17.61 [kJ/kg]

w_{turb1} = 476.4 [kJ/kg]

w_{turb2} = 1054 [kJ/kg]

Click on this line to see the array variables in the Arrays Table window

Main | Reheat_Rankine_actual

Local variables in Procedure Reheat_Rankine_actual (1 call, 0.08 sec)

η_{pump}=0.8	η_{th}=0.3784	η_{turb1}=0.8
η_{turb2}=0.8	Fluid$='Steam_IAPWS'	h_1=3592 [kJ/kg]
h_2=2996 [kJ/kg]	h_3=3115 [kJ/kg]	h_4=3691 [kJ/kg]
h_5=2373 [kJ/kg]	h_6=2637 [kJ/kg]	h_7=151.5 [kJ/kg]
h_8=165.5628 [kJ/kg]	h_9=169.0839 [kJ/kg]	P_1=14000 [kPa]
P_2=2000 [kPa]	P_3=2000 [kPa]	P_4=2000 [kPa]
P_5=6 [kPa]	P_6=6 [kPa]	P_7=6 [kPa]
P_8=14000 [kPa]	P_9=14000 [kPa]	q_{boiler}=3423 [kJ/kg]
q_{in}=3998 [kJ/kg]	q_{out}=2485 [kJ/kg]	q_{reheat}=575.4 [kJ/kg]
s_1=6.719 [kJ/kg-C]	s_2=6.719 [kJ/kg-C]	s_3=6.922 [kJ/kg-C]
s_4=7.704 [kJ/kg-C]	s_5=7.704 [kJ/kg-C]	s_6=8.544 [kJ/kg-C]
s_7=0.5208 [kJ/kg-C]	s_8=0.5208 [kJ/kg-C]	s_9=0.5323 [kJ/kg-C]
T_1=600 [C]	T_2=288 [C]	T_3=340 [C]
T_4=600 [C]	T_6=73.07 [C]	T_7=36.16 [C]
T_8=36.53 [C]	T_9=37.39 [C]	v_f=0.001006 [m^3/kg]
w_{net}=1513 [kJ/kg]	w_p=17.61 [kJ/kg]	$w_{p,isentr}$=14.08 [kJ/kg]
w_{turb1}=476.4 [kJ/kg]	$w_{turb1,isentr}$=595.6 [kJ/kg]	w_{turb2}=1054 [kJ/kg]
$w_{turb2,isentr}$=1317 [kJ/kg]	$w_{turb,tot}$=1530 [kJ/kg]	x_3=100
x_6=100	x_7=0	

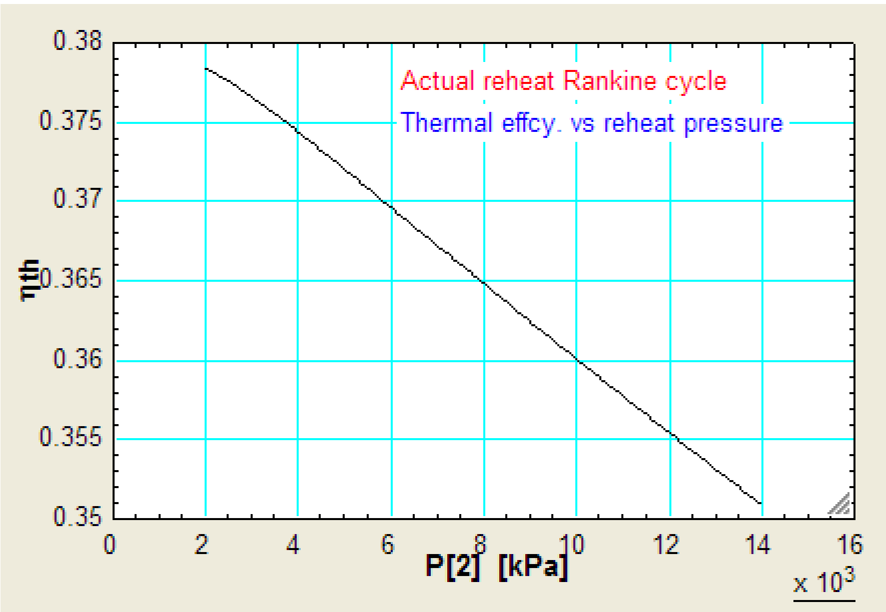
Thus: we see that the thermal effcy. when the isentropic efficiencies of HP and LPturbines and the pump are considered, becomes eta_th = 0.3784 = 37.84% … Ans.

(b) Plot the cycle thermal efficiency versus reheat pressure for pressures ranging from 2 to 12 MPa:

First, compute the Parametric Table:

1..13	P_2 [kPa]	w_{net} [kJ/kg]	q_{in} [kJ/kg]	η_{th}
Run 1	2000	1513	3998	0.3784
Run 2	3000	1471	3907	0.3766
Run 3	4000	1436	3835	0.3744
Run 4	5000	1404	3775	0.372
Run 5	6000	1376	3722	0.3696
Run 6	7000	1349	3675	0.3672
Run 7	8000	1325	3632	0.3648
Run 8	9000	1302	3592	0.3624
Run 9	10000	1280	3554	0.3601
Run 10	11000	1259	3519	0.3577
Run 11	12000	1239	3485	0.3554
Run 12	13000	1220	3453	0.3531
Run 13	14000	1201	3423	0.3509

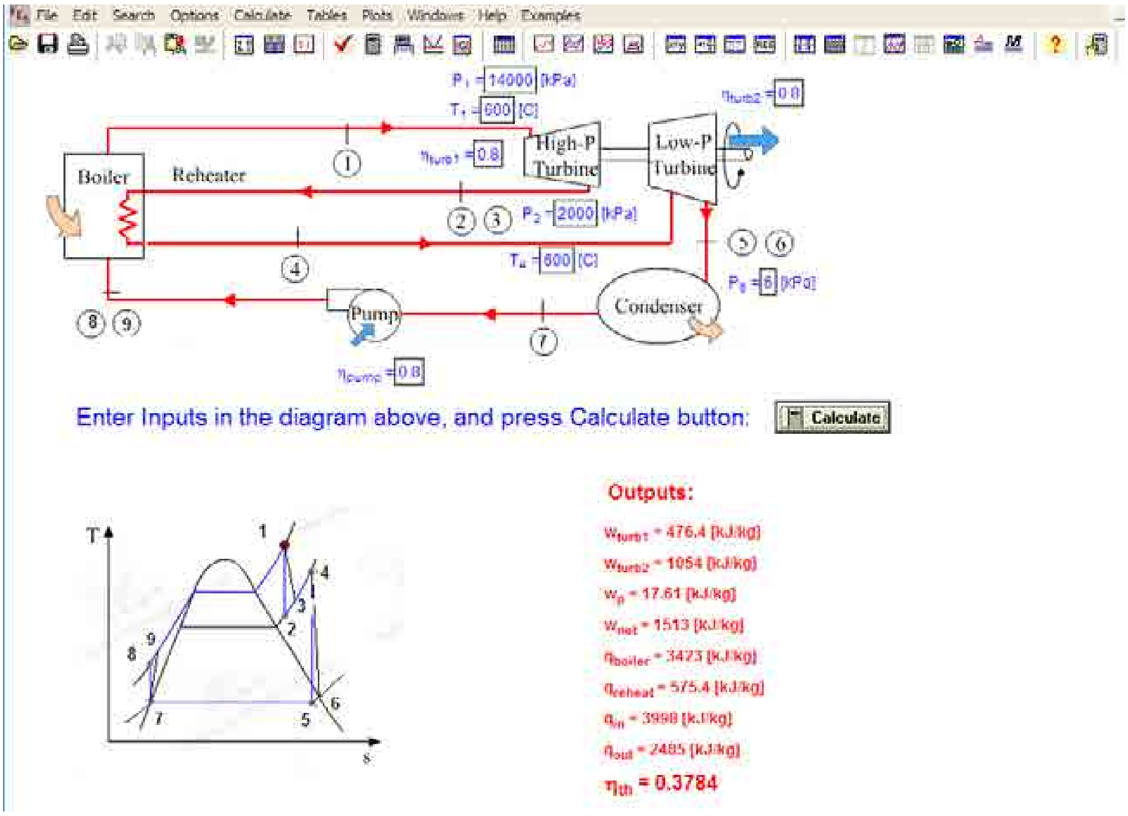
Now, plot the results:



==

(c) Use the Diagram Window in EES to input data and make calculations:

As explained in Prob. 3.3.3, we shall have Diagram window input for data, and calculations as shown below:



In the above, Inputs are from the diagram window. When you press Calculate button, above results are obtained. This confirms the results obtained in part (a) of the above problem.

===

Prob.3.3.6. A reheat cycle has the first stage supply conditions of 70 bar and 500 C. The reheat is at 3 bar and to the same temp. (i) Given that the efficiency of the first stage turbine is 80%, how much energy is added per kg of steam in the reheat coils? (ii) Assume that the same expansion efficiency exists in the second turbine. What is the thermal efficiency if the condenser pressure is 0.03 bar? [VTU-ATD-June–July 2008]

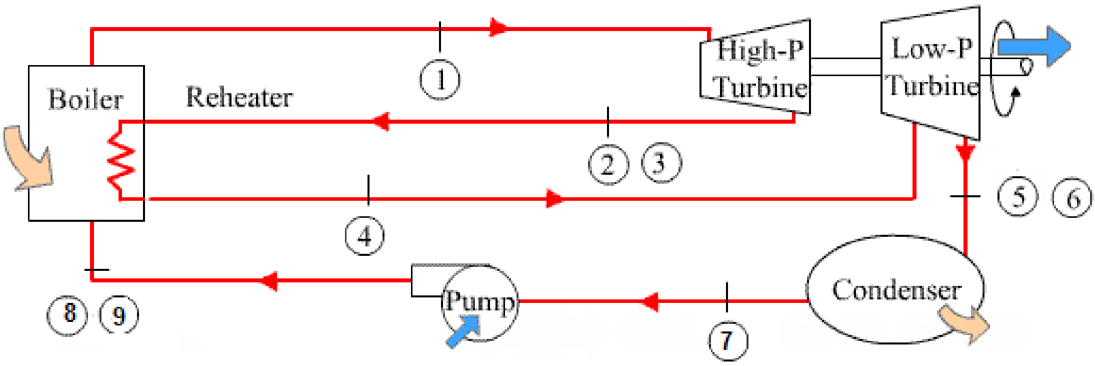


Fig.Prob.3.3.6 Actual, reheat Rankine cycle

EES Solution:

We shall use the EES Procedure developed in the previous problem, with Diagram window input of data.

Here, we have:

P[1]=7000"kPa"

P[2] = 300 "kPa….reheat pressure"

P[5] = 3 "kPa"

T[1] = 500 "C"

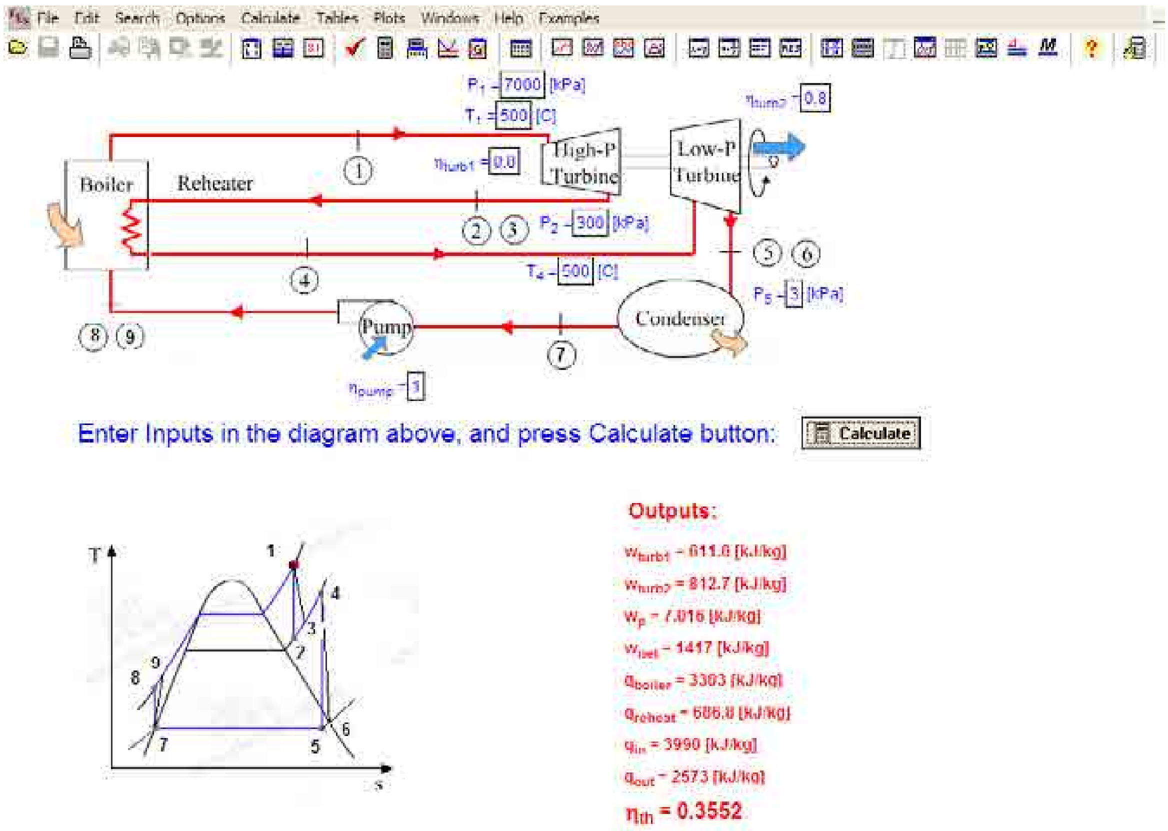
T[4] = 500 "C"

eta_turb1 = 0.8"…first stage turbine effcy."

eta_turb2 = 0.8 "…second stage turbine effcy."

eta_pump= 1"…pump effcy. assumed as 100%"

Make these entries in the schematic diagram in the EES Diagram window as shown below, and click on 'Calculate' button. Immediately, the Output results are updated:



Thus:

Heat supplied in reheat coils = q_reheat = 686.8 kJ/kg …. Ans.

Thermal efficiency = eta_th = 0.3552 = 35.52% … Ans.

===

Prob.3.3.7. A steam power plant incorporates an ideal reheat cycle to improve the existing efficiency. Steam at 30 bar and 250 C is supplied at high pressure turbine. Reheat pressure is 3 bar, reheat temp is 250 C. Condenser pressure is 0.04 bar. Determine the cycle effcy. [VTU-ATD-Dec. 2009–Jan. 2010]

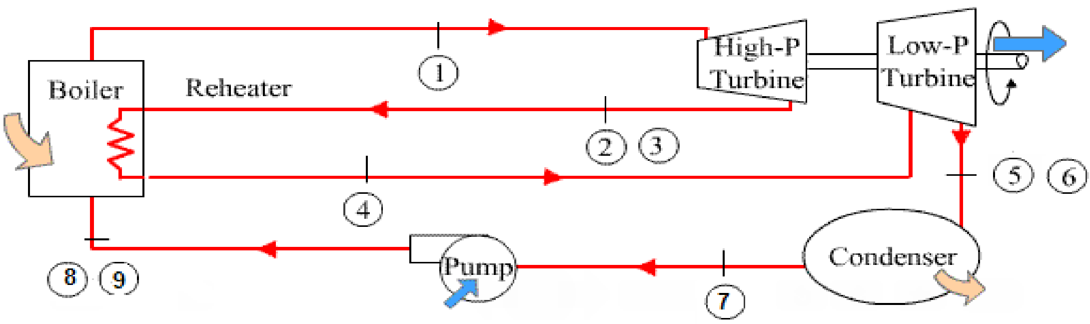


Fig.Prob.3.3.7 Actual, reheat Rankine cycle

EES Solution:

Let us use the EES Procedure written earlier, but, with the both the turbines and the pump having effcy. = 1, each.

"Data:"

P[1]=3000"kPa"

P[2] = 300 "kPa"

P[5] = 4 "kPa"

T[1] = 250 "C"

T[4] = 250 "C"

eta_turb1 = 1

eta_turb2 = 1

eta_pump= 1

"Calculations:"

CALL Reheat_Rankine_actual(P[1],P[2], P[5], T[1],T[4],eta_turb1,eta_turb2,eta_pump:w_turb1,w_turb2,w_p,w_net,q_boiler,q_reheat,q_in,q_out,eta_th)

Results:

Main | Reheat_Rankine_actual

Unit Settings: SI C kPa kJ mass deg

η_{pump} = 1	η_{th} = 0.3426	η_{turb1} = 1
η_{turb2} = 1	q_{boiler} = 2732 [kJ/kg]	q_{in} = 3261 [kJ/kg]
q_{out} = 2144 [kJ/kg]	q_{reheat} = 528.6 [kJ/kg]	w_{net} = 1117 [kJ/kg]
w_p = 3.008 [kJ/kg]	w_{turb1} = 417.3 [kJ/kg]	w_{turb2} = 702.8 [kJ/kg]

Thus: Thermal effcy. = eta_th = 0.3426 = 34.26%.... Ans.

Local variables in Procedure Reheat_Rankine_actual (1 call, 0.11 sec)

η_{pump}=1	η_{th} =0.3426	η_{turb1} =1
η_{turb2} =1	Fluid$='Steam_IAPWS'	h_1=2857 [kJ/kg]
h_2=2439 [kJ/kg]	h_3=2439 [kJ/kg]	h_4=2968 [kJ/kg]
h_5=2265 [kJ/kg]	h_6=2265 [kJ/kg]	h_7=121.4 [kJ/kg]
h_8=124.3987 [kJ/kg]	h_9=124.3987 [kJ/kg]	P_1=3000 [kPa]
P_2=300 [kPa]	P_3=300 [kPa]	P_4=300 [kPa]
P_5=4 [kPa]	P_6=4 [kPa]	P_7=4 [kPa]
P_8=3000 [kPa]	P_9=3000 [kPa]	q_{boiler}=2732 [kJ/kg]
q_{in} =3261 [kJ/kg]	q_{out} =2144 [kJ/kg]	q_{reheat} =528.6 [kJ/kg]
s_1=6.289 [kJ/kg-C]	s_2=6.289 [kJ/kg-C]	s_3=6.289 [kJ/kg-C]
s_4=7.518 [kJ/kg-C]	s_5=7.518 [kJ/kg-C]	s_6=7.518 [kJ/kg-C]
s_7=0.4224 [kJ/kg-C]	s_8=0.4224 [kJ/kg-C]	s_9=0.4224 [kJ/kg-C]
T_1=250 [C]	T_2=133.5 [C]	T_3=133.5 [C]
T_4=250 [C]	T_6=28.96 [C]	T_7=28.96 [C]
T_8=29.03 [C]	T_9=29.03 [C]	v_f =0.001004 [m^3/kg]
w_{net} =1117 [kJ/kg]	w_p=3.008 [kJ/kg]	$w_{p,isentr}$=3.008 [kJ/kg]
w_{turb1} =417.3 [kJ/kg]	$w_{turb1,isentr}$ =417.3 [kJ/kg]	w_{turb2} =702.8 [kJ/kg]
$w_{turb2,isentr}$ =702.8 [kJ/kg]	$w_{turb,tot}$=1120 [kJ/kg]	x_3=0.868
x_6 =0.8813	x_7 =0	

And,

Steam quality after expn. in first stage = x[3] = 0.868 … Ans.

