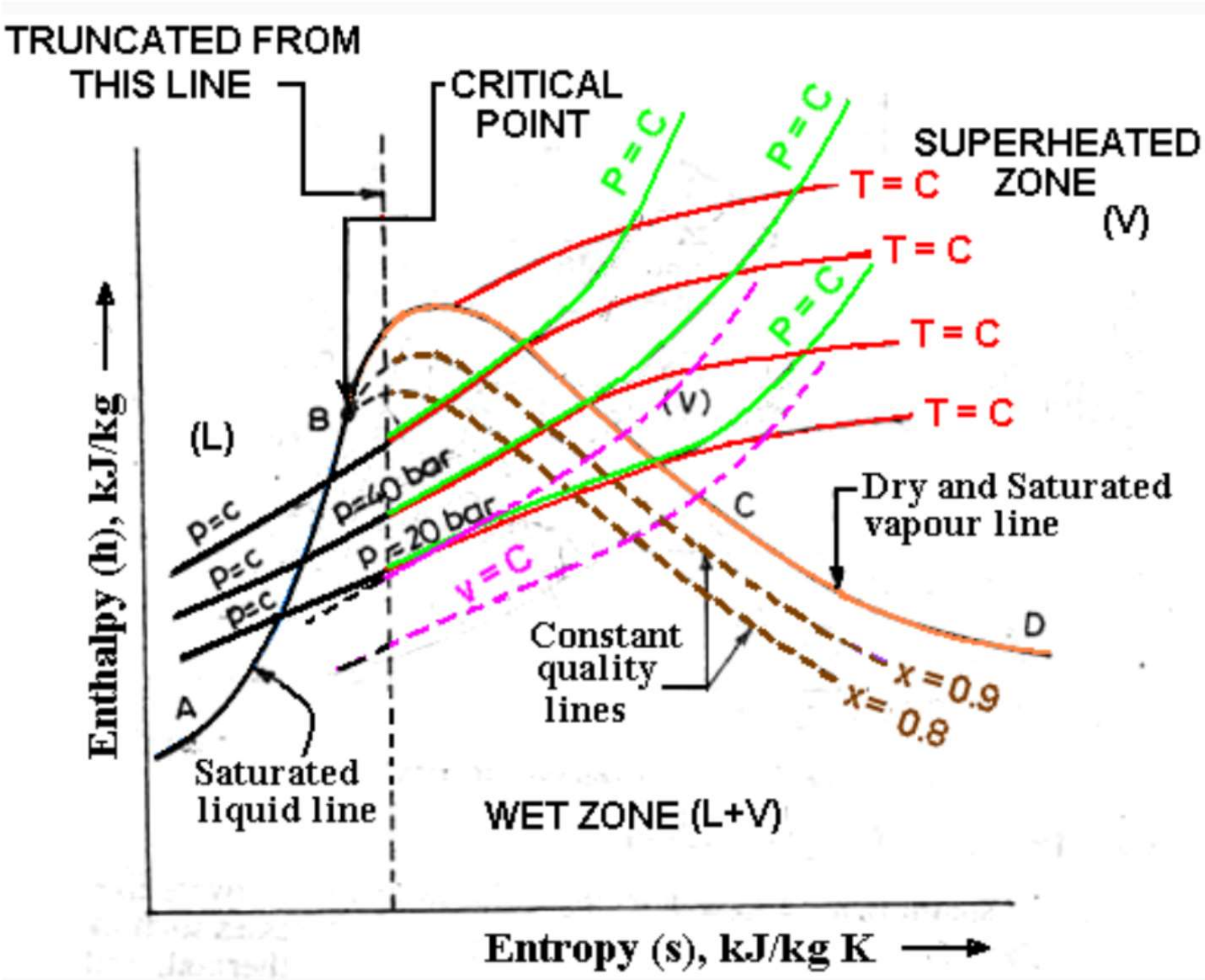
Mollier or Enthalpy-Entropy (h-s) diagram

This diagram has a series of

- constant temperature lines,
- constant pressure lines,
- constant quality lines, and
- constant volume lines.



- ➢ The Mollier diagram is used only when quality is greater than 50% and for superheated steam.
- ➢ For any state, at least two properties should be known to determine the other unknown properties of steam at that state.

Table 21.1 (a). Steam tables for saturated water and steam (temperature)

Temperature in °C (t)	Absolute Pressure in bar (p)	Specific Volume in m³/kg		Specific Enthalpy in kJ/kg			Specific Entropy in kJ/kg °K			Temperature in °C (t)
		Water (v_f)	Steam (v_g)	Water (h_f)	Evaporation (h_{fg})	Steam (h_g)	Water (s_f)	Evaporation (s_{fg})	Steam (s_g)	
0	0.006 11	0.001 000	206.16	0.0	2 501.6	2 501.6	0.000	9.158	9.158	0
1	0.006 57	0.001 000	192.61	4.2	2 499.2	2 503.4	0.015	9.116	9.131	1
2	0.007 06	0.001 000	179.92	8.4	2 496.8	2 505.2	0.031	9.074	9.105	2
3	0.007 58	0.001 000	168.17	12.6	2 494.5	2 507.1	0.046	9.033	9.079	3
4	0.008 13	0.001 000	157.27	16.8	2 492.1	2 508.9	0.061	8.992	9.053	4

Table 21.1 (b). Steam tables for saturated water and steam (pressure)

Absolute Pressure in bar (p)	Temperature in °C (t)	Specific Volume in m³/kg		Specific Enthalpy in kJ/kg			Specific Entropy in kJ/kg °K			Absolute Pressure in bar (p)
		Water (v_f)	Steam (v_g)	Water (h_f)	Evaporation (h_{fg})	Steam (h_g)	Water (s_f)	Evaporation (s_{fg})	Steam (s_g)	
0.006 1	0.000	0.001 000	206.16	0.0	2 501.6	2 501.6	0.000	9.158	9.158	0.006 1
0.010	6.980	0.001 000	129.21	29.3	2 485.0	2 514.4	0.106	8.871	8.977	0.010
0.015	13.01	0.001 001	88.351	54.6	2 470.8	2 525.4	0.195	8.635	8.830	0.015
0.020	17.51	0.001 001	67.012	73.5	2 460.2	2 533.6	0.261	8.464	8.725	0.020
0.025	21.09	0.001 002	54.340	88.4	2 451.8	2 540.2	0.312	8.333	8.645	0.025
0.030	24.10	0.001 003	45.670	101.0	2 444.6	2 545.6	0.354	8.224	8.578	0.030