Steam quality after expn. in second stage = x[6] = 0.8813 … Ans.

==

Prob. 3.3.8 A steam power plant operates on a Reheat Rankine cycle and has a net power output of 80 MW. Steam enters the HP turbine at 100 bar, 500 C and the LP turbine at 10 bar and 500 C after being reheated. It leaves the LP turbine at 0.1 bar. Assuming ideal processes (and using Mollier chart) determine: (i) quality of steam at exit of LP turbine, (ii) thermal effcy. (iii) mass flow rate of steam. [VTU-ATD-Dec. 2009–Jan. 2010]

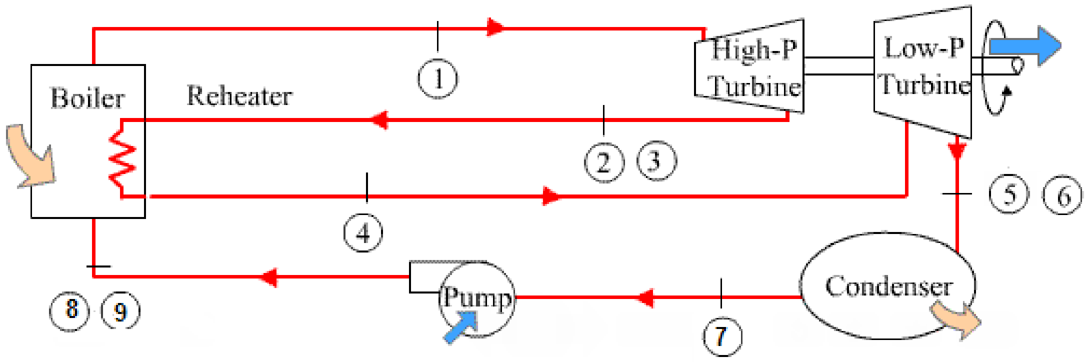


Fig.Prob.3.3.8 Actual, reheat Rankine cycle

EES Solution:

We shall use the EES Procedure written for Actual, reheat Rankine cycle, but with turbine and pump efficiencies put equal to 1:

We have:

"Data:"

P[1]=10000"kPa"

P[2] = 1000 "kPa"

P[5] = 10 "kPa"

T[1] = 500 "C"

T[4] = 500 "C"

eta_turb1 = 1

eta_turb2 = 1

eta_pump= 1

"Calculations:"

CALL Reheat_Rankine_actual(P[1],P[2], P[5], T[1],T[4],eta_turb1,eta_turb2,eta_pump:w_turb1,w_turb2,w_p,w_net,q_boiler,q_reheat,q_in,q_out,eta_th) m_steam = 80E03/w_net "kg/s … mass flow rate of steam required for an output of 80 MW"

Results:

Main | Reheat_Rankine_actual

Unit Settings: SI C kPa kJ mass deg

η_{pump} = 1	η_{th} = 0.4134	η_{turb1} = 1	η_{turb2} = 1
m_{steam} = 50.02 [kg/s]	q_{boiler} = 3173 [kJ/kg]	q_{in} = 3869 [kJ/kg]	q_{out} = 2269 [kJ/kg]
q_{reheat} = 695.4 [kJ/kg]	w_{net} = 1599 [kJ/kg]	w_p = 10.09 [kJ/kg]	w_{turb1} = 591.5 [kJ/kg]
w_{turb2} = 1018 [kJ/kg]			

Thus: Thermal effcy. = eta_th = 0.4134 = 41.34% …..Ans.

Mass flow rate of steam required to produce 80 MW net power = m_steam = 50.02 kg/s … Ans.

And, for quality of steam at exit of LP turbine, see the results in the 'Reheat_Rankine_actual' tab in the Results:

Main | Reheat_Rankine_actual

Local variables in Procedure Reheat_Rankine_actual (1 call, 0.13 sec)

η_{pump}=1	η_{th}=0.4134	η_{turb1}=1
η_{turb2}=1	Fluid$='Steam_IAPWS'	h_1=3375 [kJ/kg]
h_2=2784 [kJ/kg]	h_3=2784 [kJ/kg]	h_4=3479 [kJ/kg]
h_5=2461 [kJ/kg]	h_6=2461 [kJ/kg]	h_7=191.8 [kJ/kg]
h_8=201.8977 [kJ/kg]	h_9=201.8977 [kJ/kg]	P_1=10000 [kPa]
P_2=1000 [kPa]	P_3=1000 [kPa]	P_4=1000 [kPa]
P_5=10 [kPa]	P_6=10 [kPa]	P_7=10 [kPa]
P_8=10000 [kPa]	P_9=10000 [kPa]	q_{boiler}=3173 [kJ/kg]
q_{in}=3869 [kJ/kg]	q_{out}=2269 [kJ/kg]	q_{reheat}=695.4 [kJ/kg]
s_1=6.599 [kJ/kg-C]	s_2=6.599 [kJ/kg-C]	s_3=6.599 [kJ/kg-C]
s_4=7.764 [kJ/kg-C]	s_5=7.764 [kJ/kg-C]	s_6=7.764 [kJ/kg-C]
s_7=0.6492 [kJ/kg-C]	s_8=0.6492 [kJ/kg-C]	s_9=0.6493 [kJ/kg-C]
T_1=500 [C]	T_2=182.3 [C]	T_3=182.3 [C]
T_4=500 [C]	T_6=45.81 [C]	T_7=45.81 [C]
T_8=46.14 [C]	T_9=46.14 [C]	v_f=0.00101 [m^3/kg]
w_{net}=1599 [kJ/kg]	w_p=10.09 [kJ/kg]	$w_{p,isentr}$=10.09 [kJ/kg]
w_{turb1}=591.5 [kJ/kg]	$w_{turb1,isentr}$=591.5 [kJ/kg]	w_{turb2}=1018 [kJ/kg]
$w_{turb2,isentr}$=1018 [kJ/kg]	$w_{turb,tot}$=1609 [kJ/kg]	x_3=100
x_6=0.9487	x_7=0	

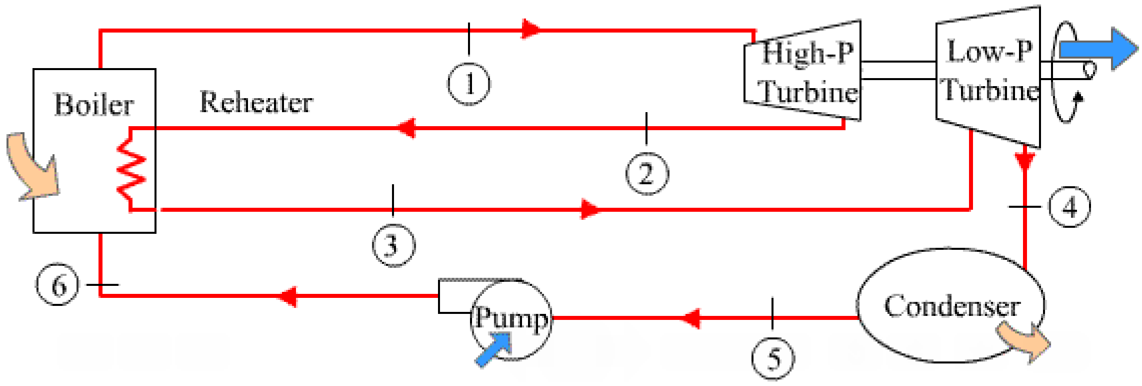
We see that:

Quality of steam at exit of LP turbine = x[6] = 0.9487 ….Ans.

==

"**Prob. 3.3.9** In a reheat cycle, steam at 500 C expands in a HP turbine till it is sat. vap. It is then reheated at constant pressure to 400 C and then expanded in a LP turbine to 40 C. If the max. moisture content at the turbine exhaust is limited to 15%, find (i) the reheat pressure, (ii) pressure of steam at inlet to the HP turbine, (iii) net specific work output, (iv) thermal efficiency, and (v) steam rate. Assume all ideal processes. [VTU-ATD-Dec. 2011]"

Note: This problem is the same as Prob.3.2.2 solved with Mathcad.



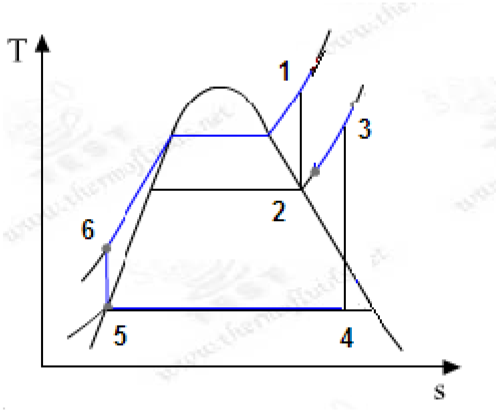


Fig.Prob.3.3.9 Ideal Reheat Rankine cycle and T-s diagram

EES Solution:

"Data:"

T[1]=500[C]"…HP turbine inlet temp"

T[3]=400[C]"…LP turbine inlet temp"

x[5]=0"…sat. liq. to pump inlet"

x[2]=1"..sat. vap. at exit of HP turbine"

x[4]=0.85"..quality of steam at exit of LP turbine"

T[4]=40[C]"…temp at exit of LP turbine"

"-------------------------------"

"Calculations:"

"See Diagram window for fig."

P[3]=P[2]

P[5]=P[4]

P[6]=P[1]

T[5]=T[4]

```
P[4]=P_sat(Steam_NBS,T=T[4])"finds P[4]"

s[4]=Entropy(Steam_NBS,x=x[4],P=P[4])"finds s[4]"

h[4]=Enthalpy(Steam_NBS,x=x[4],P=P[4])

s[3]=s[4]

h[3]=Enthalpy(Steam_NBS,T=T[3],s=s[3])"finds h[3]"

P[3]=Pressure(Steam_NBS,T=T[3],s=s[3])"finds P[3]"

h[2]=Enthalpy(Steam_NBS,x=x[2],P=P[2])"finds h[2]"

s[2]=Entropy(Steam_NBS,x=x[2],P=P[2])"finds s[2]"

T[2]=Temperature(Steam_NBS,P=P[2],x=x[2])"finds T[2]"

s[1]=s[2]

h[1]=Enthalpy(Steam_NBS,T=T[1],s=s[1])"finds h[1]"

P[1]=Pressure(Steam_NBS,T=T[1],h=h[1])"finds P[1]"

h[5]=Enthalpy(Steam_NBS,T=T[5],x=x[5])"finds h[5]"

s[5]=Entropy(Steam_NBS,x=x[5],P=P[5])"finds s[5]"

s[6]=s[5]

"Pump Work:"

v_f=VOLUME(steam_NBS,P=P[5],x=x[5])"…sp. vol. of liq. at pump inlet"

w_p=v_f*(P[6]-P[5])"…pump work"

h[6]=h[5]+w_p"finds h[6]"

T[6]=TEMPERATURE(steam_NBS,P=P[6],h=h[6])"finds T6"
```

"Turbine Work:"

w_turb=(h[1]-h[2])+(h[3]-h[4]) "...total turbine work"

"Thermal effcy.:"

q_in=(h[1]-h[6])+(h[3]-h[2]) "...heat input"

q_out=h[4]-h[5]

w_net=w_turb-w_p "...net work output"

eta_th=w_net/q_in "....thermal effcy."

"Steam rate:"

SSC=3600/w_net"kg/kWh"

Result:

Unit Settings: SI C kPa kJ mass deg

η_{th} = 0.4264

q_{in} = 3565 [kJ/kg]

q_{out} = 2045 [kJ/kg]

SSC = 2.368 [kg/kWh]

v_f = 0.001008 [m³/kg]

w_{net} = 1520 [kJ/kg]

w_p = 15.65 [kJ/kg]

w_{turb} = 1536 [kJ/kg]

And:

Sort	h_i	P_i [kPa]	s_i	T_i [C]	x_i
[1]	3302	15539	6.322	500	
[2]	2800	2099	6.322	214.9	1
[3]	3246	2099	7.103	400	
[4]	2212	7.381	7.103	40	0.85
[5]	167.5	7.381	0.5723	40	0
[6]	183.2	15539	0.5723	40.47	

Thus:

Reheat pressure = P[2] = 2099 kPa = 20.99 bar … Ans.

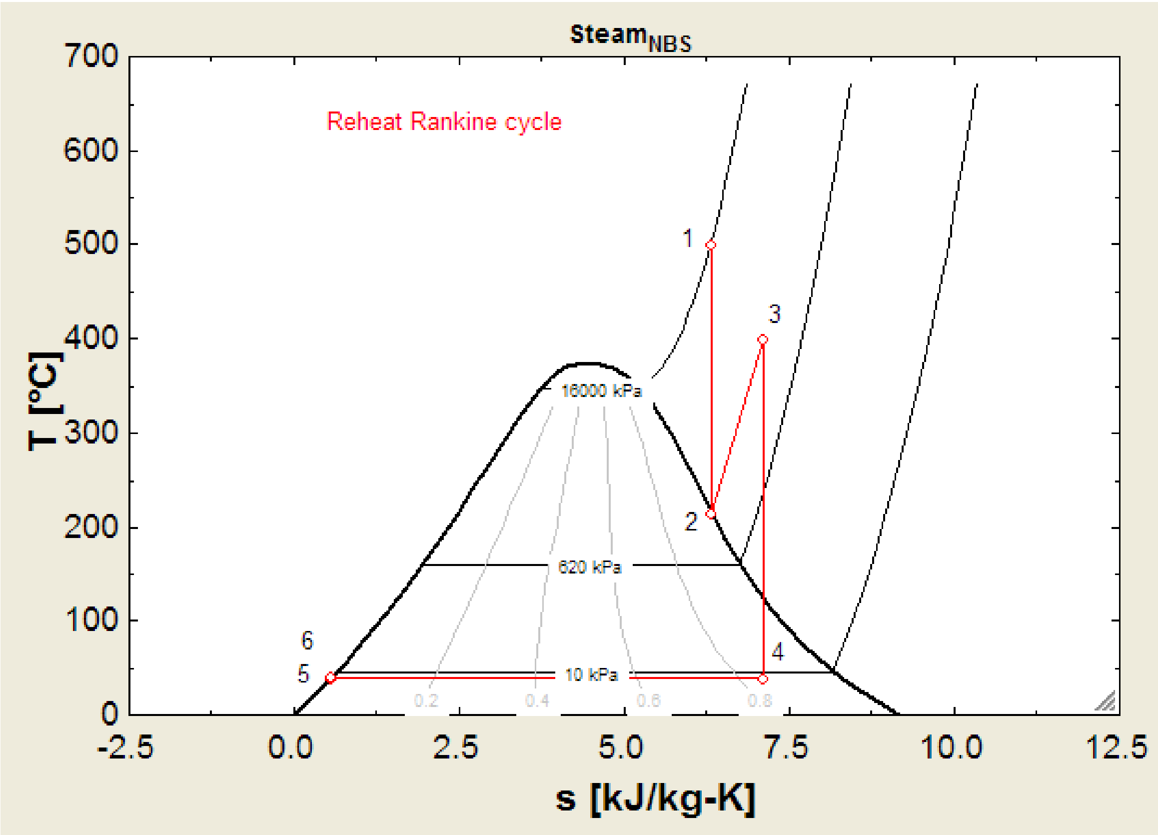
Inlet pressure to HP turbine = P[1] = 15539 kPa = 155.39 bar … Ans.

Net work output = w_net = 1520 kJ/kg … Ans.

Thermal effcy. = eta_th = 0.4264 = 42.64% … Ans.

SSC = 2.368 kg/kWh … Ans.

(b) Plot the cycle on a T-s diagram:

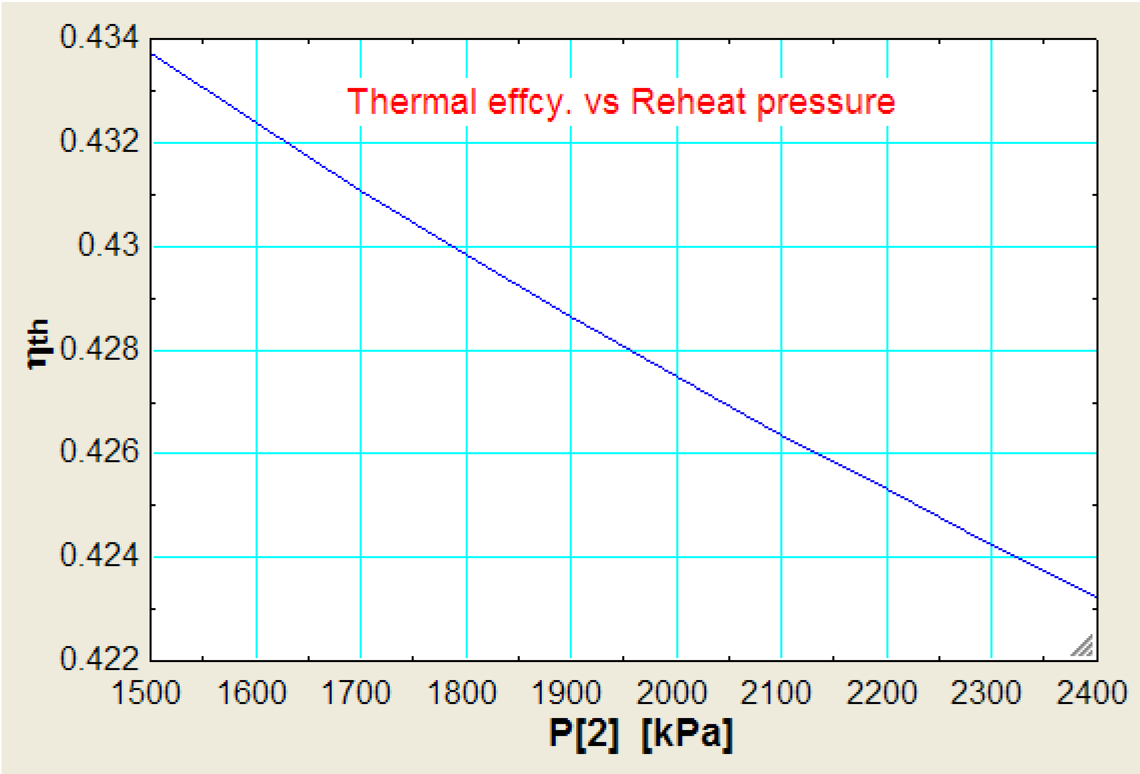


(c) Plot Thermal effcy. vs reheat pressure:

First, produce the Parametric Table:

1..10	η_{th}	P_2 [kPa]
Run 1	0.4337	1500
Run 2	0.4324	1600
Run 3	0.4311	1700
Run 4	0.4298	1800
Run 5	0.4286	1900
Run 6	0.4275	2000
Run 7	0.4264	2100
Run 8	0.4253	2200
Run 9	0.4243	2300
Run 10	0.4232	2400

Now, plot the results:



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"**Prob.3.3.10** Steam enters a steam turbine using reheat cycle at 150 bar and 350 C. The reheat pressure is 25 bar and exhaust pressure is 0.05 bar. Temp of reheated steam is 300 C. Calculate the cycle efficiency and power developed for a steam flow rate of 3000 kg/h. [VTU-ATD-Jan.–Feb. 2003]"

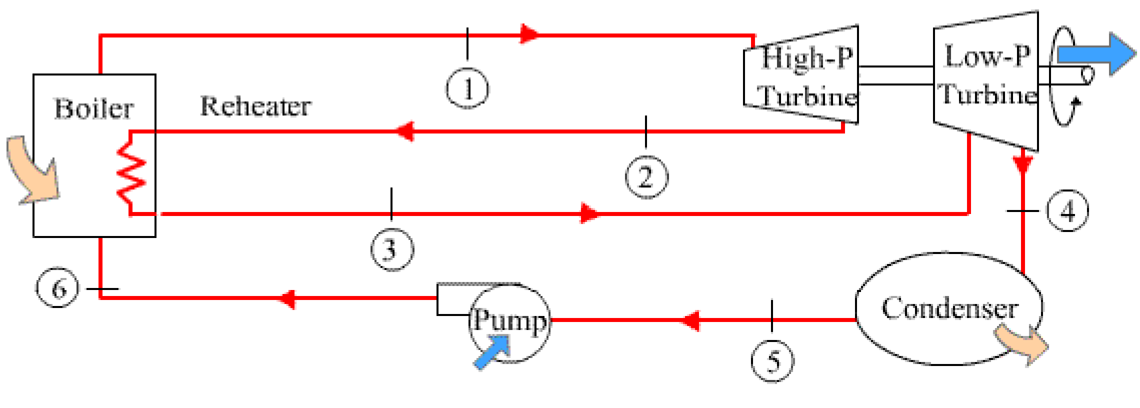


Fig.Prob.3.3.10 Ideal Reheat Rankine cycle

Note: T-s diagram is drawn later.

EES Solution:

“Data:”

P[1]=15000[kPa]“….at HP turbine inlet”

P[2]=2500[kPa]“..reheat pressure”

P[3]=P[2]“…at inlet to LP turbine”

P[4]=5[kPa]“…condenser pressure”

P[5]=P[4]“…at inlet to pump”

P[6]=P[1]“…outlet of pump”

T[1]=350[C]“…at inlet to HP turbine”

T[3]=300[C]“..reheat temp… at inlet to LP turbine”

x[5]=0“…at inlet to pump…sat. liq.”

“---”

"Calculations:"

```
T[4]=T_SAT(steam,P=P[4])"…condenser pressure"

T[5]=T[4]"….inlet to pump"

h[1]=ENTHALPY(steam,T=T[1],P=P[1])"finds h1"

s[1]=ENTROPY(steam,T=T[1],P=P[1])"..finds s1"

s[2]=s[1]"…for isentropic expn. in HP turbine"

h[2]=ENTHALPY(steam,s=s[2],P=P[2])"finds h2"

T[2]=TEMPERATURE(steam,P=P[2],h=h[2])"finds T2"

x[2]=QUALITY(Steam,h=h[2],P=P[2])"finds x2"

s[3]=ENTROPY(steam,T=T[3],P=P[3])"…entropy at state point 3, entry to LP turbine"

s[4]=s[3] ]"…for isentropic expn. in LP turbine"

h[3]=ENTHALPY(steam,s=s[3],P=P[3])"finds h3"

h[4]=ENTHALPY(steam,s=s[4],P=P[4])"finds h4"

x[4]=QUALITY(Steam,h=h[4],P=P[4])"finds x4"

h[5]=ENTHALPY(steam,P=P[5],x=x[5])"finds h5"

s[5]=ENTROPY(steam,P=P[5],x=x[5])"finds s5"

s[6]=s[5]"…for isentropic compression in pump"
```

"Pump Work:"

```
v_f=VOLUME(steam,P=P[5],x=x[5])"…sp. vol. at entry to pump"

w_p=v_f*(P[6]-P[5])"…pump work, isentropic"
```

h[6]=h[5]+w_p"..enthalpy at state point 6, at exit of pump"

T[6]=TEMPERATURE(steam,P=P[6],h=h[6])"finds T6"

"Turbine Work:"

w_turb=(h[1]-h[2])+(h[3]-h[4])"…combined work of both HP and LP turbines"

"Thermal effcy.:"

q_in=(h[1]-h[6])+(h[3]-h[2])"…heat input"

q_out=h[4]-h[5]"…heat rejected in condenser"

w_net=w_turb-w_p"…net work output"

eta_th=w_net/q_in"…thermal effcy."

"Power:"

m=3000/3600"kg/s … mass flow rate of steam"

Power=m * w_net "..net power developed"

Results:

Unit Settings: SI C kPa kJ mass deg

η_{th} = 0.4009

m = 0.8333 [kg/s]

Power = 1052 [kW]

q_{in} = 3150 [kJ/kg]

q_{out} = 1887 [kJ/kg]

v_f = 0.001005 [m³/kg]

w_{net} = 1263 [kJ/kg]

w_p = 15.07 [kJ/kg]

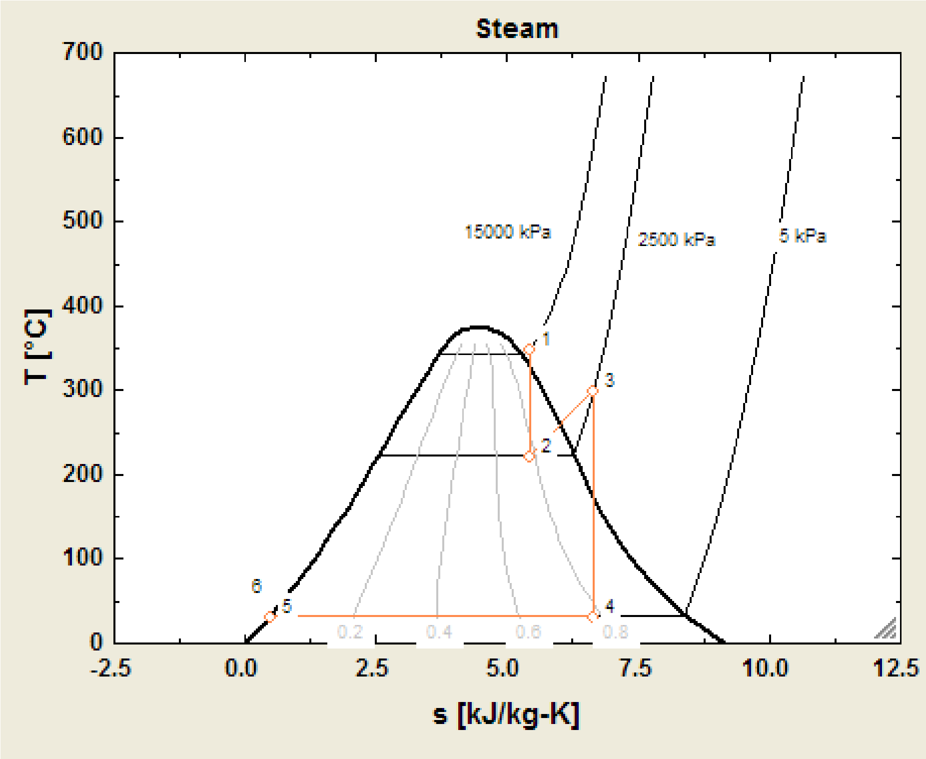
w_{turb} = 1278 [kJ/kg]

Sort	1 h_i	2 P_i [kPa]	3 s_i	4 T_i [C]	5 x_i
[1]	2691	15000	5.44	350	
[2]	2397	2500	5.44	224	0.7797
[3]	3008	2500	6.642	300	
[4]	2025	5	6.642	32.88	0.7789
[5]	137.7	5	0.4761	32.88	0
[6]	152.8	15000	0.4761	33.26	

Thus: Thermal effcy. = eta_th = 0.4009 = 40.09% …. Ans.

Power developed for a steam flow rate of 3000 kg/h = Power = 1052 kW … Ans.

Cycle on the T-s diagram:

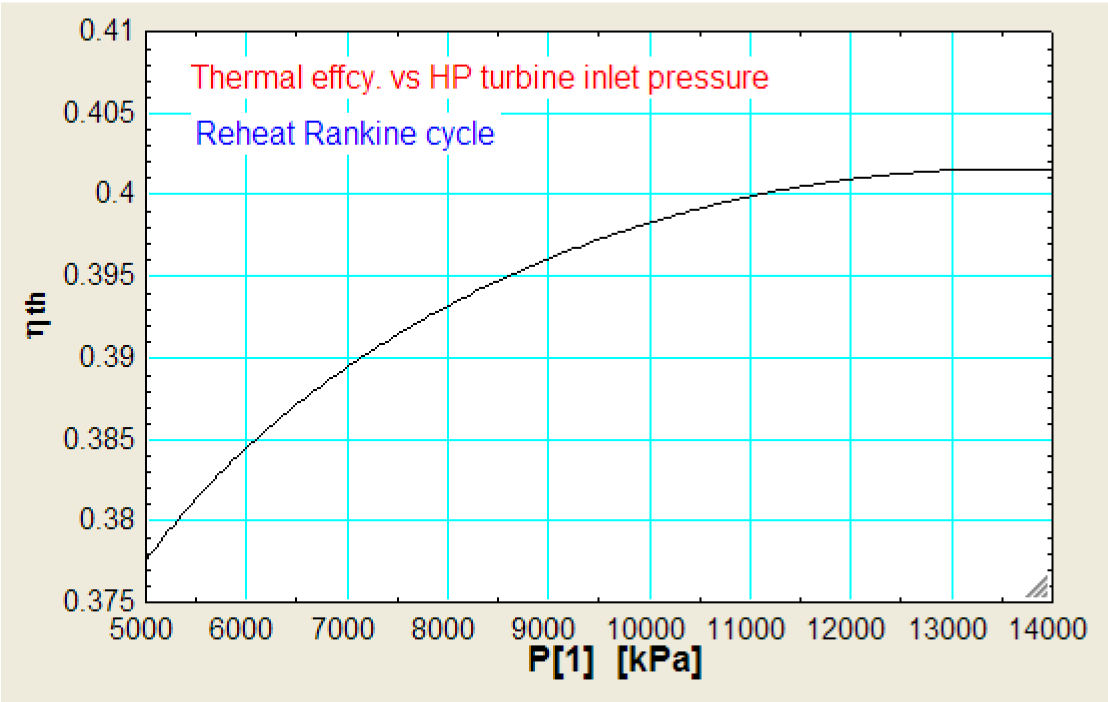


a) **Plot eta_th vs HP turbine inlet pressure, P[1]:**

Parametric Table:

1..10	P_1 [kPa]	η_{th}
Run 1	5000	0.3776
Run 2	6000	0.3845
Run 3	7000	0.3894
Run 4	8000	0.3932
Run 5	9000	0.3961
Run 6	10000	0.3983
Run 7	11000	0.3999
Run 8	12000	0.4009
Run 9	13000	0.4015
Run 10	14000	0.4015

Now, plot the results:

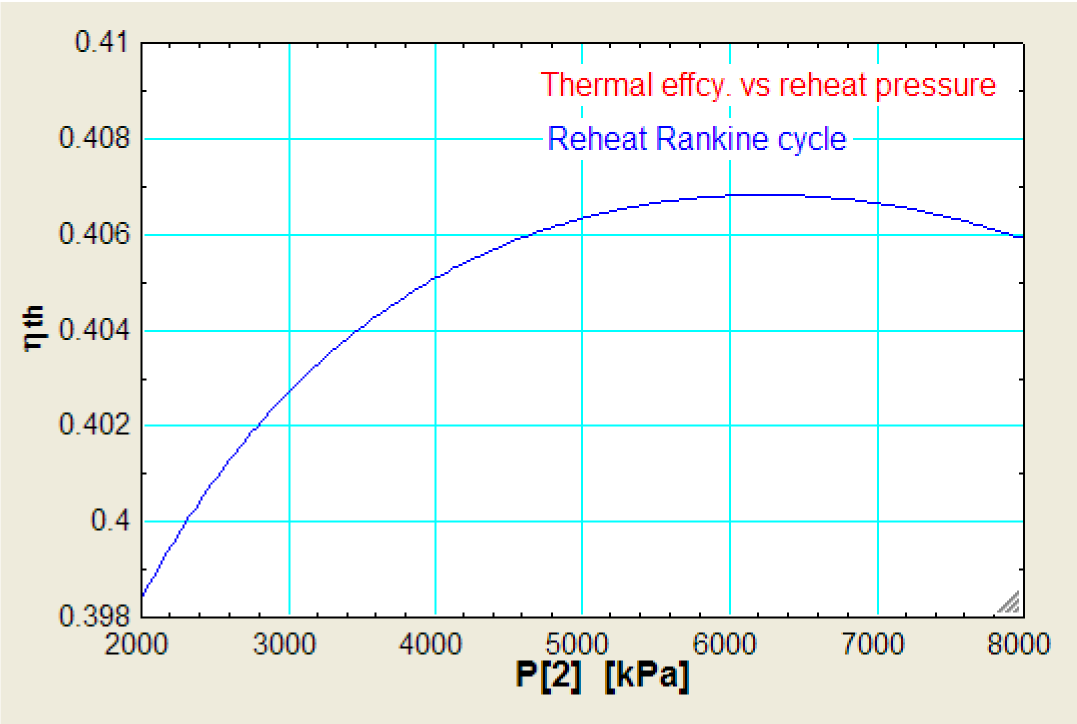


b) **Plot eta_th vs reheat pressure, P[2]:**

Parametric Table:

1..13	P_2 [kPa]	η_{th}
Run 1	2000	0.3984
Run 2	2500	0.4009
Run 3	3000	0.4027
Run 4	3500	0.4041
Run 5	4000	0.4051
Run 6	4500	0.4058
Run 7	5000	0.4063
Run 8	5500	0.4067
Run 9	6000	0.4068
Run 10	6500	0.4068
Run 11	7000	0.4066
Run 12	7500	0.4063
Run 13	8000	0.4059

Now, plot the results:



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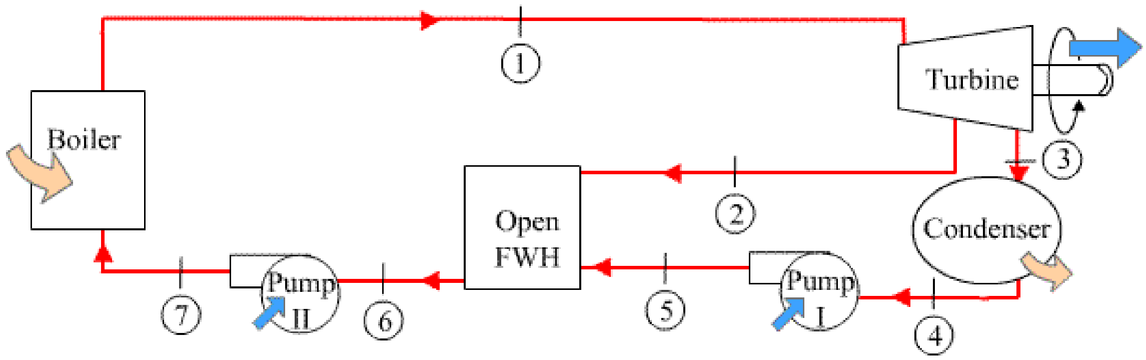
Regenerative Rankine cycle:

Prob.3.3.11 In a regenerative Rankine cycle, with one open feed water heater (FWH), steam enters the first turbine stage at 12 MPa, 520 C and expands to 1 MPa, where some of the steam is extracted and diverted to the open FWH operating at 1 MPa. The remaining steam expands through the second turbine stage to the condenser pressure of 6 kPa. Sat. liquid exits the open FWH at 1 MPa. For isentropic processes in turbines and pumps, determine for the cycle (a) thermal efficiency (b) fraction of steam entering the first turbine stage that is diverted to the open FWH, and (c) the mass flow rate of steam entering the first turbine stage, if the net power output is 330 MW. [Ref: 3]



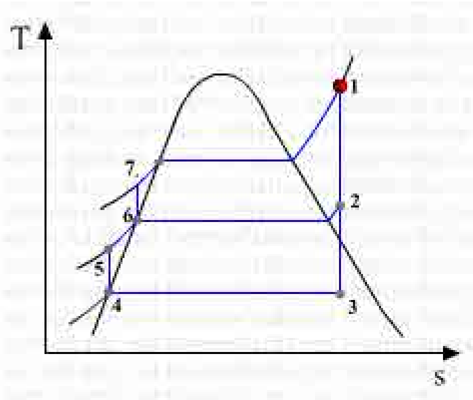


Fig.Prob.3.3.11 (a) Ideal regenerative Rankine cycle with one open FWH, and (b) T-s diagram

EES Solution:

"Data:"

P[1]=12000[kPa]"…at entry to first stage turbine"

P[2]=1000[kPa]"…at exit of first stage turbine, and inlet of second stage turbine, inlet to open FWH"

P[3]=6[kPa]"…at exit of second stage turbine, inlet to condenser"

P[4]=P[3]" exit of condenser, inlet to pump-1"

P[5]=P[2]" exit of pump-1,inlet to open FWH, sat. liq."