Table 21.2 (a). Steam tables for specific volume of superheated steam

Absolute Pressure in bar (p)	Saturation Temperarature in °C (t_s)	Specific Volume (v) in m³/kg at Various Temperatures in °C										
		100	150	200	250	300	350	400	500	600	700	800
0.02	17.5	86.08	97.63	109.2	120.7	132.2	143.8	155.3	178.4	201.5	224.6	247.6
0.04	29.0	43.03	48.81	54.58	60.35	66.12	71.89	77.66	89.20	100.7	112.3	123.8
0.06	36.2	28.68	32.53	36.38	40.23	44.08	47.93	51.77	59.47	67.16	74.85	82.54
0.08	41.5	21.50	24.40	27.28	30.17	33.06	35.94	38.83	44.60	50.37	56.14	61.91
0.10	45.8	17.20	19.51	21.83	24.14	26.45	28.75	31.06	35.68	40.30	44.91	49.53

Table 21.2 (b). Steam tables for enthalpy of superheated steam

Absolute Pressure in bar (p)	Saturation Tempurature in °C (t_s)	Enthalpy (h) in kJ/kg at Various Temperatures in °C										
		100	150	200	250	300	350	400	500	600	700	800
0.02	17.5	2 688.5	2 783.7	2 880.0	2 977.7	3 076.8	3 177.5	3 279.7	3 489.2	3 705.6	3 928.8	4 158.7
0.04	29.0	2 688.3	2 783.5	2 879.9	2 977.6	3 076.8	3 177.4	3 279.7	3 489.2	3 705.6	3 928.8	4 158.7
0.06	36.2	2 688.0	2 783.4	2 879.8	2 977.6	3 076.7	3 177.4	3 279.6	3 489.2	3 705.6	3 928.8	4 158.7
0.08	41.5	2 687.8	2 783.2	2 879.7	2 977.5	3 076.7	3 177.3	3 279.6	3 489.1	3 705.5	3 928.8	4 158.7
0.10	45.8	2 687.5	2 783.1	2 879.6	2 977.4	3 076.6	3 177.3	3 279.6	3 489.1	3 705.5	3 928.8	4 158.7

Table 21.2 (c). Steam tables for entropy of superheated steam

Absolute Pressure in bar (p)	Saturation Temperature in °C (t_s)	Entropy (s) in kJ/kg °K at Various Temperatures in °C										
		100	150	200	250	300	350	400	500	600	700	800
0.02	17.5	9.193	9.433	9.648	9.844	10.025	10.193	10.351	10.641	10.904	11.146	11.371
0.04	29.0	8.873	9.113	9.328	9.524	9.705	9.874	10.031	10.321	10.585	10.827	11.051
0.06	36.2	8.685	8.925	9.141	9.337	9.518	9.686	9.844	10.134	10.397	10.639	10.864
0.08	41.5	8.552	8.792	9.008	9.204	9.385	9.554	9.711	10.001	10.265	10.507	10.731
0.10	45.8	8.449	8.689	8.905	9.101	9.282	9.450	9.608	9.898	10.162	10.404	10.628

Find the specific volume, enthalpy and internal energy of wet steam at 18 bar with dryness fraction (x) = 0.85, by using Steam Tables and Mollier chart.

(a) BY USING STEAM TABLES

By using steam tables (for dry saturated steam):

From steam tables for dry saturated steam at 18 bar pressure,

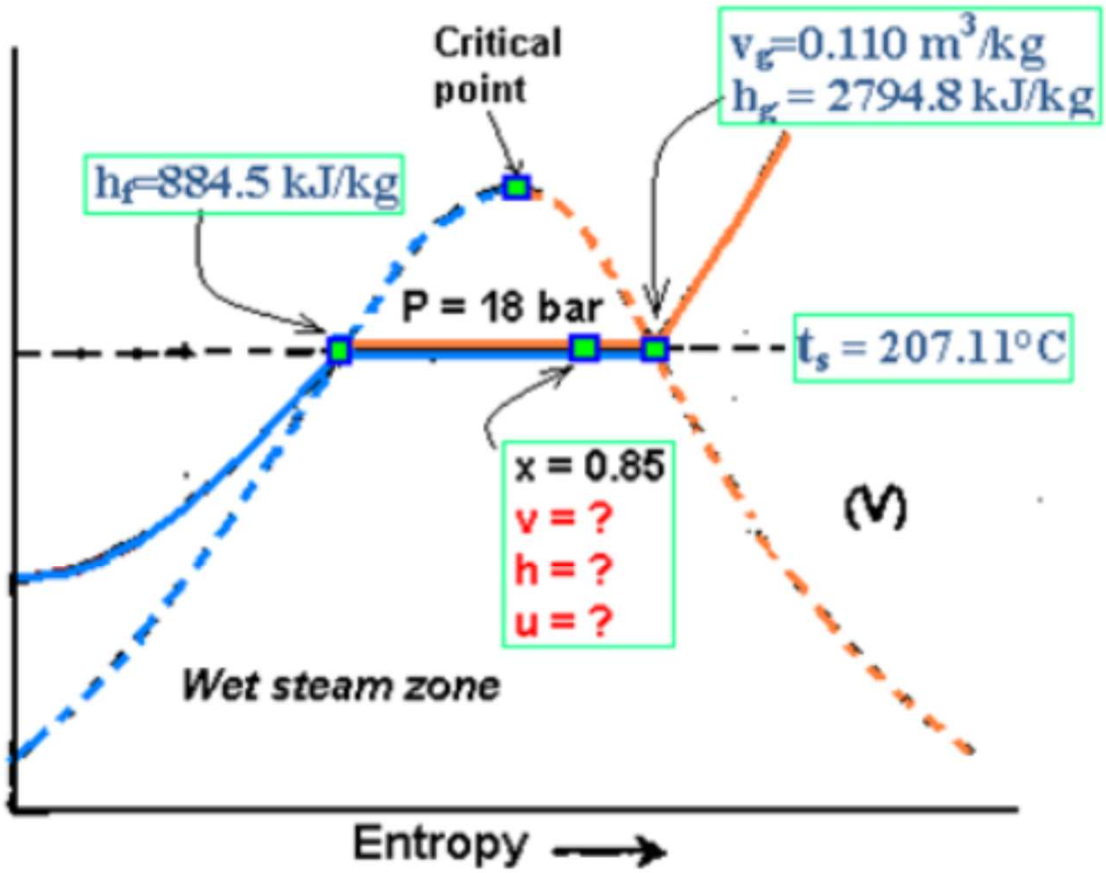
$t_s = 207.11°C$,

$h_f = 884.5$ kJ/kg,

$h_g = 2794.8$ kJ/kg,

$h_{fg} = 1910.3$ kJ/kg,

$v_g = 0.110$ m^3/kg.



(i) Specific enthalpy of wet steam, h :

Formula: Specific enthalpy of wet steam, $h = h_f + xh_{fg}$

$h = h_f + xh_{fg} = 884.6 + 0.85 \times 1910.3 = \mathbf{2508.35\ kJ/kg.}$

(ii) Specific Internal energy of wet steam,

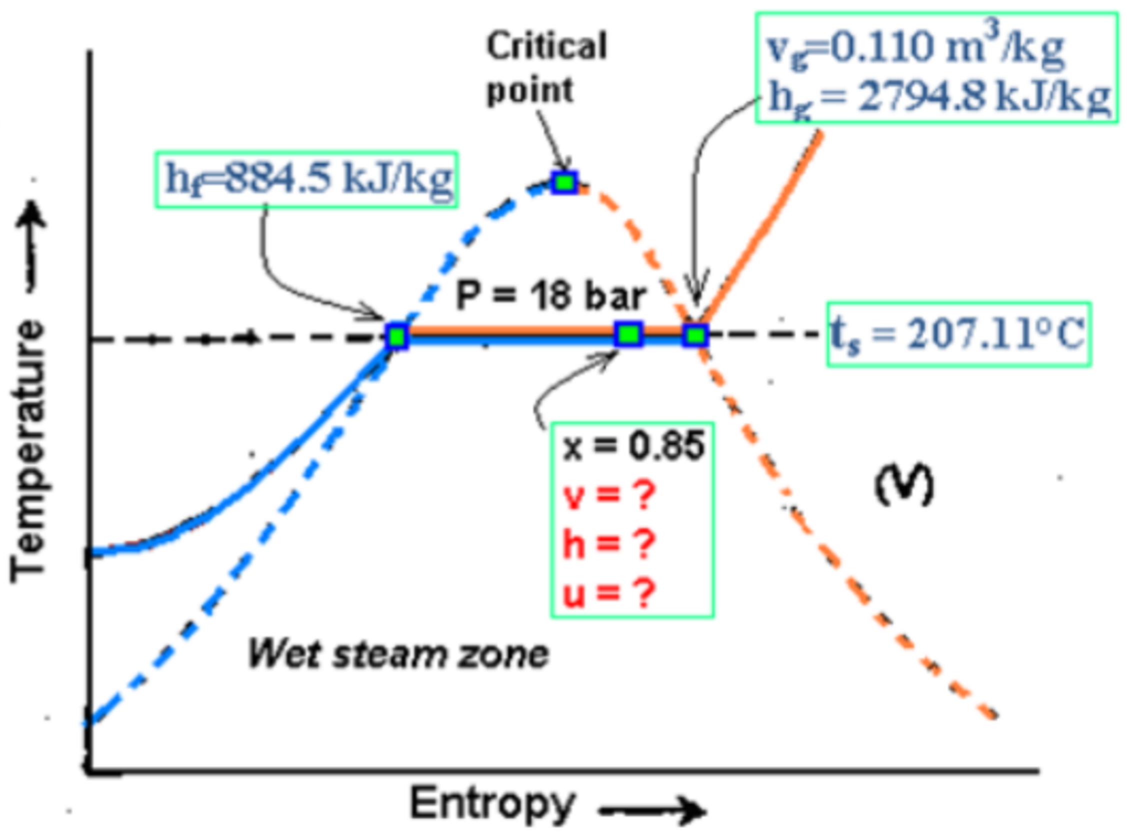
Formula: Specific internal energy of wet steam, $u = h - pv$

$u = h - pv = 2508.35 - 18 \times 10^2 (0.0935) = \mathbf{2340.75\ kJ/kg}$

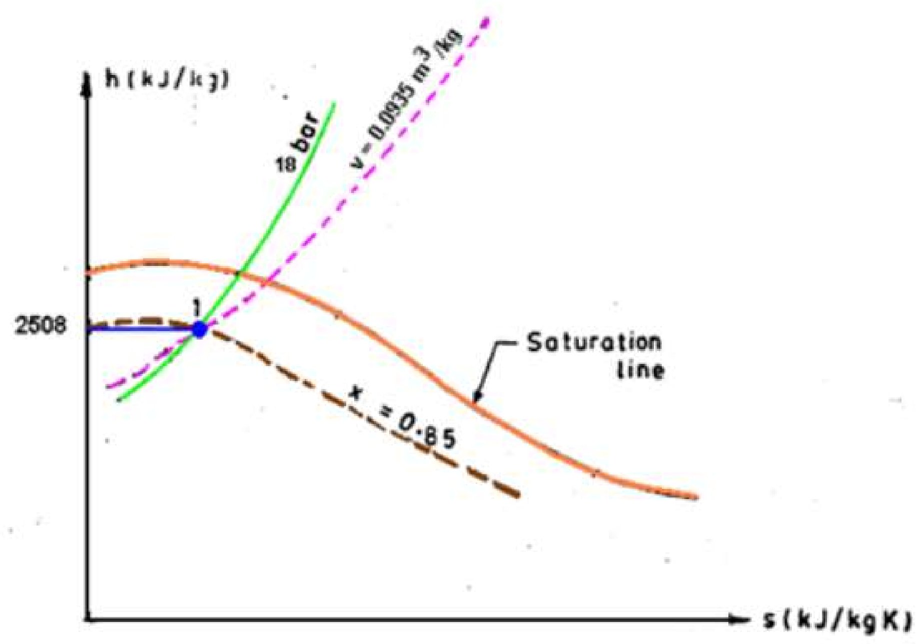
(iii) Determine specific volume of wet steam, v :

Formula: Specific volume of wet steam, $v = x.v_g$

$v = x.v_g = 0.85 \times 0.110 = \mathbf{0.0935\ m^3/kg.}$



(b) BY USING MOLLIER CHART



Locate point '1' at an intersection of 18 bar pressure line and 0.85 dryness fraction line.

Read the value of enthalpy (h) and specific volume (v) from Mollier diagram corresponding to point '1'.

(i) Specific enthalpy of wet steam, **h = 2508 KJ/kg**

(ii) Specific volume of wet steam, **v = 0.0935 m^3/kg**

(iii) Specific Internal energy of wet steam, u

$$\mathbf{u} = h - pv$$

$$= 2508 - 18 \times 10^2 (0.0935) = \mathbf{2340\ \ kJ/kg}$$

Find the internal energy of 1 kg of steam at 20 bar when

(i) It is superheated, its temperature being 400°C.

(ii) It is wet, its dryness being 0.9

Assume superheated steam to behave as a perfect gas from the commencement of superheat and thus obeys Charle's law. Specific heat for steam = 2 kJ/kg K.