P[6]=P[5]"…exit of open FWH, sat. liq., inlet to pump-2"

P[7]=P[1]"…exit of pump-2, inlet to boiler"

T[1]=520[C]

x[4] = 0"…sat. liq."

x[6] = 0"…sat. liq."

Power = 330E03"kW…total power developed"

"---"

"Calculations:"

```
h[1]=ENTHALPY(steam,T=T[1],P=P[1])"finds h1"

s[1]=ENTROPY(steam,T=T[1],P=P[1])"..finds entropy"

s[2]=s[1]"…for isentropic expn. in first stage turbine"

h[2]=ENTHALPY(steam,s=s[2],P=P[2])"finds h2"

T[2]=TEMPERATURE(steam,P=P[2],h=h[2])"finds T2, after expn in first stage"

x[2]=QUALITY(Steam,h=h[2],P=P[2])"finds x2"

s[3]=s[2]"..for isentropic expn in second stage turbine"

s[4]= ENTROPY(steam,T=T[4],x=x[4])"..finds entropy"

h[3]=ENTHALPY(steam,s=s[3],P=P[3])"finds h3"

x[3]=QUALITY(Steam,h=h[3],P=P[3])"finds x3, Quality of steam entering the Condenser"

h[4]=ENTHALPY(steam,x=x[4],P=P[4])"finds h4"

T[4]=T_SAT(steam, P=P[4])"finds T4"

s[5]=s[4]"…isentr. comprn. in pump-1"

h[5]=ENTHALPY(steam,s=s[5],P=P[5])"finds h5"

T[5]=TEMPERATURE(steam, P=P[5],s=s[5])"finds T5"

T[6]=T_SAT(steam, P=P[6])"finds T6"

h[6] = ENTHALPY(steam,x=x[6],P=P[6])"finds h6"

s[6]=ENTROPY(steam,T=T[6],x=x[6])"..finds entropy"

s[7] = s[6] "…for isentropic comprn in pump-2"

"At point 2, fraction 'y' is diverted to Open Feed water heater, and (1- y) expands in second stage turbine to T3"
```

"Heat balance around the Open FWH:"

y * h[2]+(1- y) * h[5] = h[6]"finds y"

T[7]=TEMPERATURE(steam, P=P[7],s=s[7])"finds T7"

h[7] = ENTHALPY(steam,s=s[7],P=P[7])"finds h7"

"Pump-1 Work:"

v_f1=VOLUME(steam,P=P[4],x=x[4])"..m^3/kg…sp. vol. of liq. at entry to pump-1"

w_p1= (1- y) * v_f1 * (P[5]-P[4])"..kJ/kg …. work input to pump-1"

"Pump-2 Work:"

v_f2 = VOLUME(steam,P=P[6],x=x[6])"…m^3/kg … sp. vol. of liq. at entry to pump-1"

w_p2=v_f2 * (P[7]-P[6])"..kJ/kg …. work input to pump-2"

"Turbine Work:"

w_turb1=(h[1]-h[2])"kJ/kg …. work output of stage-1 of turbine"

w_turb2=(1- y) * (h[2]-h[3])"kJ/kg …. work output of stage 1 of turbine"

w_turbtotal=w_turb1+w_turb2"kJ/kg …. combined work output of stage 1 an 2 of turbine"

"Thermal effcy.:"

q_in=(h[1]-h[7])"kJ/kg … heat supplied"

q_out=(1-y)*(h[3]-h[4])"kJ/kg … heat rejected"

w_net=w_turbtotal-(w_p1+w_p2)"kJ/kg … net work output"

eta_th=w_net/q_in"…thermal effcy."

"Specific Steam Consumption (SSC):"

SSC=3600/w_net"kg/kWh"

"Mass flow rate of steam for a net power output of 330 MW:"

m_steam = Power / w_net "kg/s"

Results:

Unit Settings: SI C kPa kJ mass deg

η_{th} = 0.4554	m_{steam} = 275.8 [kg/s]	Power = 330000 [kW]
q_{in} = 2627 [kJ/kg]	q_{out} = 1430 [kJ/kg]	SSC = 3.009 [kg/kWh]
v_{f1} = 0.001006 [m^3/kg]	v_{f2} = 0.001127 [m^3/kg]	w_{net} = 1196 [kJ/kg]
w_{p1} = 0.7666 [kJ/kg]	w_{p2} = 12.4 [kJ/kg]	w_{turb1} = 638 [kJ/kg]
w_{turb2} = 571.5 [kJ/kg]	$w_{turbtotal}$ = 1210 [kJ/kg]	y = 0.2337

Also:

Sort	h_i	P_i [kPa]	s_i	T_i [C]	x_i
[1]	3402	12000	6.556	520	
[2]	2764	1000	6.556	179.9	0.9932
[3]	2018	6	6.556		0.773
[4]	151.5	6	0.5208	36.17	0
[5]	152.5	1000	0.5208	36.19	
[6]	762.9	1000	2.139	179.9	0
[7]	775.2	12000	2.139	181.4	

Thus:

Thermal effcy. = eta_th = 0.4554 = 45.54% … Ans.

Fraction of steam flowing in to the HP turbine that is diverted to open FWH = 0.2337 … Ans.

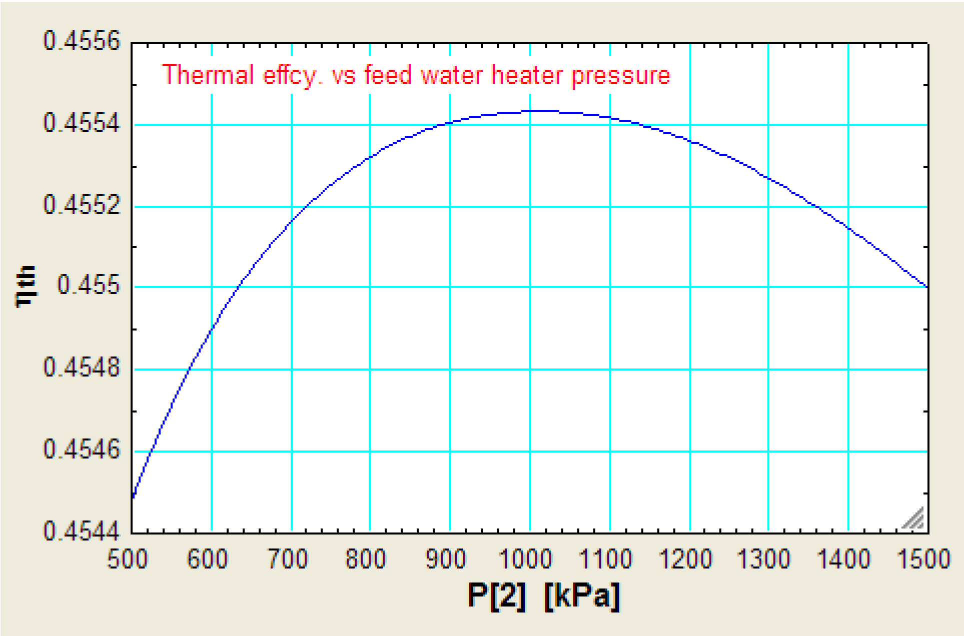
Steam flow rate required for a net power output of 330 MW = m_steam = 275.8 kg/s …. Ans.

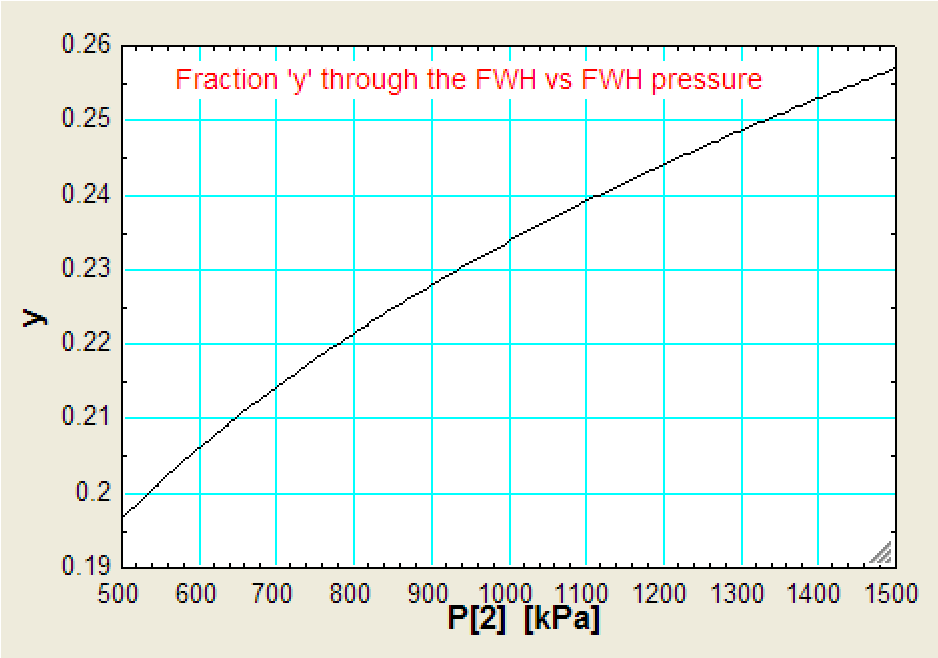
(b)Plot eta_th and fraction 'y' for various feed water heater pressures, ranging from 0.5 to 1.5 MPa:

First, compute the Parametric Table:

1..11	P_2 [kPa]	η_{th}	y
Run 1	500	0.4545	0.1966
Run 2	600	0.4549	0.2061
Run 3	700	0.4552	0.2143
Run 4	800	0.4553	0.2214
Run 5	900	0.4554	0.2279
Run 6	1000	0.4554	0.2337
Run 7	1100	0.4554	0.2391
Run 8	1200	0.4554	0.244
Run 9	1300	0.4553	0.2486
Run 10	1400	0.4551	0.2529
Run 11	1500	0.455	0.257

Now, plot the results:





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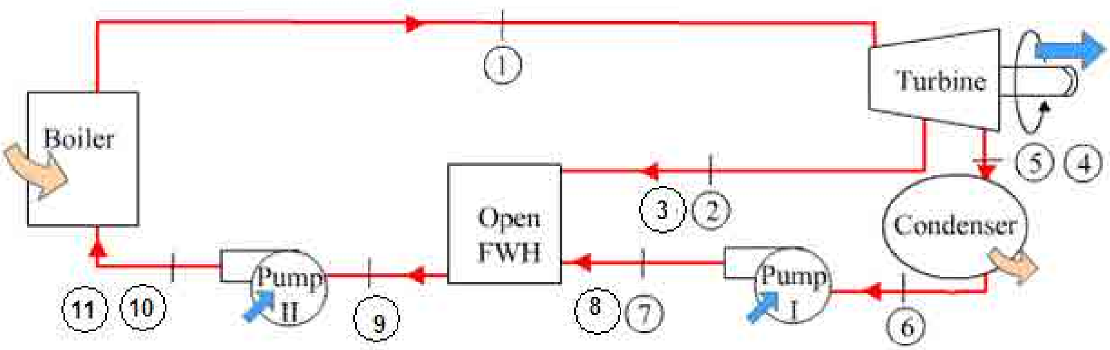
Prob.3.3.12 In the regenerative Rankine cycle of Prob.3.3.11, include the isentropic efficiencies of both the turbines and both the pumps, and calculate thermal efficiency and the fraction 'y' flowing through the open FWH. Take all isentropic efficiencies as 0.8.



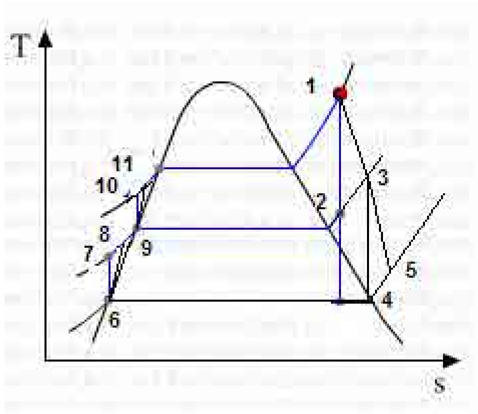


Fig.Prob.3.3.11 (a) Actual regenerative Rankine cycle with one open FWH, and (b) T-s diagram

EES Solution:

"Data:"

P[1]=12000[kPa]"…at entry to first stage turbine"

P[2]=1000[kPa]"…at exit of first stage turbine, isentropic"

P[3] = P[2]"…actual exit of turbine-1, inlet to open FWH"

P[4]=6[kPa]"…at isentropic exit of second stage turbine"

P[5]=P[4]" actual exit of second stage turbine, and inlet to condenser"

P[6]=P[4]" exit of condenser, sat.liq., inlet to pump-1."

P[7]=P[2]"…isentropic exit of pump-1"

P[8] = P[7] ".actual exit of pump-1, and inlet to open FWH"

P[9] = P[8]"…exit of open FWH, sat.liq., inlet to pump-2"

P[10] = P[1] "…isentropic exit of pump-2"

P[11] = P[10] "..actual exit of pump-2, inlet to boiler"

T[1]=520[C]

x[6] = 0"…sat. liq."

```
x[9] = 0"…sat. liq."

eta_turb1 = 0.8"..isentropic effcy. of turbine-1"

eta_turb2 = 0.8"..isentropic effcy. of turbine-2"

eta_pump1 = 0.8"..isentropic effcy. of pump-1"

eta_pump2 = 0.8"..isentropic effcy. of pump-2"

Power = 330E03"kW…total power developed"

"-------------------------------------------"

"Calculations:"
h[1]=ENTHALPY(steam,T=T[1],P=P[1])"finds h1"

s[1]=ENTROPY(steam,T=T[1],P=P[1])"..finds entropy"

s[2]=s[1]"…for isentropic expn. in first stage turbine"
```

```
h[2]=ENTHALPY(steam,s=s[2],P=P[2])"finds h2"

T[2]=TEMPERATURE(steam,P=P[2],h=h[2])"finds T2, after isentr. expn in first stage"

x[2]=Quality(Steam,T=T[2],h=h[2])"…quality after isentr expn in turbine-1 stage"

w_turb1_isentr=(h[1]-h[2])"kJ/kg ….isentropic work output of stage-1 of turbine"

w_turb1=(h[1]-h[2]) * eta_turb1"kJ/kg ….actual work output of stage-1 of turbine"

h[3] = h[1] – w_turb1 "kJ/kg …. enthalpy at state point 3"

T[3]=TEMPERATURE(steam,P=P[3],h=h[3])"finds T3, after actual expn in first stage turbine"

s[3]=ENTROPY(steam,h=h[3],T=T[3])"..finds entropy at point 3"

x[3]=Quality(Steam,T=T[3],h=h[3])"…quality after actual expn in turbine-1 stage"

s[4] = s[3] "…isentr. expn. in stage-2 of turbine"

h[4]=ENTHALPY(steam,s=s[4],P=P[4])"finds h4, after isentr. expn in stage-2"

w_turb2_isentr=(h[3]-h[4])"kJ/kg ….isentr work output of stage-2 of turbine"

w_turb2= w_turb2_isentr * eta_turb2"kJ/kg ….actual work output of stage-2 of turbine"

h[5] = h[3] – w_turb2 "kJ/kg …. enthalpy at state point 5"

T[4]=TEMPERATURE(steam,P=P[4],h=h[4])"finds T4, after isentr expn in second stage turbine"

T[5]=TEMPERATURE(steam,P=P[5],h=h[5])"finds T5, after actual expn in second stage turbine"

s[5]=ENTROPY(steam,h=h[5],T=T[5])"..finds entropy at point 5"

x[4]=Quality(Steam,T=T[4],h=h[4])"…quality after isentr expn in turbine-2 stage"

x[5]=Quality(Steam,T=T[5],h=h[5])"…quality after actualr expn in turbine-2 stage"

T[6]=T_SAT(steam, P=P[6])"finds T6"

s[6]= ENTROPY(steam,T=T[6],x=x[6])"..finds entropy"
```

s[7] = s[6] "…for isentr compression in pump-1"

h[6]=ENTHALPY(steam,x=x[6],P=P[6])"finds h6, at exit of condenser, and entry to pump-1"

v_f6 = Volume(Steam,x=x[6],P=P[6])"…m^3/kg…sp. vol. of liq. at point 6, entry to pump-1"

w_p1_isentr = v_f6 * (P[7] – P[6]) "kJ/kg ….isentr work required for pump"

w_p1 = w_p1_isentr / eta_pump1 ".kJ/kg … actual work of pump-1"

h[7] = h[6] + w_p1_isentr "kJ/kg … enthalpy at isentr exit of pump-1"

h[8] = h[6] + w_p1 "kJ/kg …. enthalpy at actual exit of pump-1"

T[7]=TEMPERATURE(steam,P=P[7],h=h[7])"finds T7, after isentr comprn in pump-1"

T[8]=TEMPERATURE(steam,P=P[8],h=h[8])"finds T8, after actual comprn in pump-1"

s[8]=ENTROPY(steam,h=h[8],T=T[8])"..finds entropy at point 8"

"At point 3, fraction 'y' is diverted to Open Feed water heater, and (1- y) expands in second stage turbine to T5"

"Heat balance around the Open FWH:"

h[9] = ENTHALPY(steam,x=x[9],P=P[9])"finds h9"

y = (h[9] – h[8]) / (h[3] – h[8])"finds y"

T[9]=T_SAT(steam, P=P[9])"finds T9"

s[9]= ENTROPY(steam,T=T[9],x=x[9])"..finds entropy"

s[10] = s[9] "…for isentr. comprn in pump-2"

v_f9 = Volume(Steam,x=x[9],P=P[9])"…m^3/kg…sp. vol. of liq. at point 9"

w_p2_isentr = v_f9 * (P[10] – P[9])"kJ/kg … isentr work of pump-2"

w_p2 = w_p2_isentr / eta_pump2 ".kJ/kg … actual work of pump-2"

h[10] = h[9] + w_p2_isentr "kJ/kg … enthalpy at isentr exit of pump2" h[11] = h[9] + w_p2 “kJ/kg …. enthalpy at actual exit of pump-2”

T[10]=TEMPERATURE(steam,P=P[10],h=h[10])“finds T10, after isentr comprn in pump-2”

T[11]=TEMPERATURE(steam,P=P[11],h=h[11])“finds T11, after actual comprn in pump-2”

s[11]=ENTROPY(steam,h=h[11],T=T[11])“..finds entropy at point 11”

“Turbine Work:”

w_turbtotal=w_turb1+(1 – y) * w_turb2“kJ/kg …. combined work output of stage 1 an 2 of turbine”

“Thermal effcy.:”

q_in=(h[1]-h[11])“kJ/kg … heat supplied”

q_out=(1- y) * (h[5]-h[6])“kJ/kg … heat rejected”

w_net=w_turbtotal-(w_p1* (1 – y) + w_p2)“kJ/kg … net work output”

eta_th=w_net/q_in“…thermal effcy.”

"SSC:"

SSC=3600/w_net"kg/kWh"

"Mass flow rate of steam for a net power output of 330 MW:"

m_steam = Power / w_net "kg/s"

Results:

Unit Settings: SI C kPa kJ mass deg

η_{pump1} = 0.8
η_{pump2} = 0.8
η_{th} = 0.3755
η_{turb1} = 0.8
η_{turb2} = 0.8
m_{steam} = 335 [kg/s]
Power = 330000 [kW]
q_{in} = 2624 [kJ/kg]
q_{out} = 1639 [kJ/kg]
SSC = 3.654 [kg/kWh]
v_{f6} = 0.001006
v_{f9} = 0.001127
w_{net} = 985.2 [kJ/kg]
w_{p1} = 1.251 [kJ/kg]
$w_{p1,isentr}$ = 1 [kJ/kg]
w_{p2} = 15.5 [kJ/kg]
$w_{p2,isentr}$ = 12.4 [kJ/kg]
w_{turb1} = 510.4 [kJ/kg]
$w_{turb1,isentr}$ = 638 [kJ/kg]
w_{turb2} = 632.1 [kJ/kg]
$w_{turb2,isentr}$ = 790.1 [kJ/kg]
$w_{turbtotal}$ = 1002 [kJ/kg]
y = 0.2228

And:

Sort	h_i	P_i [kPa]	s_i	T_i [C]	x_i
[1]	3402	12000	6.556	520	
[2]	2764	1000	6.556	179.9	0.9932
[3]	2892	1000	6.825	227.6	100
[4]	2102	6	6.825	36.17	0.8075
[5]	2260	6	7.336	36.17	0.8729
[6]	151.5	6	0.5208	36.17	0
[7]	152.5	1000	0.5208	36.19	
[8]	152.7	1000	0.5216	36.25	
[9]	762.9	1000	2.139	179.9	0
[10]	775.3	12000	2.139	181.5	
[11]	778.4	12000	2.146	182.2	

Thus:

When the isentropic efficiencies of both the turbines and pumps are taken in to account,

Thermal effcy. = eta_th = 0.3755 = 37.55% …. Ans.

Fraction y passing through the open FWH = y = 0.2228 ….Ans.

Mass flow of steam for a net output of 330 MW = m_steam = 335 kg/s … Ans.

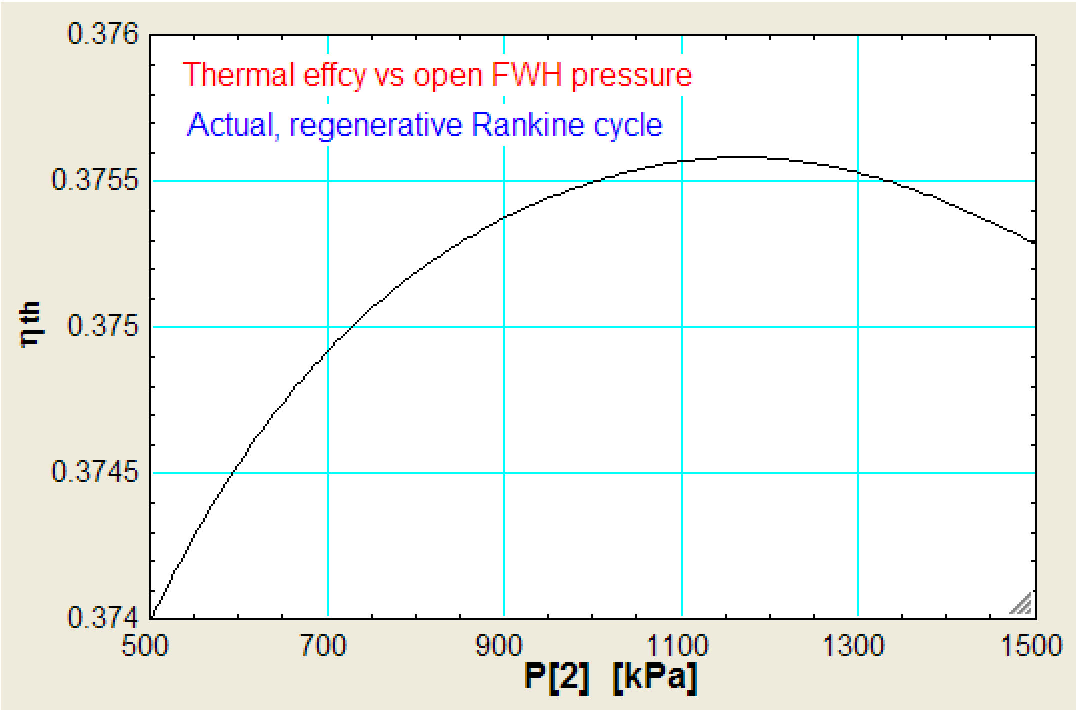
Note: Compare these values with those obtained in Prob. 3.3.11, where all the isentropic efficiencies were 100%.

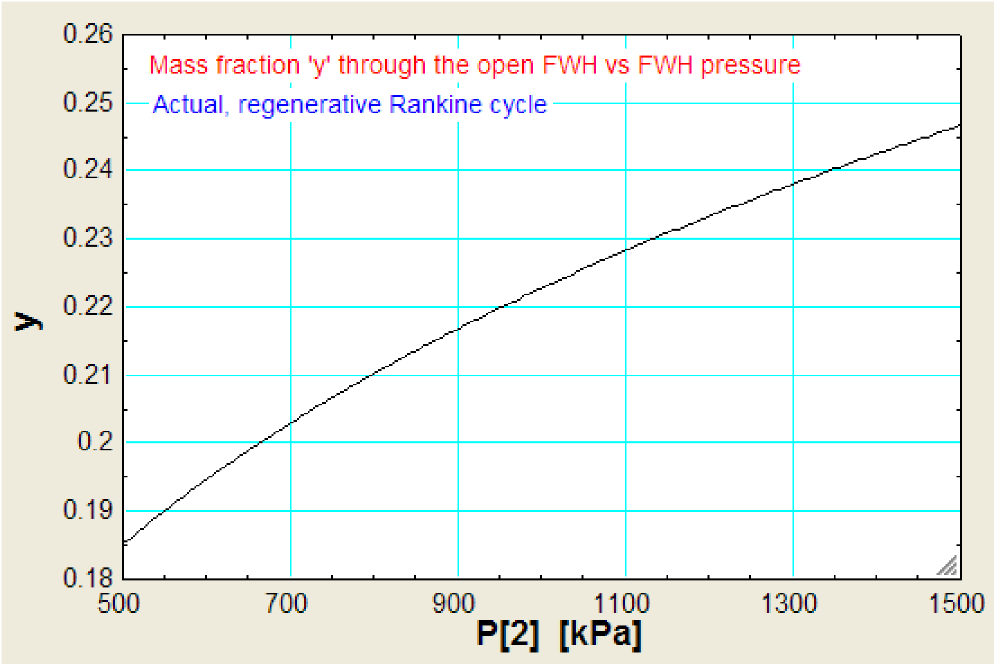
(b)Plot eta_th and fraction 'y' for various feed water heater pressures, ranging from 0.5 to 1.5 MPa:

First, compute the Parametric Table:

1..11	P_2 [kPa]	η_{th}	y
Run 1	500	0.374	0.1852
Run 2	600	0.3745	0.1947
Run 3	700	0.3749	0.2029
Run 4	800	0.3752	0.2102
Run 5	900	0.3754	0.2168
Run 6	1000	0.3755	0.2228
Run 7	1100	0.3756	0.2283
Run 8	1200	0.3756	0.2333
Run 9	1300	0.3755	0.2381
Run 10	1400	0.3754	0.2425
Run 11	1500	0.3753	0.2467

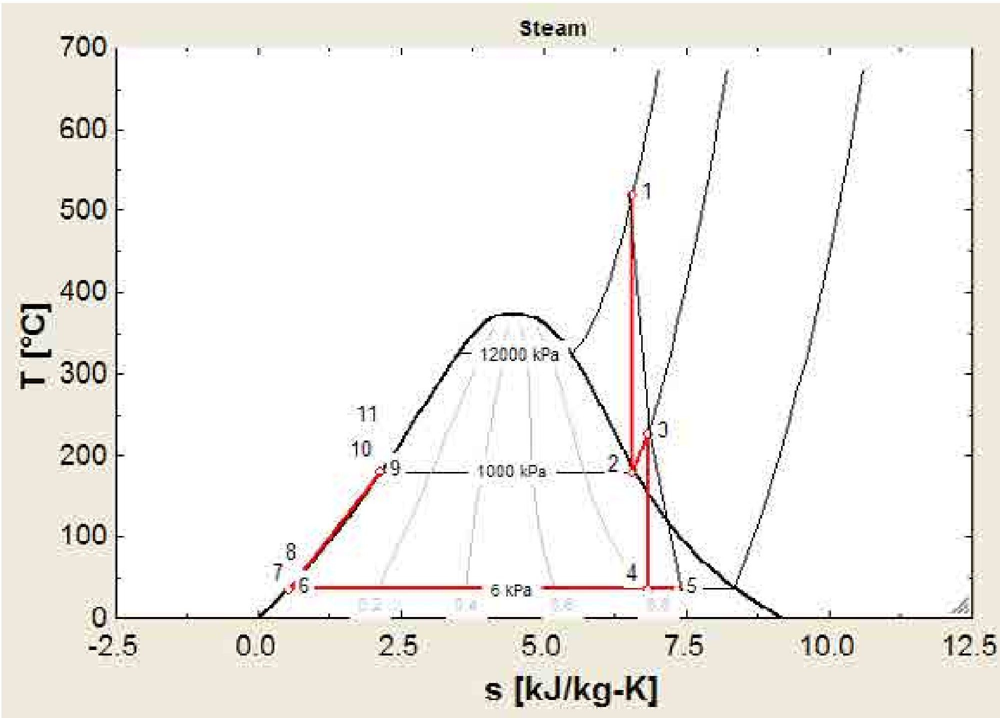
Now, plot the results:





c) **Plot the cycle on T-s diagram in EES:**

We first get the Property plot for Steam, and then overlay the T-s diagram over it using the Array Table:



==

"**Prob. 3.3.13** In a regenerative Rankine cycle of Prob. 3.3.11, include the isentropic efficiencies of both the turbines and both the pumps, and calculate thermal efficiency and the fraction 'y' flowing through the open FWH. Take all isentropic efficiencies as 0.8 **Use the Diagram Window in EES to enter input variables.**"

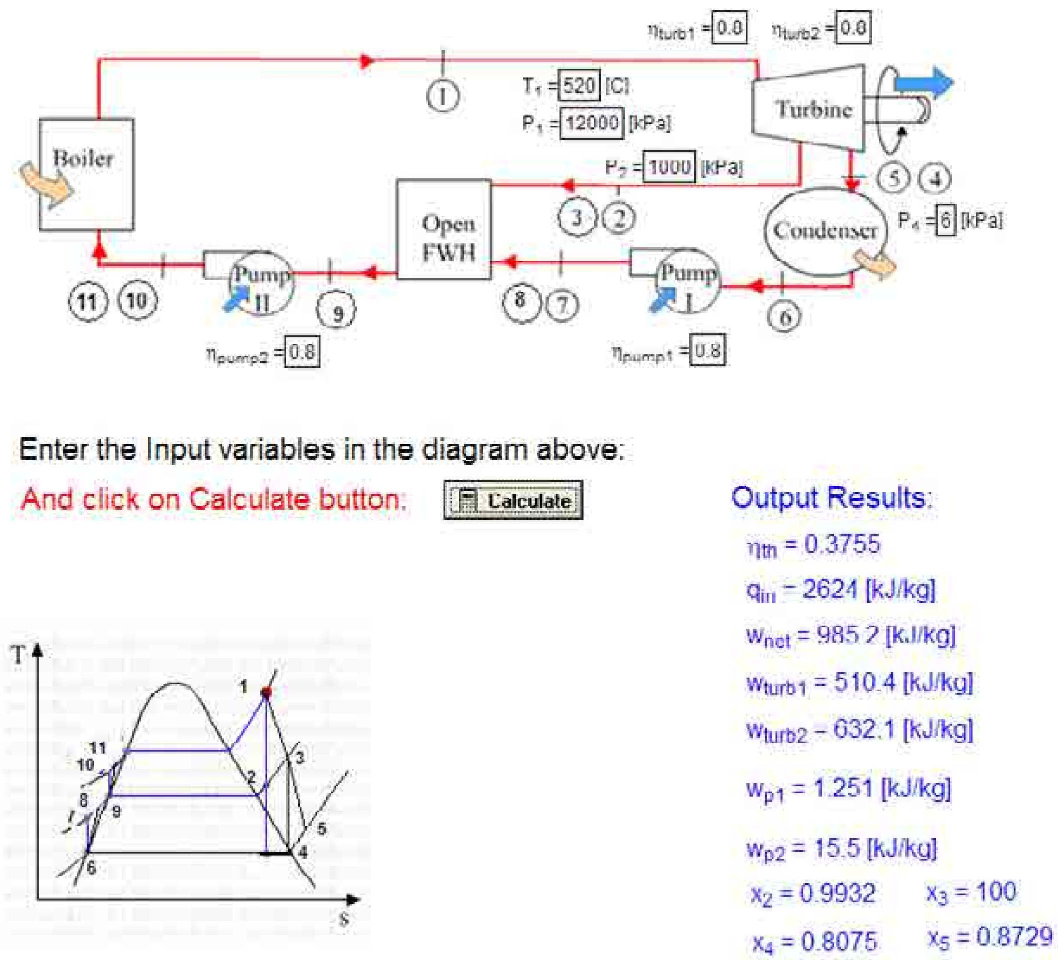
EES Solution:

The EES program is the same as used for Prob.3.3.12.

But, now make inputs from the Diagram Window of EES.

See Prob. 3.3.3 for the detailed procedure and steps.

Diagram window looks as follows, with data as given in previous problem:

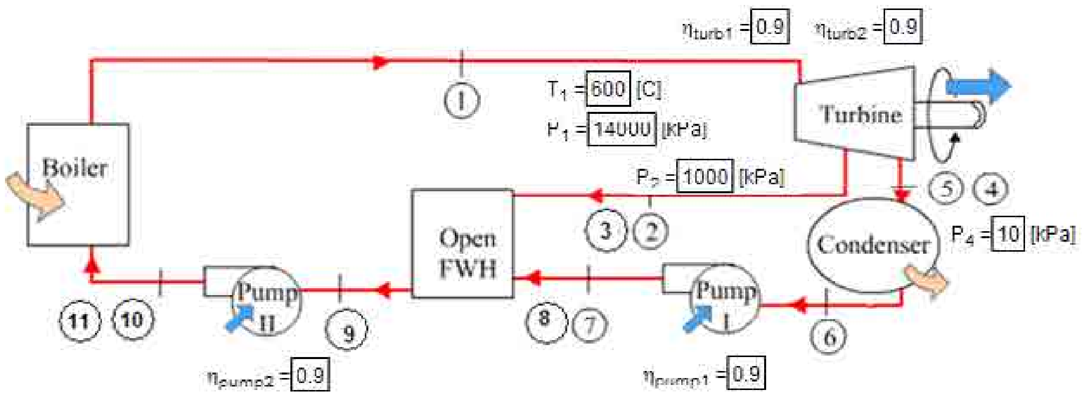


Note in the above: quality, x[3] = 100 means that it is in the superheated region.

Now, we shall change the data as:

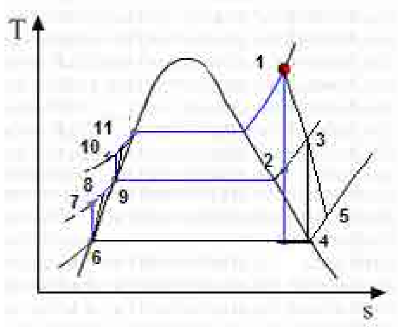
Turbine inlet pressure, P[1] = 14000 kPa, P[2] = 1000 kPa, condenser pressure, P[4] = 10 kPa, T[1] = 600 C, all isentropic efficiencies as 90%.

First, make these changes in the Diagram window when it is in 'development mode' (i.e. when the Diagram window tool bar is visible). Then, change the Diagram window to the 'Application mode' by pressing (control + D), and the tool bar disappears, Now, click on the 'Calculate' button, and we get:



Enter the Input variables in the diagram above:

And click on Calculate button: Calculate



Output Results:

η_{th} = 0.4214

q_{in} = 2811 [kJ/kg]

w_{net} = 1185 [kJ/kg]

w_{turb1} = 676.7 [kJ/kg]

w_{turb2} = 664.2 [kJ/kg]

w_{p1} = 1.111 [kJ/kg]

w_{p2} = 16.28 [kJ/kg]

x_2 = 100 x_3 = 100

x_4 = 0.8294 x_5 = 0.8602

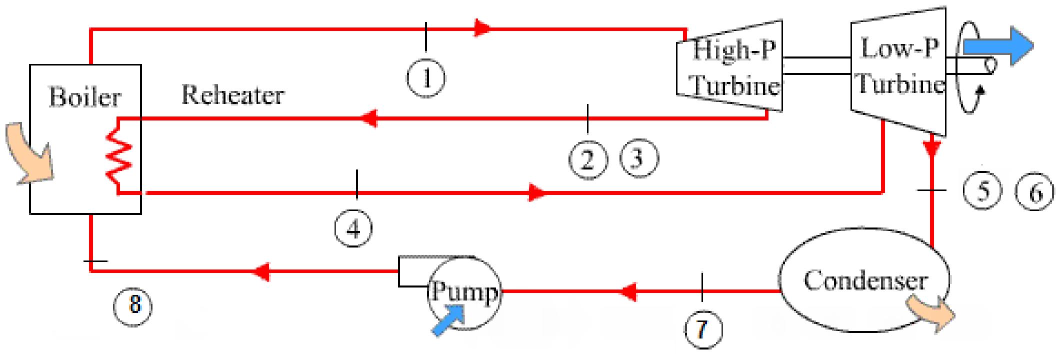
Now, observe from Output Results that values of eta_th etc. have changed. Quality = 100 indicates 'superheated region'.