Solution:

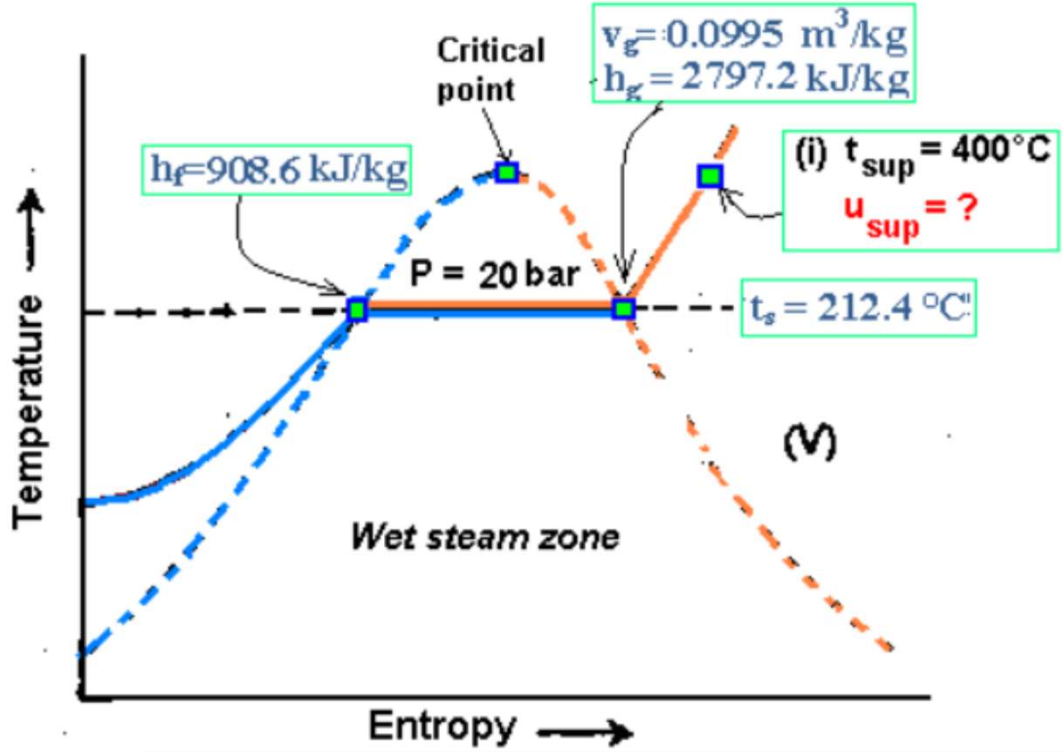
Given: Mass of steam, m = 1 kg; Pressure of steam, p = 20 bar

By using steam table (for dry saturated steam):

From steam tables for dry saturated steam at 20 bar, we have:

$$t_s = 212.4\ ^\circ C;\ h_f = 908.6\ kJ/kg;\ h_g = 2797.2\ kJ/kg;$$

$$h_{fg} = 1888.6\ kJ/kg;\ v_g = 0.0995\ m^3/kg$$



(i) Steam is superheated, its temperature being 400°C.

Given: Temperature of superheated steam, $t_{sup} = 400°C$

or $T_{sup} = 400+273 = 673$ K

Specific heat of superheated steam, $C_{ps} = 2.3$ kJ/kg K.

Internal energy of superheated steam, $u_{sup} = h_{sup} - p.v_{sup}$

$$h_{sup} = h_f + h_{fg} + C_{ps}(t_{sup} - t_s)$$

$$= 908.6 + 1888.6 + 2.3\,(400 - 212.4) \quad = \mathbf{3228.68\ kJ/kg}$$

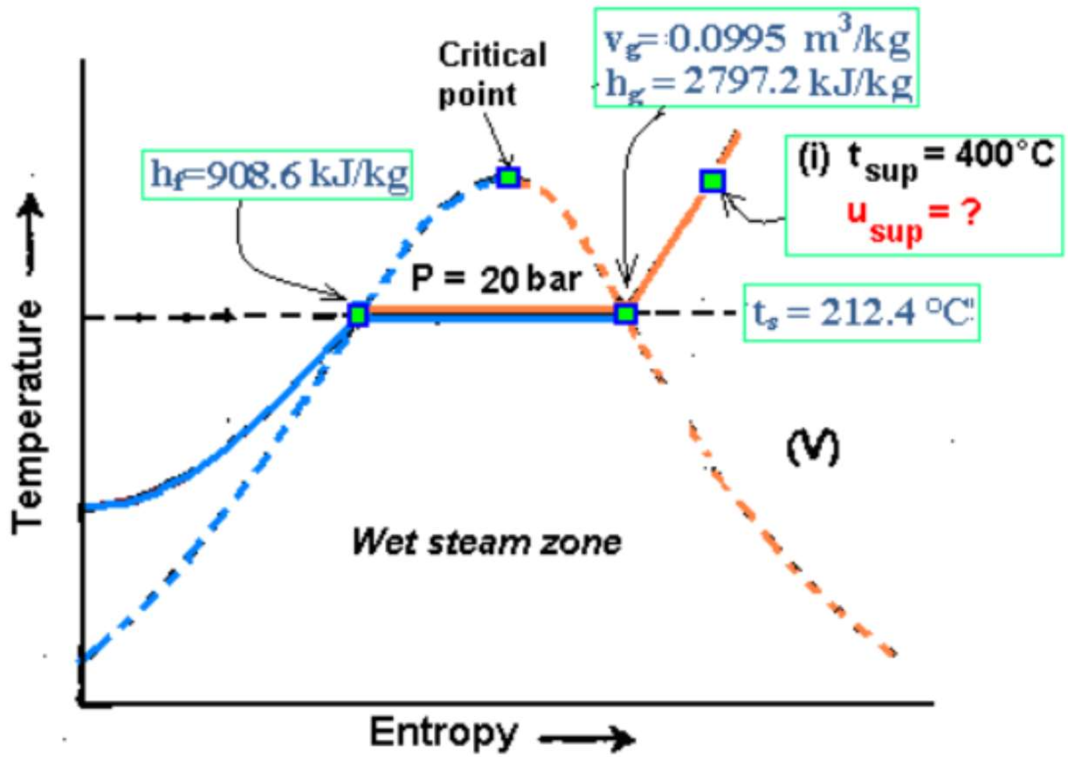
v_{sup} can be found out by Charle's law

$$\frac{v_{sup}}{v_g} = \frac{T_{sup}}{T_g} \qquad \text{or} \qquad \frac{v_{sup}}{v_g} = \frac{T_{sup}}{T_s}$$

$$\text{or}\ \ \mathbf{v_{sup}} = v_g\left(\frac{T_{sup}}{T_s}\right) = 0.0995\left(\frac{673}{212.4+273}\right) = \mathbf{0.1379\ m^3/kg}$$

Internal energy, $\mathbf{u_{sup}} = h_{sup} - p\,.v_{sup}$

$$= 3228.68 - 20 \times 10^5 \times 0.1379 \times 10^{-3} = \mathbf{2952.88\ KJ/kg}$$



(ii) Steam is wet, its dryness (x) being 0.9

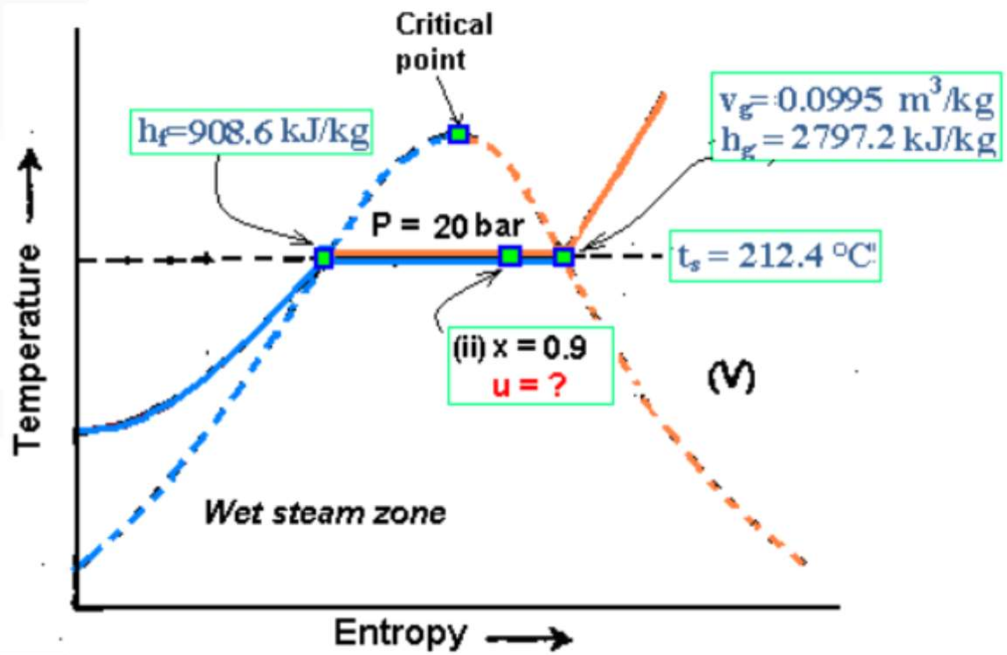
Given: Dryness fraction, $x = 0.9$;   Pressure of steam, $p = 20$ bar

By using steam table (for dry saturated steam):

From steam tables for dry saturated steam at 20 bar, we have:

$\mathbf{t_s = 212.4\ °C;\ h_f = 908.6\ kJ/kg;\ \ h_g = 2797.2\ kJ/kg;}$

$\mathbf{h_{fg} = 1888.6\ kJ/kg;\quad v_g = 0.0995\ m^3/kg}$



Determine internal energy of 1 kg of wet steam

Formula: Internal energy of wet steam, $u = h - p.v$

Finding unknown, h and v;

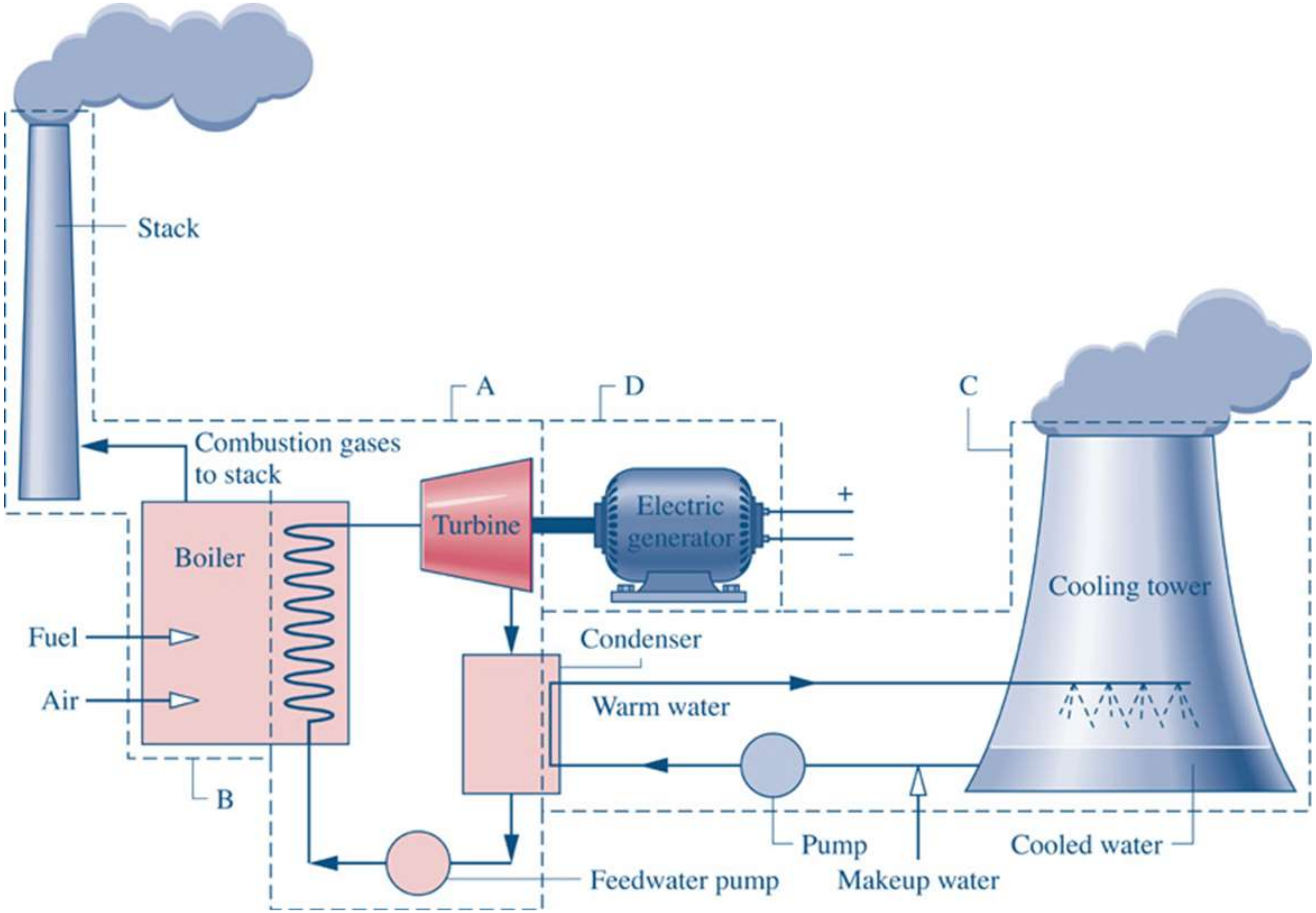
For wet steam, we have

$\mathbf{h} = h_f + x.\ h_{fg} = 908.6 + 0.9 \times 1888.6 = \mathbf{2608.34\ KJ/kg}$