Thus, calculation with Diagram window inputs is very convenient.

==

3.4 Problems solved with TEST:

Prob. 3.4.1 A reheat cycle has the first stage supply conditions of 70 bar, 500 C. The reheat is at 3 bar and to the same temp. (i) Given that the efficiency of the first turbine is 80%, how much energy is added per kg of steam in reheat coils? (ii) Assume that the expansion efficiency exists in the second turbine. What is the thermal effcy. if the condenser pressure is 0.03 bar? [VTU-ATD-June–July, 2008]



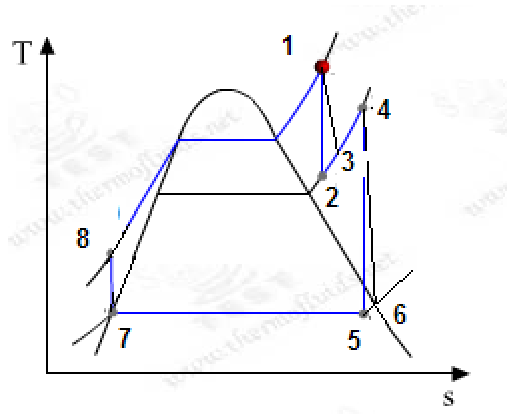
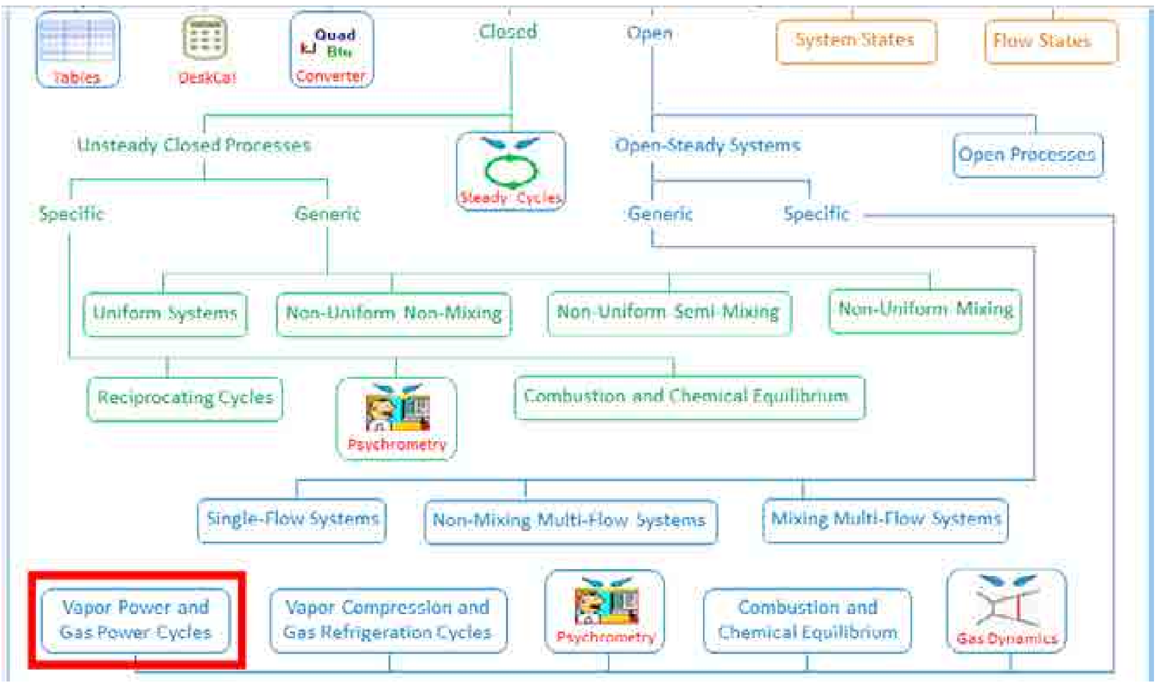


Fig.Prob.3.4.1(a) Actual Rankine cycle with reheat, and (b) T-s diagram

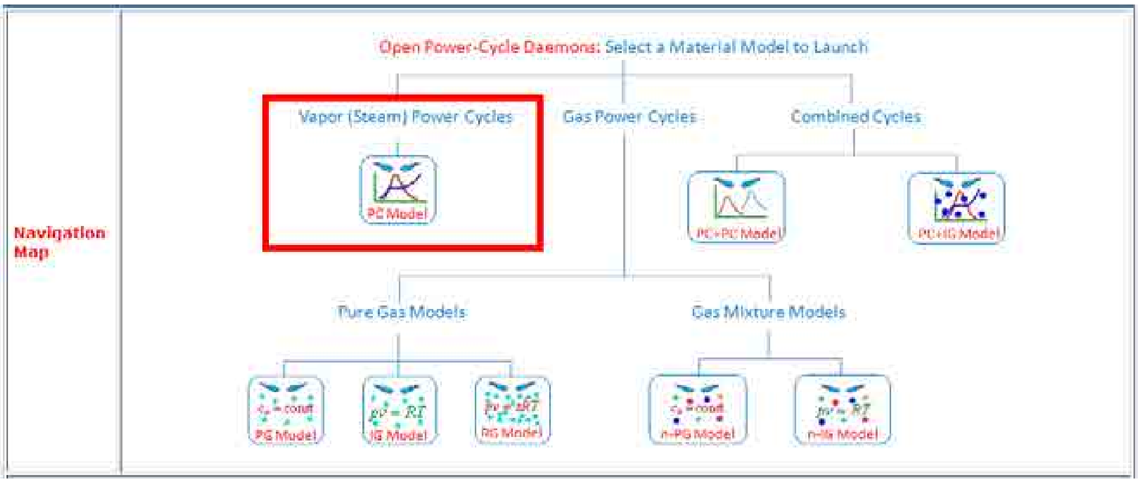
TEST Solution:

Following are the steps:

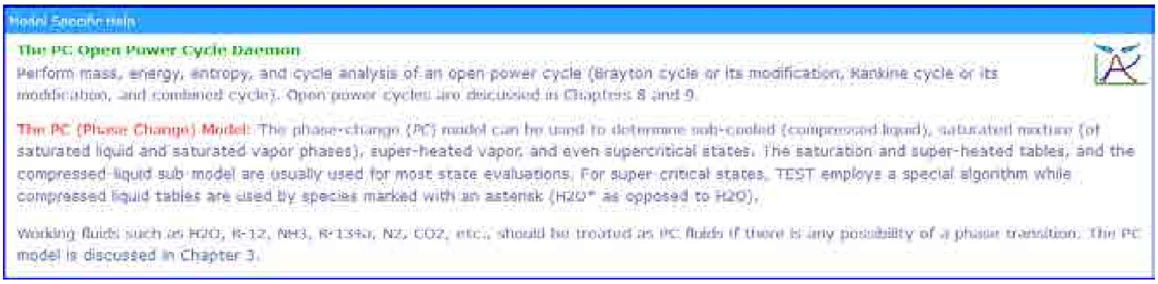
16. From the TEST daemon tree, select the 'Vapour Power and Gas Power cycles' daemon:



17. Clicking on 'Vapour Power and Gas Power cycles' brings up the window for material selection.



Hovering the mouse pointer over 'Vapor (Steam) Power Cycles', brings up the following explanatory message:



18. Click on 'Vapor (Steam) Power Cycles', and H2O is selected by default for working substance. Fill in the conditions for State 1, i.e. state at entry to compressor: p1= 7000 kPa, T1= 500 C, and mdot1 = 1 kg/s. Press Enter. Immediately, all properties at State 1 are calculated:

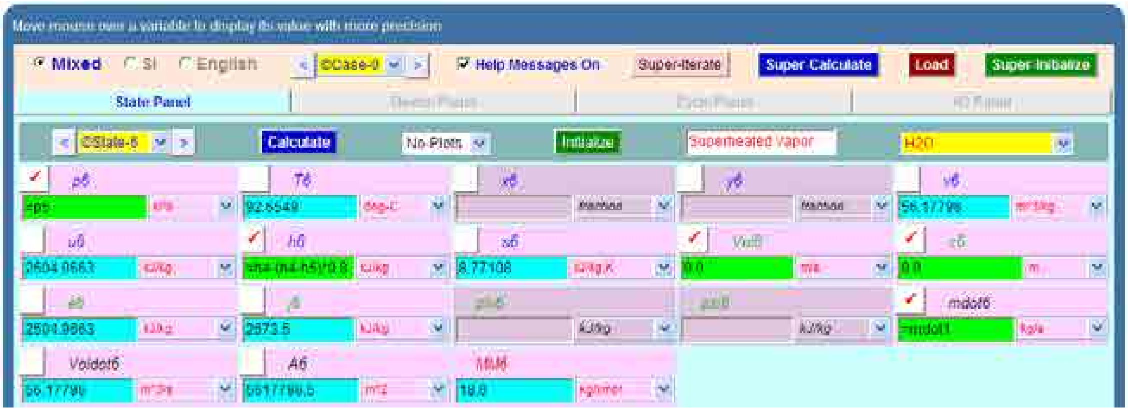
19. For State 2: Enter p2, s2 = s1 (for isentropic process 1-2), and mdot2 = mdot1. Hit Enter. We get:

20. For State 3: It represents the state after actual expansion, taking in to account the isentropic effcy. of turbine. Enter p3 = p2, h3 = h1 – (h1 – h2) * 0.8 where 0.8 is the turbine effcy. and mdot3 = mdot1. Hit Enter. We get:

21. For State 4: we have: p4 = p3, T4 = T1, mdot4 = mdot1. Hit Enter. We get:

22. For State 5: Enter p5 = 3 kpa, s5 = s4, mdot5 = mdot1, and hit Enter. We get:

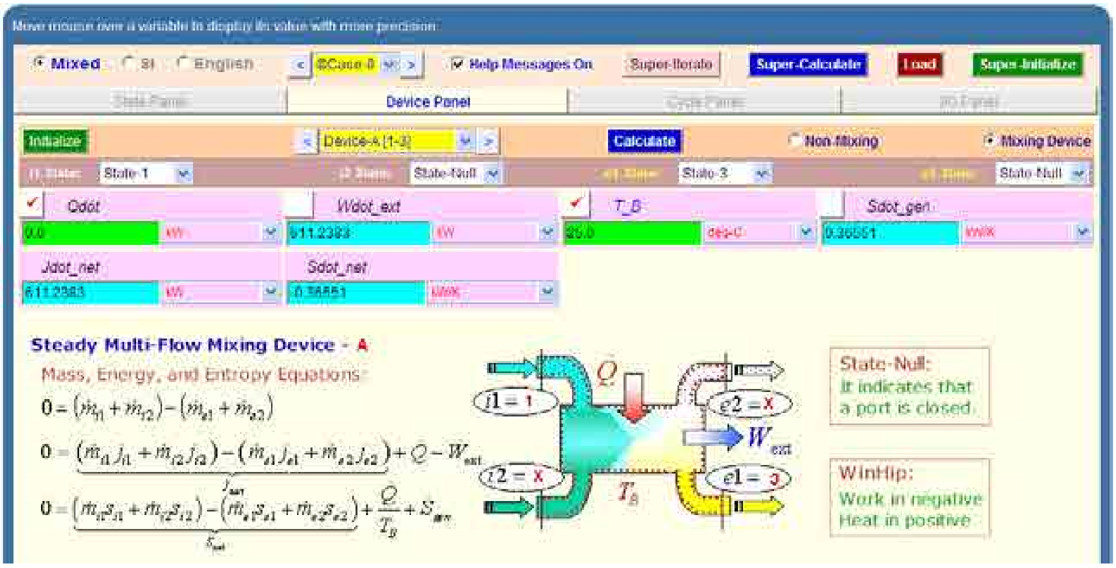
23. For State 6: i.e. actual exit of turbine-2: Enter p6 = p5, h6 = h4 – (h4 – h5) * 0.8 where 0.8 is isentropic effcy. of turbine. And mdot6 = mdot1. Hit Enter. We get:



24. For State 7: i.e. entry to pump: Enter p7 = p6, x7 = 0 (for sat. liq.), and mdot7 = mdot1. Hit Enter. We get:

25. For State 8: i.e. exit of pump: Enter p8 = p1, s8 = s7 (for isentropic compression 7-8), and mdot8 = mdot1. Hit Enter. We get:

26. Now, go to Device panel. For device A, enter State 1 and State 3 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And Qdot1 = 0 since in this process there is no external heat transfer. Hit Enter. We get:

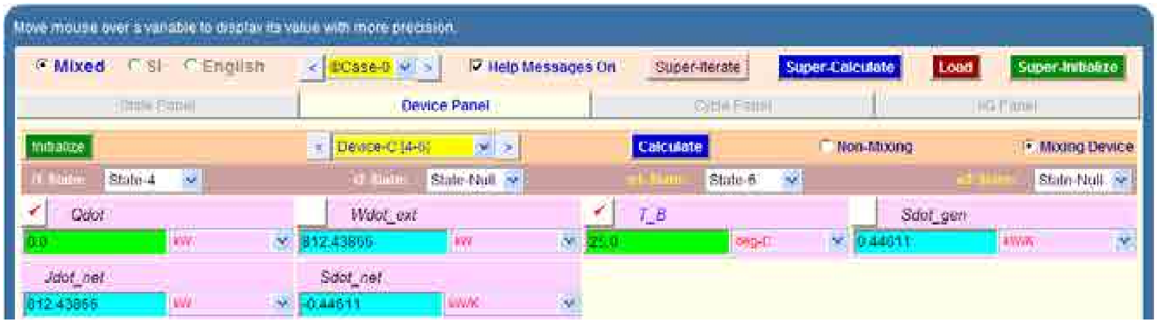


Note that work of Turbine-1 is 611.2383 kW.

27. Similarly for Device B: enter State 3 and State 4 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process no external work transfer occurs. Hit Enter. We get:

Note that Qdot for process 3-4 is amount of reheat = 686.9116 kW (Ans.)

28. And, for Device C: enter State 4 and State 6 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Qdot = 0 since for this process no external heat transfer occurs. Hit Enter. We get:



Note that work output of Turbine-2 is: 812.438 kW.

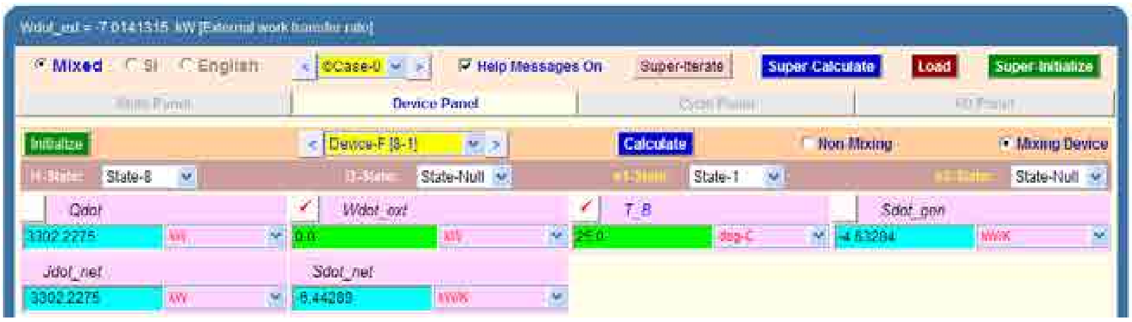
29. And, for Device D: enter State 6 and State 7 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process no external work transfer occurs. Hit Enter. We get:

Note that process 6-7 is heat removal in condenser; heat removed is: 2572.4763 kW.

30. Now, for Device E: enter State 7 and State 8 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Qdot = 0 since for this process (in the pump) no external heat transfer occurs. Hit Enter.

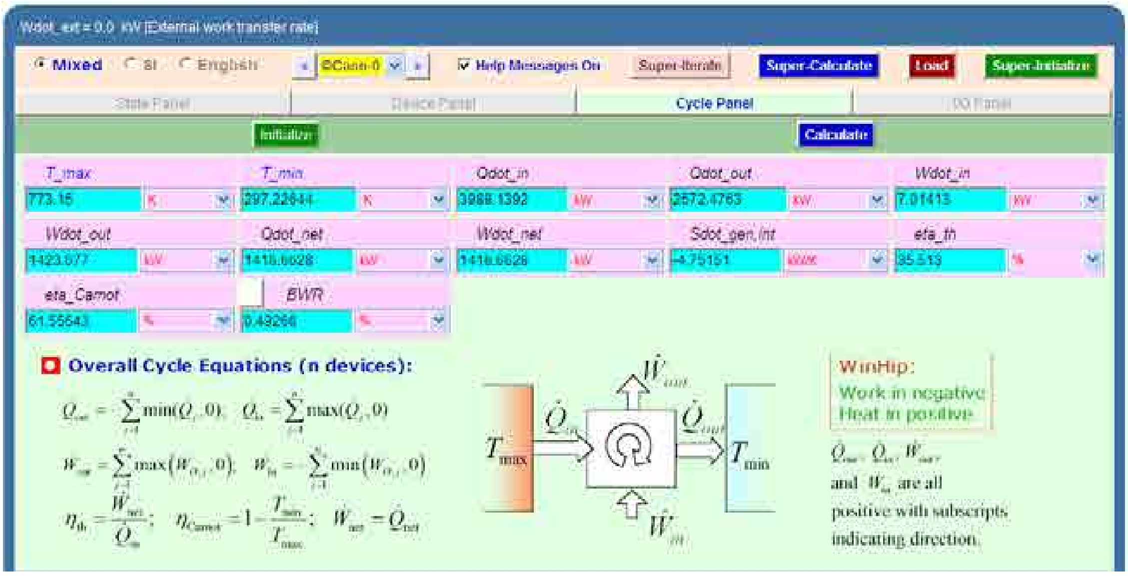
Note that pump work is 7.01413 kW (Ans.)