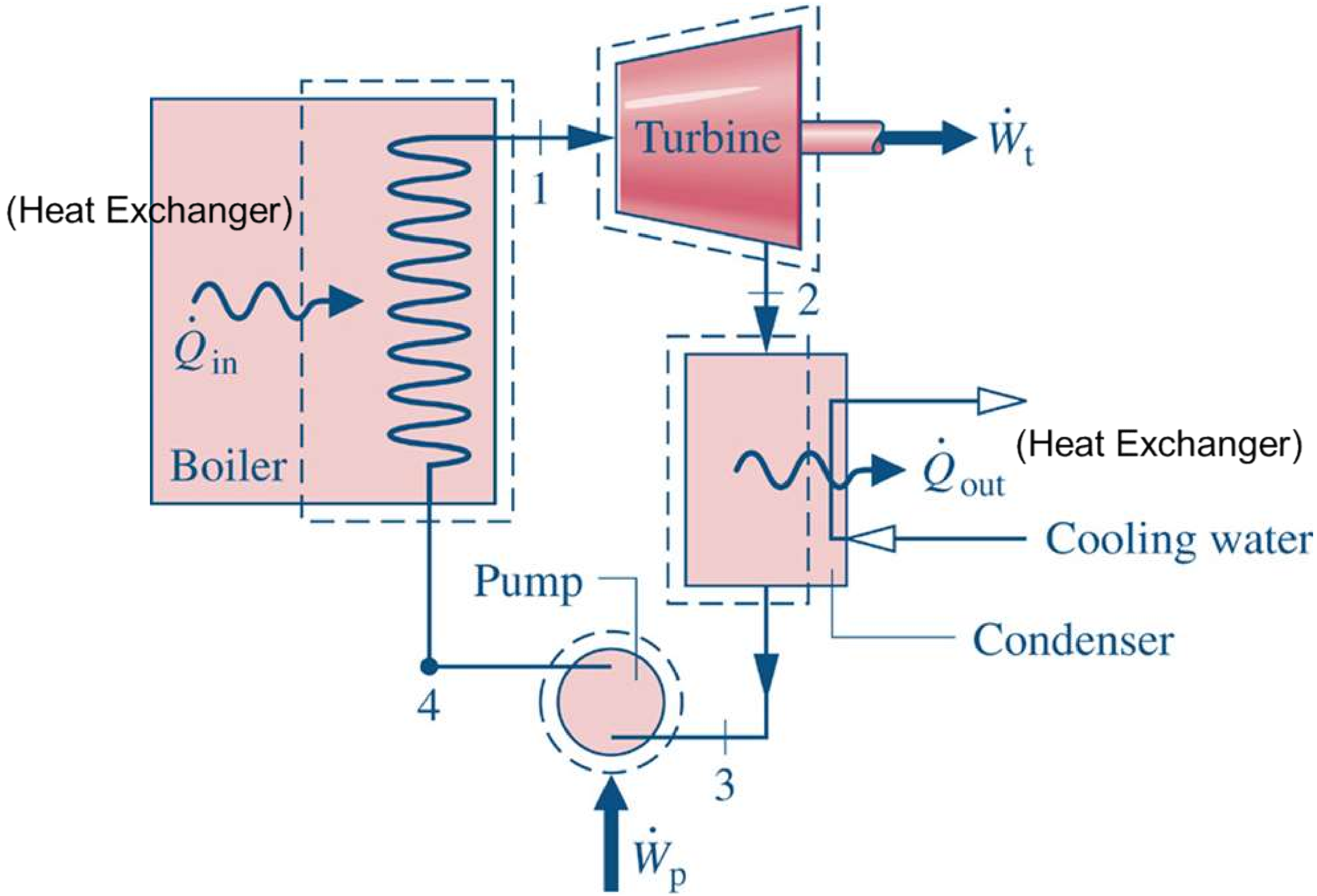
$\mathbf{v} = x\ v_g = 0.9 \times 0.0995 = \mathbf{0.8955 m^3/kg}$

Internal energy, $\mathbf{u} = h - p\ .v\quad = 2608.34 - 20 \times 10^5 \times 0.8955 \times 10^{-3} = \mathbf{2429.24\ KJ/kg}$