31. And, for Device F: enter State 8 and State 1 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process (in the boiler) no external work transfer occurs. Hit Enter.
And, SuperCalculate.



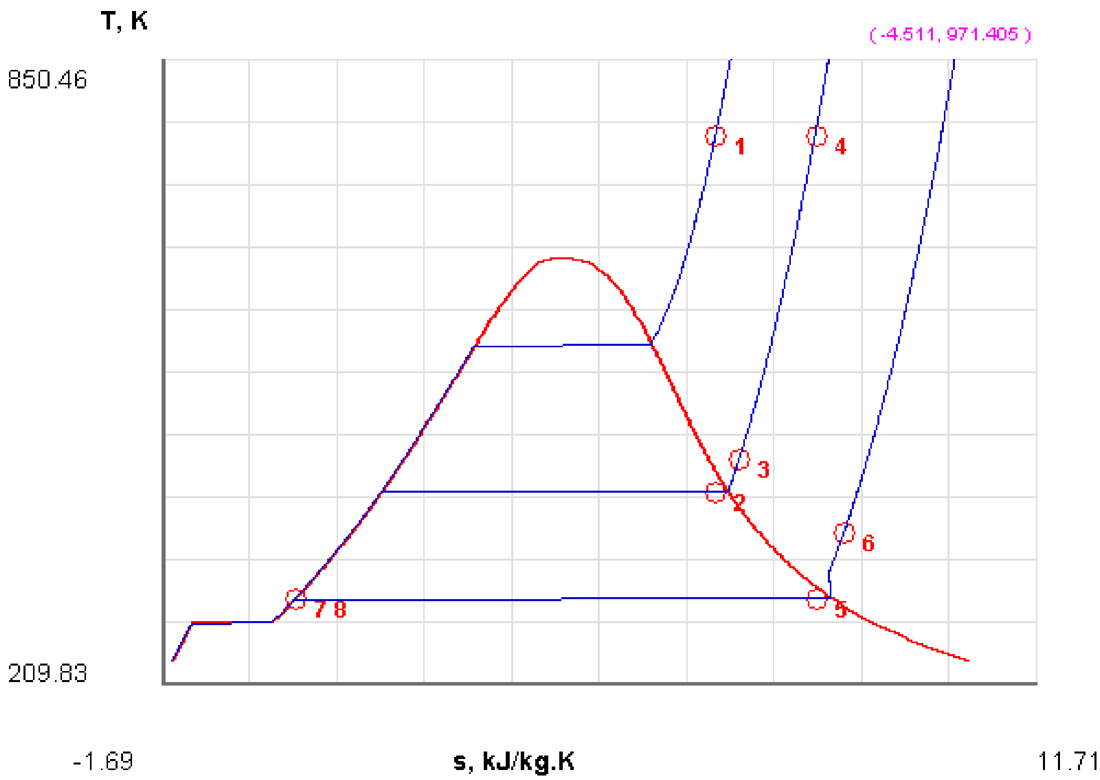
Note that heat supplied in boiler is Qdot = 3302.2275 kW.

32. Now, go to cycle panel. It gives the major parameters of this cycle:



We observe that Wdot_net = 1416.6628 kW, eta_th = 35.513% … Ans.

33. From the Plots widget, choose T-s diagram, and we get:



34. I/O panel gives the TEST code etc:

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

Daemon Path: Systems>Open>SteadyState>Specific>PowerCycle>PC-Model; v-10.cb01

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

States {

State-1: H2O;

Given: { p1= 7000.0 kPa; T1= 500.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 1.0 kg/s; }

State-2: H2O;

Given: { p2= 300.0 kPa; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= "mdot1" kg/s; }

State-3: H2O;

Given: { p3= “p2” kPa; h3= “h1-(h1-h2)*0.8” kJ/kg; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= “mdot1” kg/s; }

State-4: H2O;

Given: { p4= “p3” kPa; T4= “T1” deg-C; Vel4= 0.0 m/s; z4= 0.0 m; mdot4= “mdot1” kg/s; }

State-5: H2O;

Given: { p5= 3.0 kPa; s5= “s4” kJ/kg.K; Vel5= 0.0 m/s; z5= 0.0 m; mdot5= “mdot1” kg/s; }

State-6: H2O;

Given: { p6= “p5” kPa; h6= “h4-(h4-h5)*0.8” kJ/kg; Vel6= 0.0 m/s; z6= 0.0 m; mdot6= “mdot1” kg/s; }

State-7: H2O;

Given: { p7= “p6” kPa; x7= 0.0 fraction; Vel7= 0.0 m/s; z7= 0.0 m; mdot7= “mdot1” kg/s; }

State-8: H2O;

Given: { p8= “p1” kPa; s8= “s7” kJ/kg.K; Vel8= 0.0 m/s; z8= 0.0 m; mdot8= “mdot1” kg/s; }

}

Analysis {

Device-A: i-State = State-1; e-State = State-3; Mixing: true;

Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

Device-B: i-State = State-3; e-State = State-4; Mixing: true;

Given: { Wdot_ext= 0.0 kW; T_B= 25.0 deg-C; }

Device-C: i-State = State-4; e-State = State-6; Mixing: true;

Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

Device-D: i-State = State-6; e-State = State-7; Mixing: true;

Given: { Wdot_ext= 0.0 kW; T_B= 25.0 deg-C; }

Device-E: i-State = State-7; e-State = State-8; Mixing: true;

Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

Device-F: i-State = State-8; e-State = State-1; Mixing: true;

Given: { Wdot_ext= 0.0 kW; T_B= 25.0 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	7000.0	773.2		0.0481	3073.29	3410.27	6.797
# 02	300.0	406.7	1.0	0.5837	2471.1	2646.22	6.797
# 03	300.0	441.4		0.6639	2599.86	2799.03	7.163
# 04	300.0	773.2		1.1867	3129.94	3485.94	8.325
# 05	3.0	297.2	1.0	44.292	2337.61	2470.39	8.325
# 06	3.0	365.8		56.178	2504.97	2673.5	8.771
# 07	3.0	297.2	0.0	0.001	101.02	101.02	0.354
# 08	7000.0	297.2		0.001	101.02	108.04	0.354

 # Cycle Analysis Results:

Calculated: T_max= 773.15 K; T_min= 297.22644 K; Qdot_in= 3989.1392 kW;

Qdot_out= 2572.4763 kW; Wdot_in= 7.01413 kW; Wdot_out= 1423.677 kW;

Qdot_net= 1416.6628 kW; **Wdot_net= 1416.6628 kW**; Sdot_gen,int= -4.75151 kW/K;

eta_th= 35.513 %; eta_Carnot= 61.55643 %; BWR= 0.49268 %;

#******CALCULATE VARIABLES: Type in an expression starting with an '=' sign ('= mdot1*(h2-h1)', '= sqrt(4*A1/PI)', etc.) and press the Enter key)*********

#Reheat = (h4-h3) =h4-h3 = 686.91162109375 kW; Thermal effcy. = 35.51%….(Ans.)

(b) Plot the variation of eta_th and Wdot_net with reheat pressure (P2); vary P2 from 3 bar to 33 bar:

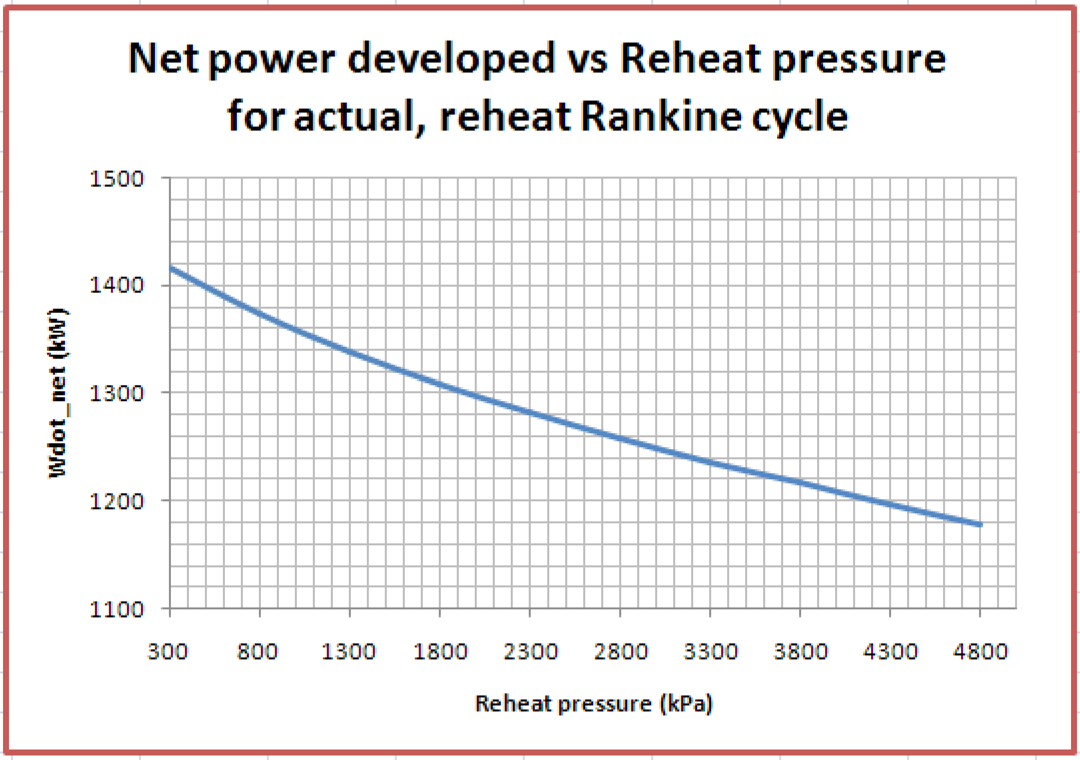
The procedure is quite simple:

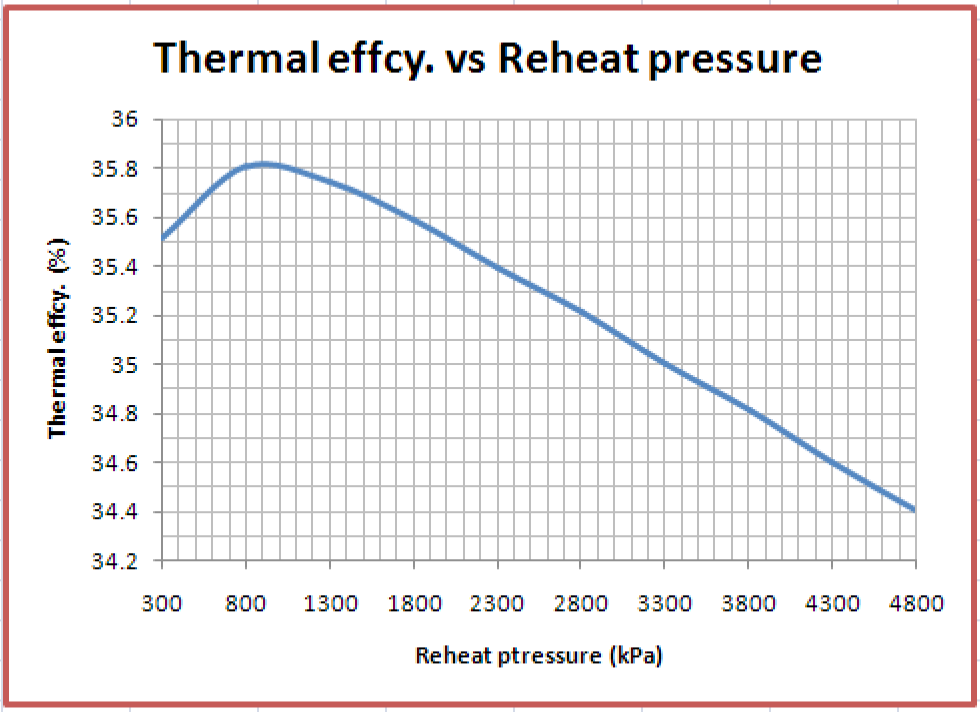
i. Go to State 2 in the States panel, change the value pf P2 to desired value
ii. Click on Calculate and then SuperCalculate.
iii. Go to Cycle panel read off the values of eta_th and Wdot_net
iv. Repeat this procedure for the next value of P2
v. Tabulate the values of P2 and eta_th and Wdot_net, and plot the graphs using EXCEL

Following are the results:

P2 (kPa)	Wdot_net (kW)	eta_th (%)
300	1416.6628	35.513
800	1373.5829	35.807
1300	1338.7622	35.742
1800	1308.7335	35.587
2300	1281.5952	35.392
2800	1258.3715	35.21
3300	1235.8524	35.0
3800	1216.2567	34.815
4300	1196.2806	34.6
4800	1178.3009	34.404

Now, plot the results in EXCEL:





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Prob.3.4.2 In an ideal reheat, regenerative cycle,the HP turbine receives steam at 20 bar, 300 C. After expansion to 7 bar, the steam is reheated to 300 C and expands in an intermediate pressure turbine to 1 bar. A fraction of steam is now extracted for feed water heating in an open type feed water heater. The remaining steam expands in a low pressure turbine to a final pressure of 0.05 bar. [VTU]

Determine:

a) Cycle thermal effcy. (b) SSC in kg/kWh (c) Quality of steam entering the condenser

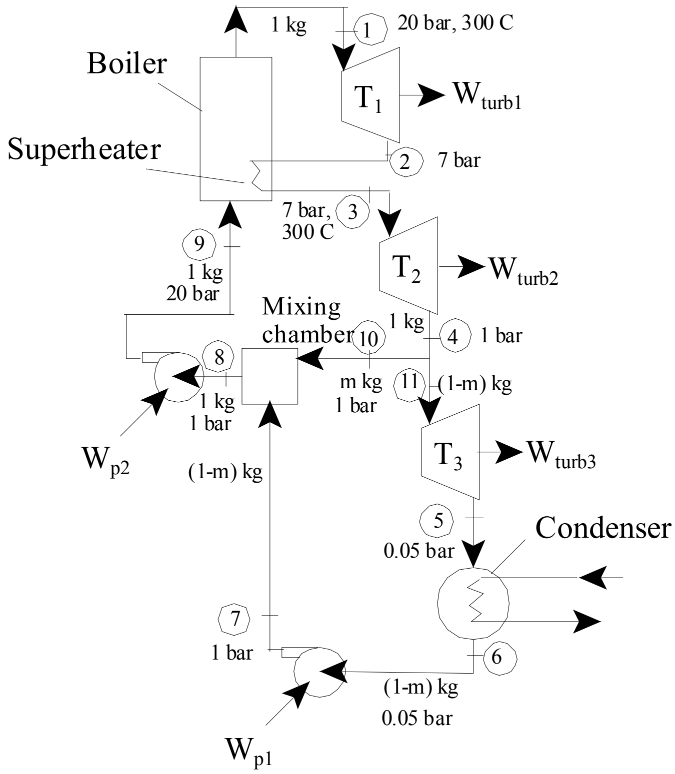


Fig.Prob.3.4.2. Regenerative Rankine cycle with reheat

TEST Solution:

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

3. Click on 'Vapor (Steam) Power Cycles', and H2O is selected by default for working substance. Fill in the conditions for State 1, i.e. state at entry to compressor: p1= 2000 kPa, T1= 300 C, and mdot1 = 1 kg/s. Press Enter. Immediately, all properties at State 1 are calculated:

4. For State 2: Enter p2 = 700 kPa, s2 = s1 (for isentropic process 1-2), and mdot2 = 1 kg/s. Hit Enter. We get:

5. For State 3: It represents the state after reheating. Enter p3 = p2, T3 = 300 C and mdot3 = 1 kg/s. Hit Enter. We get:

6. For State 4: we have: p4 = 100 kPa, s4 = s3, mdot4 = 1 kg/s. Hit Enter. We get:

7. For State 5: Enter p5 = 5 kPa, s5 = s4, mdot5 = 1- (h8 – h7) / (h4 – h7), and hit Enter. WE get this expression for mdot5 from a heat balance on the mixing chamber. We get:

Note that x5 = 0.861. This is the quality of steam entering the condenser …. Ans.

8. For State 6: i.e. exit condenser: Enter p6 = p5, x6 = 0 (for sat. liq.) and mdot6 = mdot5. Hit Enter. We get:

9. For State 7: i.e. exit of pump-1: Enter p7 = 100 kPa, s7 = s6 (for isentropic comprn. in pump), and mdot7 = mdot5. Hit Enter. We get:

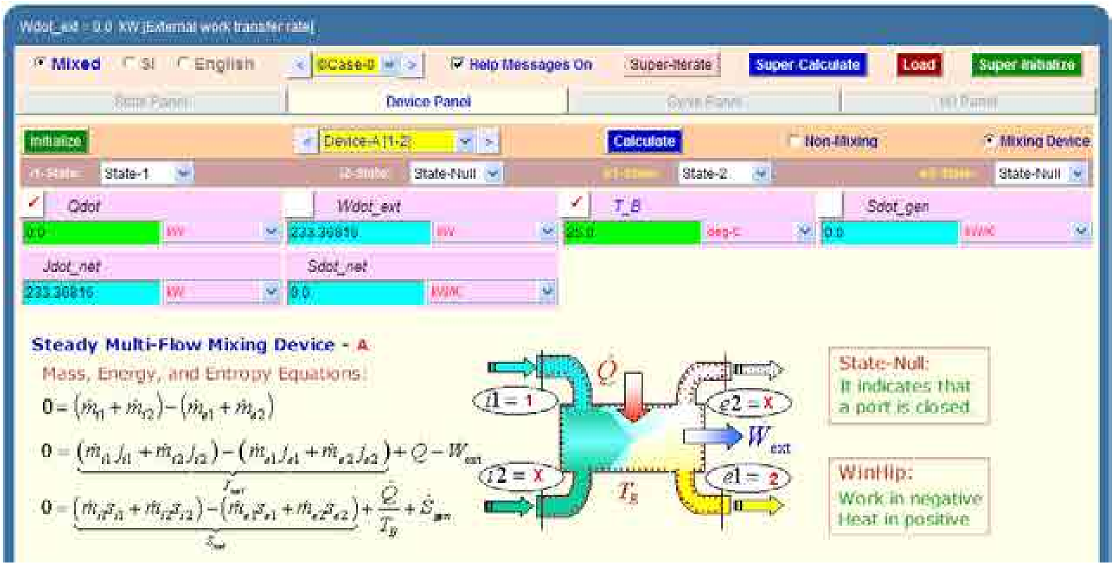
10. For State 8: i.e. exit of mixing chamber and entry to pump-2: Enter p8 = 100 kPa, x8 = 0 (for sat. liq.), and mdot8 = 1 kg/s. Hit Enter. We get:

11. For State 9: i.e. exit of pump-2 and entry boiler: Enter p8 = 2000 kPa, s9 = s8 (for isentropic comprn. in pump), and mdot9 = 1 kg/s. Hit Enter. We get:

12. For State 10: i.e. exit of Turbine-2 and entry to mixing chamber: Enter p10 = 100 kPa, h10 = h4 and mdot10 = (1 – mdot5) kg/s. (See the schematic diagram of system). Hit Enter. We get:

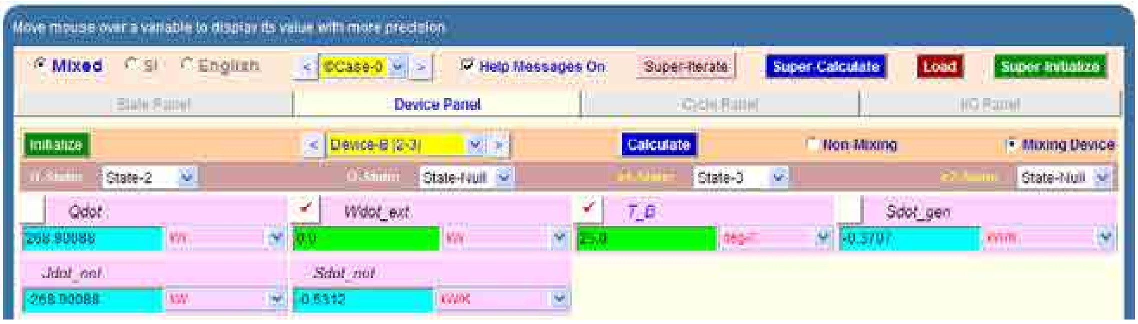
13. State 11: i.e. entry to turbine-3. Enter p11 = p4, h11 = h4 and mdot11 = mdot5. Hit Enter:

14. Now, go to Device panel. For device A, enter State 1 and State 2 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And Qdot = 0 since in this process there is no external heat transfer. Hit Enter. We get:



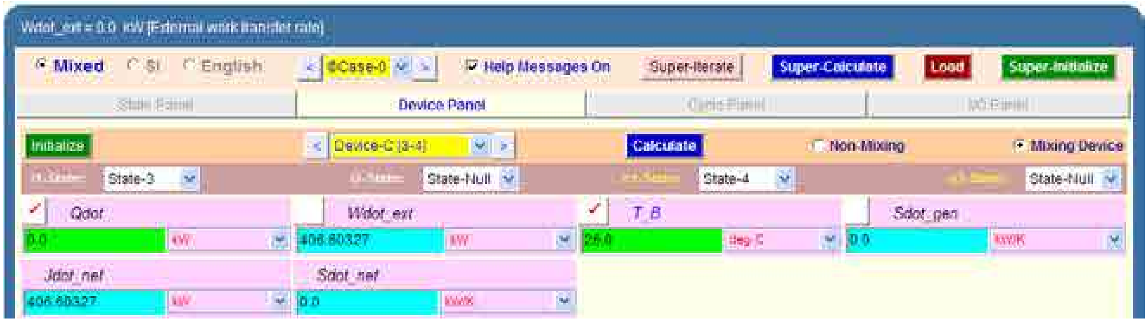
Note that work of Turbine-1 is 233.368 kW.

15. Similarly for Device B: enter State 2 and State 3 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process no external work transfer occurs. Hit Enter. We get:



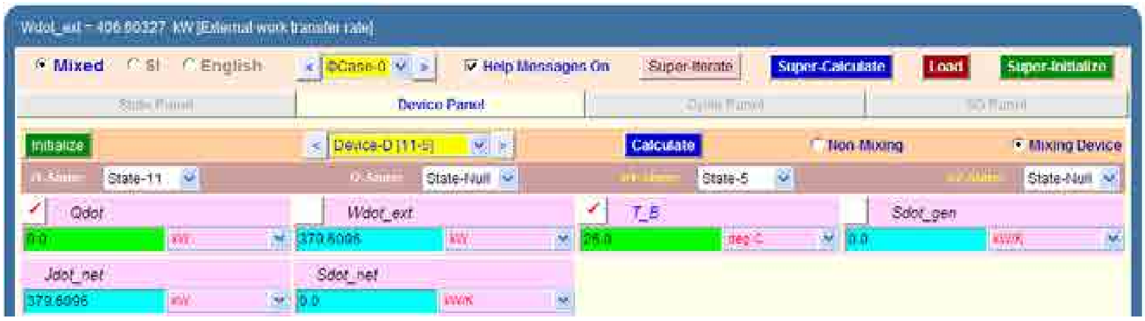
Note that Qdot for process 2-3 is amount of reheat = 268.9 kW (Ans.)

16. And, for Device C: enter State 3 and State 4 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Qdot = 0 since for this process no external heat transfer occurs. Hit Enter. We get:



Note that work output of Turbine-2 is: Wdot_ext = 406.6 kW.

17. And, for Device D: enter State 11 and State 5 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Qdot = 0 since for this process no external heat transfer occurs. Hit Enter. We get:

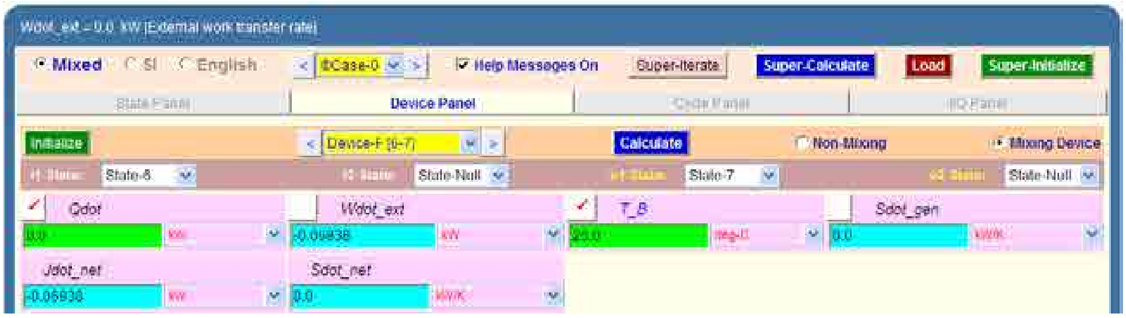


Note that process 11-5 is expansion in turbine-3; Work = Wdot_ext = 379.61 kW.

18. Now, for Device E: enter State 5 and State 6 for i1-state and e1-state respectively. Also, select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process (in the condenser) no external work transfer occurs. Hit Enter. We get:

Note that heat removed in condenser is 1855.425 kW (Ans.)

19. And, for Device F: enter State 6 and State 7 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Qdot = 0 since for this process (in the pump-1) no external heat transfer occurs. Hit Enter. We get:

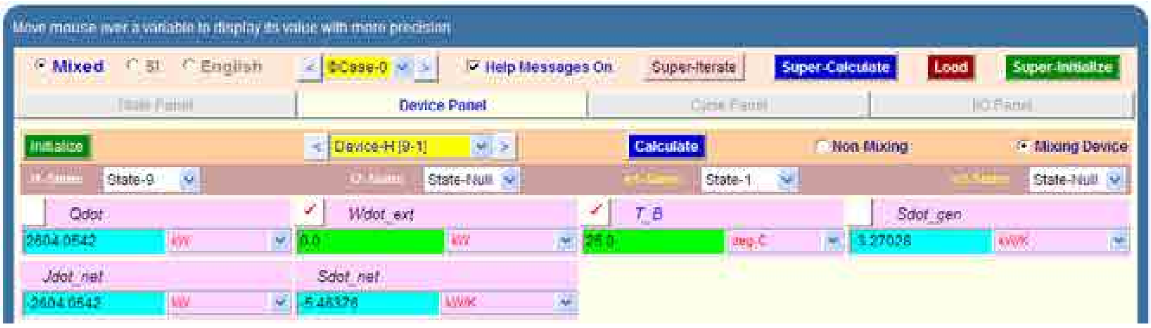


Note that required for pump-1 is Wdot_ext = 0.069 kW.

20. Device G: enter State 8 and State 9 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Qdot = 0 since for this process (in the pump-2) no external heat transfer occurs. Hit Enter. We get:

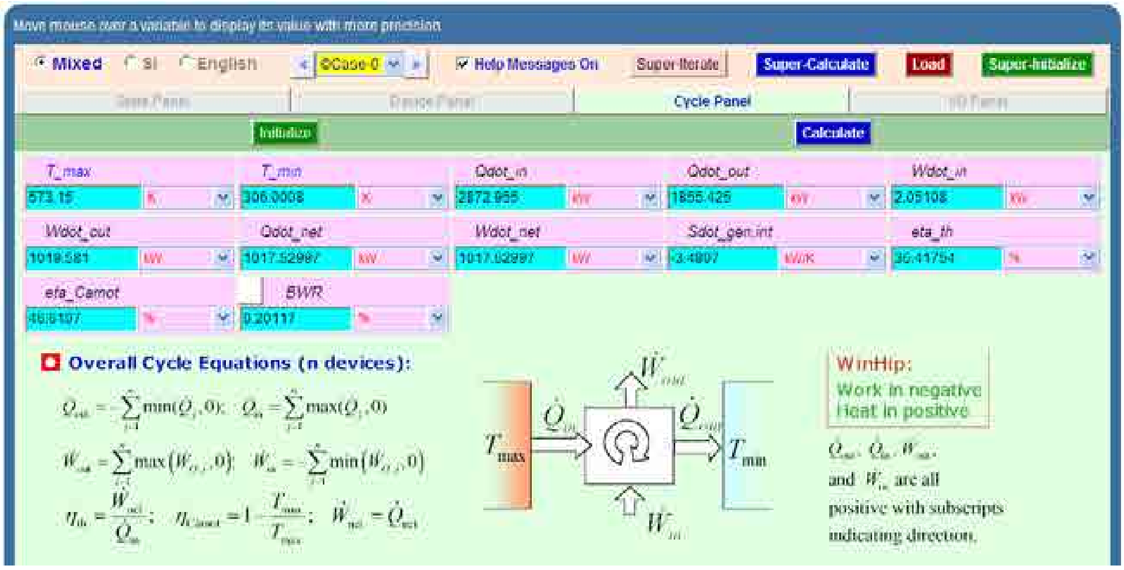
Note that required for pump-2 is Wdot_ext = 1.98 kW.

21. Device H: enter State 9 and State 1 for i1-state and e1-state respectively. Also, since there is only one stream select Null state for i2-state and e2-state. And, Wdot_ext = 0 since for this process (in the boiler) no external work transfer occurs. Hit Enter. We get:



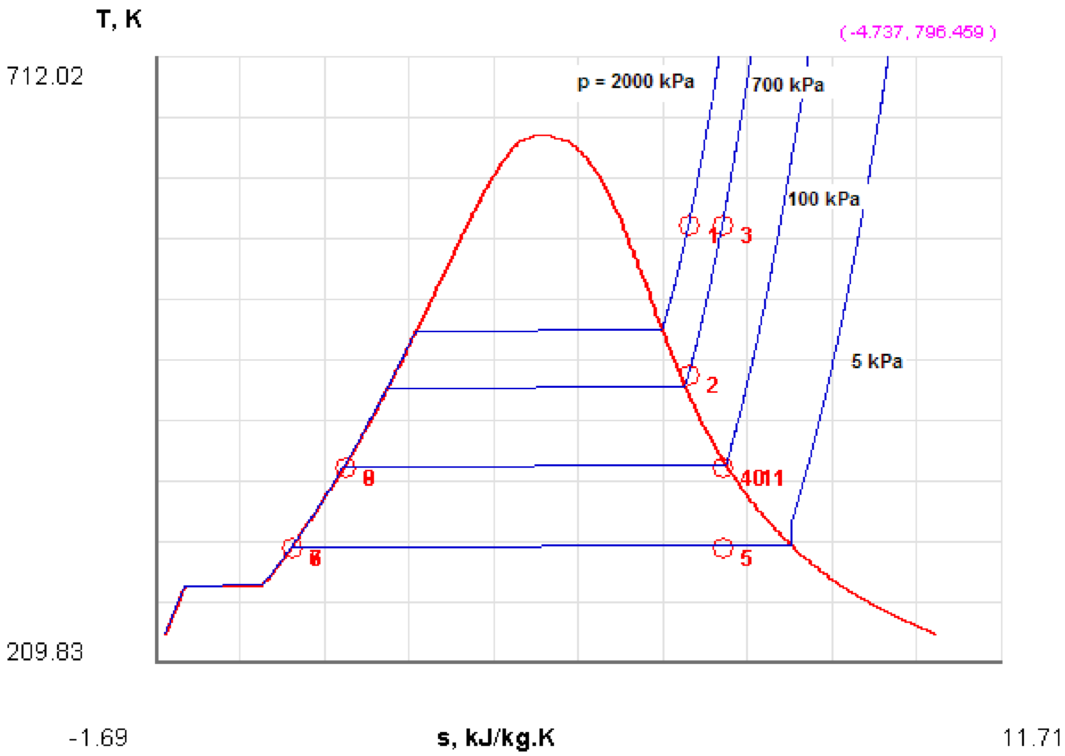
Note that heat supplied in boiler = Qdot = 2604.05 kW.

22. Now, go to cycle panel. It gives the major parameters of this cycle:



We observe that Wdot_net = 1017.53 kW, eta_th = 35.418% … Ans.

23. From the Plots widget, choose T-s diagram, and we get:



24. I/O panel gives the TEST code etc:

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

Daemon Path: Systems>Open>SteadyState>Specific>PowerCycle>PC-Model; v-10.cb01

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

States {

State-1: H2O;

Given: { p1= 2000.0 kPa; T1= 300.0 deg-C; Vel1= 0.0 m/s; z1= 0.0 m; mdot1= 1.0 kg/s; }

State-2: H2O;

Given: { p2= 700.0 kPa; s2= "s1" kJ/kg.K; Vel2= 0.0 m/s; z2= 0.0 m; mdot2= 1.0 kg/s; }

State-3: H2O;

Given: { p3= “p2” kPa; T3= 300.0 deg-C; Vel3= 0.0 m/s; z3= 0.0 m; mdot3= 1.0 kg/s; }

State-4: H2O;

Given: { p4= 100.0 kPa; s4= “s3” kJ/kg.K; Vel4= 0.0 m/s; z4= 0.0 m; mdot4= 1.0 kg/s; }

State-5: H2O;

Given: { p5= 5.0 kPa; s5= “s4” kJ/kg.K; Vel5= 0.0 m/s; z5= 0.0 m; mdot5= “1-(h8-h7)/(h4-h7)” kg/s; }

State-6: H2O;

Given: { p6= “p5” kPa; x6= 0.0 fraction; Vel6= 0.0 m/s; z6= 0.0 m; mdot6= “mdot5” kg/s; }

State-7: H2O;

Given: { p7= 100.0 kPa; s7= “s6” kJ/kg.K; Vel7= 0.0 m/s; z7= 0.0 m; mdot7= “mdot6” kg/s; }

State-8: H2O;

Given: { p8= 100.0 kPa; x8= 0.0 fraction; Vel8= 0.0 m/s; z8= 0.0 m; mdot8= 1.0 kg/s; }

State-9: H2O;

Given: { p9= 2000.0 kPa; s9= “s8” kJ/kg.K; Vel9= 0.0 m/s; z9= 0.0 m; mdot9= 1.0 kg/s; }

State-10: H2O;

Given: { p10= 100.0 kPa; h10= “h4” kJ/kg; Vel10= 0.0 m/s; z10= 0.0 m; mdot10= “(1-mdot5)” kg/s; }

State-11: H2O;

Given: { p11= “p4” kPa; h11= “h4” kJ/kg; Vel11= 0.0 m/s; z11= 0.0 m; mdot11= “mdot5” kg/s; }

}

```
Analysis {

        Device-A: i-State = State-1; e-State = State-2; Mixing: true;

        Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

        Device-B: i-State = State-2; e-State = State-3; Mixing: true;

        Given: { Wdot_ext= 0.0 kW; T_B= 25.0 deg-C; }

        Device-C: i-State = State-3; e-State = State-4; Mixing: true;

        Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

        Device-D: i-State = State-11; e-State = State-5; Mixing: true;

        Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

        Device-E: i-State = State-5; e-State = State-6; Mixing: true;

        Given: { Wdot_ext= 0.0 kW; T_B= 25.0 deg-C; }

        Device-F: i-State = State-6; e-State = State-7; Mixing: true;

        Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

        Device-G: i-State = State-8; e-State = State-9; Mixing: true;

        Given: { Qdot= 0.0 kW; T_B= 25.0 deg-C; }

        Device-H: i-State = State-9; e-State = State-1; Mixing: true;

        Given: { Wdot_ext= 0.0 kW; T_B= 25.0 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	2000.0	573.2		0.1255	2772.54	3023.48	6.766
#02	700.0	449.6		0.2817	2592.88	2790.11	6.766
#03	700.0	573.2		0.3715	2798.95	3059.01	7.297
#04	100.0	372.8	1.0	1.6767	2484.73	2652.41	7.297
#05	5.0	306.0	0.9	24.3499	2103.9	2225.3	7.297
#06	5.0	306.0	0.0	0.001	137.71	137.72	0.476
#07	100.0	306.0		0.001	137.69	137.79	0.476
#08	100.0	372.8	0.0	0.001	417.34	417.44	1.303
#09	2000.0	372.8		0.001	417.34	419.42	1.303
#10	100.0	372.8	1.0	1.6767	2484.73	2652.41	7.297
#11	100.0	372.8	1.0	1.6767	2484.73	2652.41	7.297

 # Cycle Analysis Results:

Calculated: T_max= 573.15 K; T_min= 306.0008 K; Qdot_in= 2872.955 kW;

Qdot_out= 1855.425 kW; Wdot_in= 2.05108 kW; Wdot_out= 1019.581 kW;

Qdot_net= 1017.52997 kW; **Wdot_net= 1017.52997 kW;** Sdot_gen,int= -3.4807 kW/K;

eta_th= 35.41754 %; eta_Carnot= 46.6107 %; BWR= 0.20117 %;

==

3.5 References:

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