A Simple Vapor Power Plant

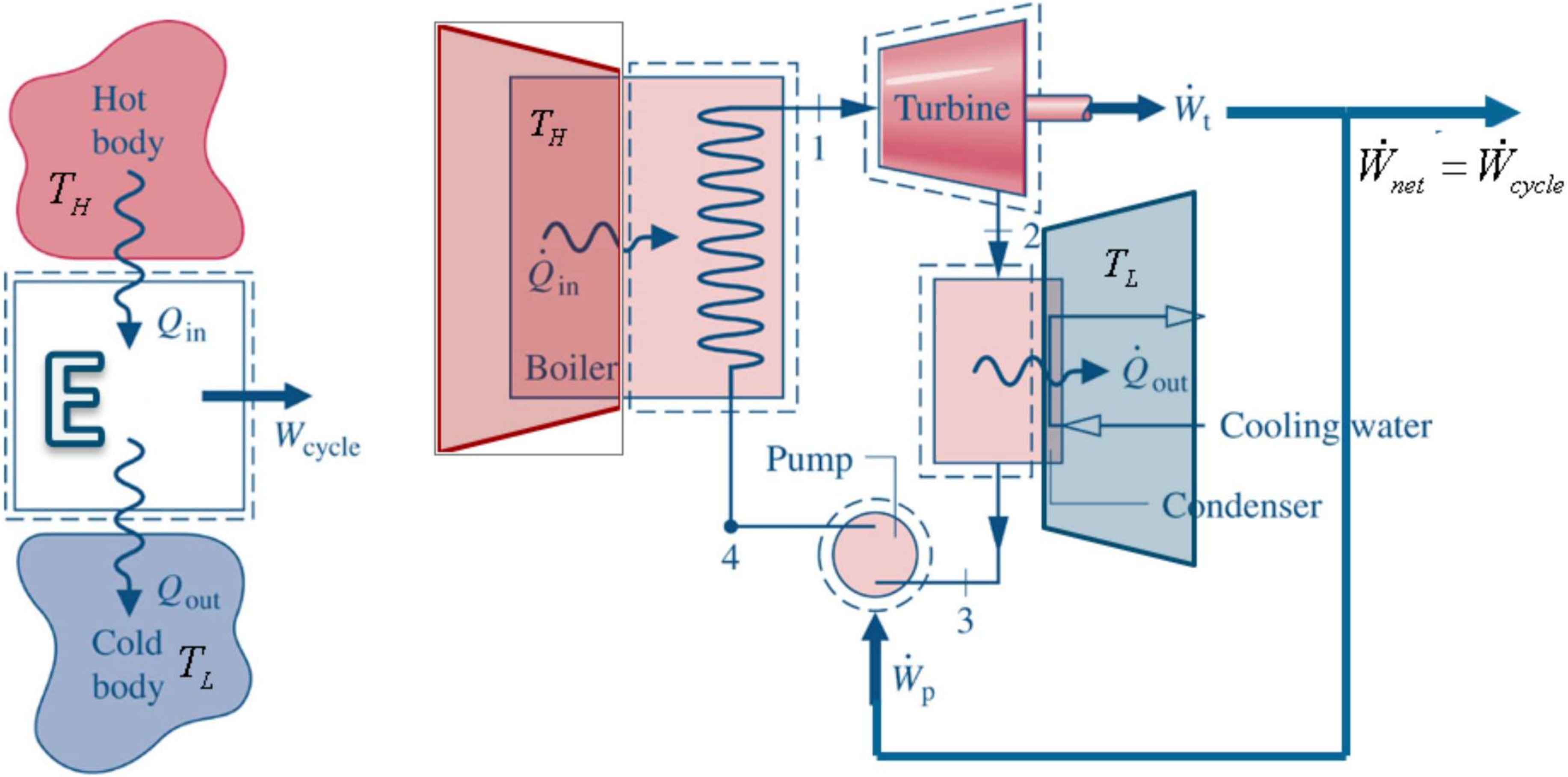


The Rankine Cycle - Components



The Rankine Cycle – A Heat Engine

(Heat Source)



(Heat Sink)

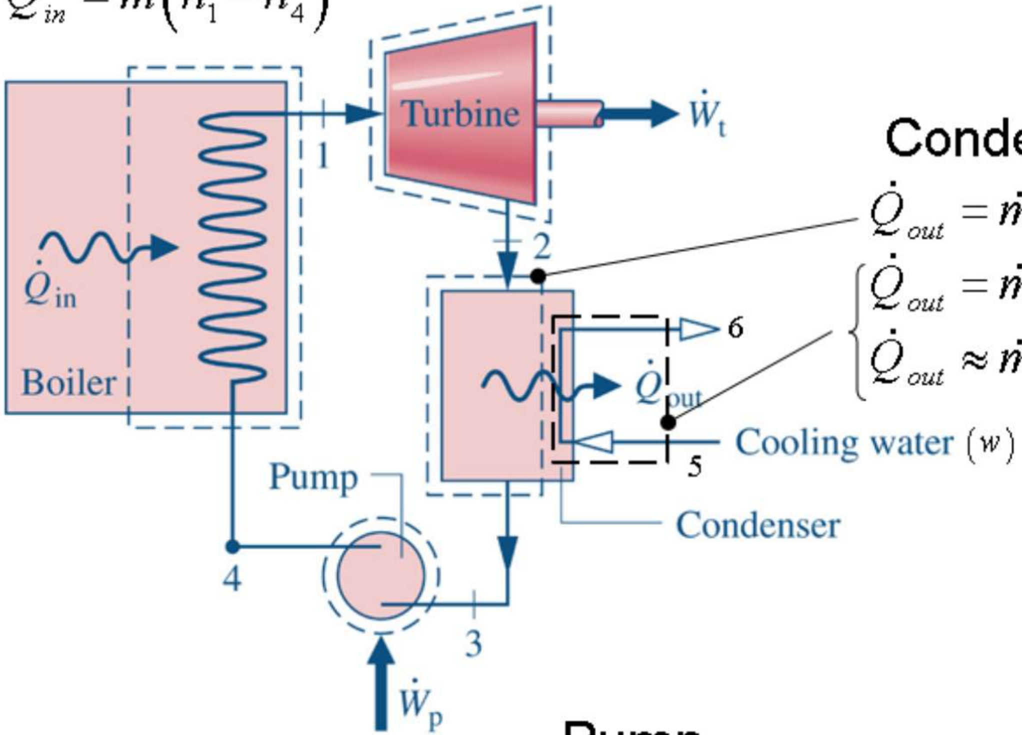
Component Analysis

Boiler

$$\dot{Q}_{in} = \dot{m}\left(h_1 - h_4\right)$$

Turbine

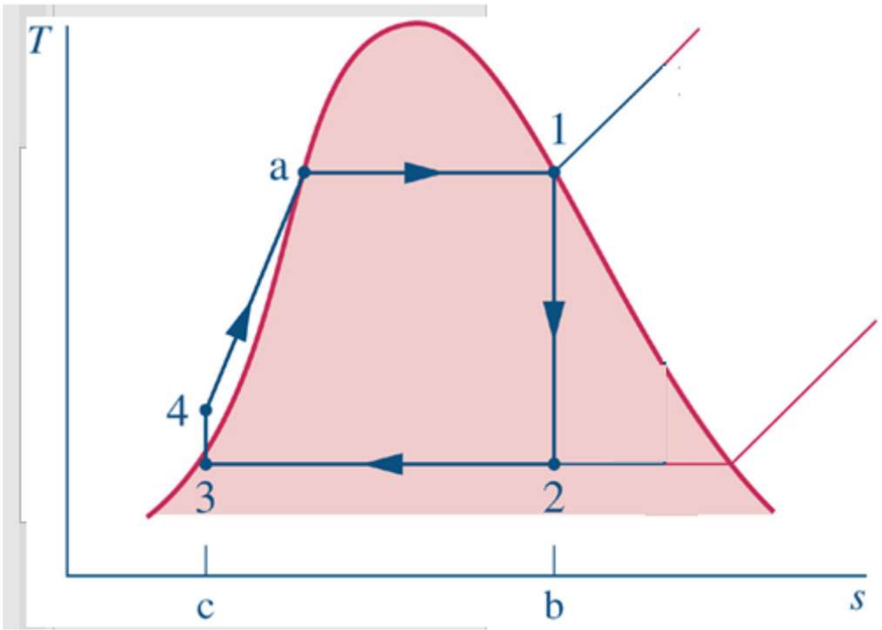
$$\dot{W}_t = \dot{m}\left(h_1 - h_2\right)$$



Condenser

$$\dot{Q}_{out} = \dot{m}\left(h_2 - h_3\right)$$

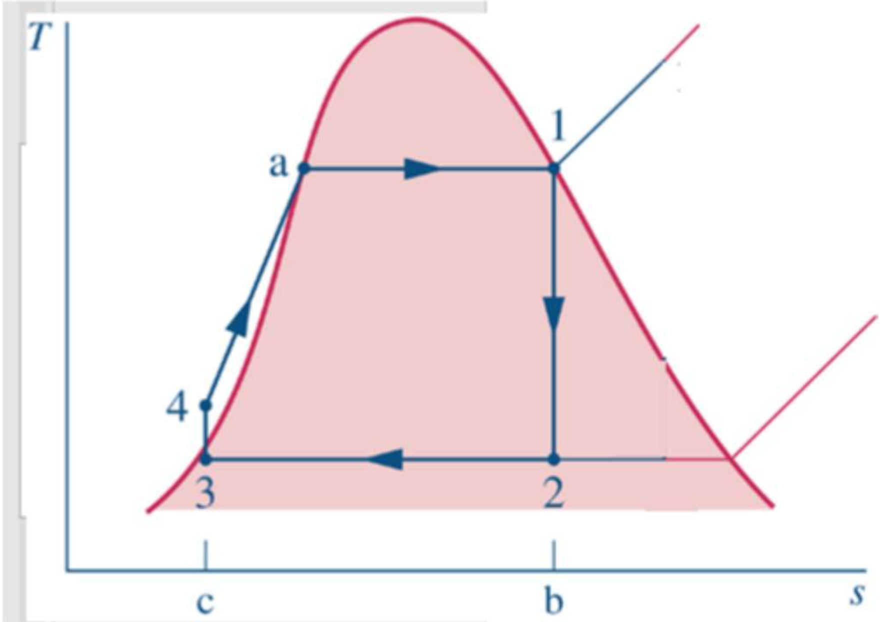
$$\begin{cases} \dot{Q}_{out} = \dot{m}_w\left(h_6 - h_5\right) \\ \dot{Q}_{out} \approx \dot{m}_w c_p\left(T_6 - T_5\right) \end{cases}$$



Pump

$$\dot{W}_p = \dot{m}\left(h_4 - h_3\right)$$

Performance Parameters



Thermal Efficiency

$$\eta_{th} = \frac{\text{energy sought}}{\text{energy that costs}} = \frac{\dot{W}_t - \dot{W}_p}{\dot{Q}_{in}}$$

$$= \frac{\dot{m}\left(h_1 - h_2\right) - \dot{m}\left(h_4 - h_3\right)}{\dot{m}\left(h_1 - h_4\right)} = \frac{\left(h_1 - h_2\right) - \left(h_4 - h_3\right)}{\left(h_1 - h_4\right)}$$

Heat Rate

$$\text{HR} = \frac{\text{energy input to the cycle}}{\text{net work output}} = \frac{\dot{Q}_{in}}{\left(\dot{W}_t - \dot{W}_p\right)} = \frac{\left(h_1 - h_4\right)}{\left[\left(h_1 - h_2\right) - \left(h_4 - h_3\right)\right]}$$

Back Work Ratio

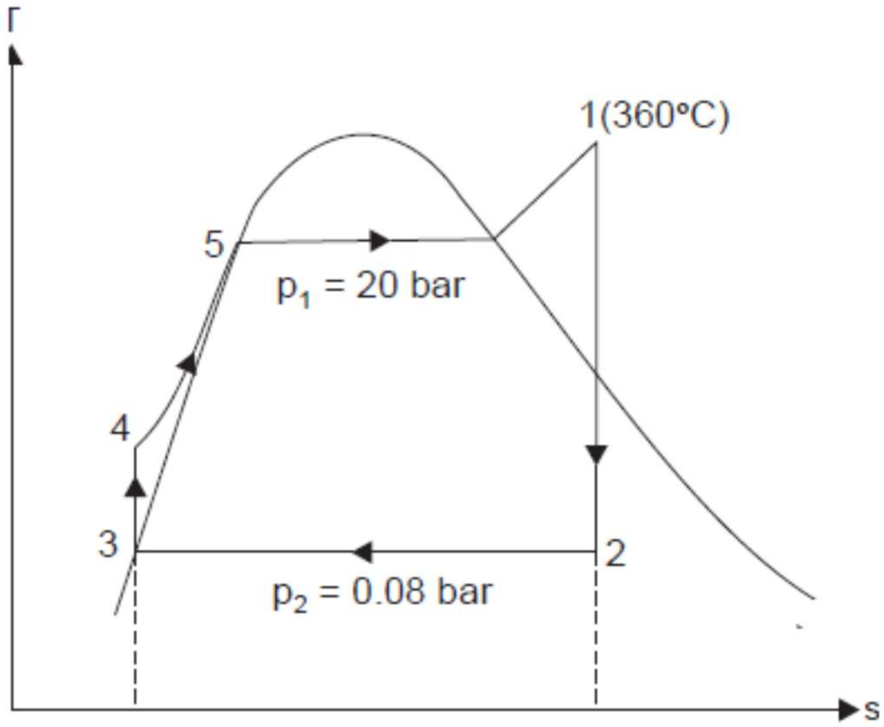
$$\text{bwr} = \frac{\text{pump work required}}{\text{turbine work delivered}} = \frac{\dot{W}_p}{\dot{W}_t} = \frac{\dot{m}\left(h_4 - h_3\right)}{\dot{m}\left(h_1 - h_2\right)} = \frac{\left(h_4 - h_3\right)}{\left(h_1 - h_2\right)}$$

In a steam turbine steam at 20 bar, 360°C is expanded to 0.08 bar. It then enters a condenser, where it is condensed to saturated liquid water. The pump feeds back the water into the boiler. Assume ideal processes, find per kg of steam the net work and the cycle efficiency.

Solution. Boiler pressure p_1 = 20 bar (360°C)

Condenser pressure, p_2 = 0.08 bar

From steam tables :



At 20 bar (p_1), 360°C : $h_1 = 3159.3$ kJ/kg

$s_1 = 6.9917$ kJ/kg-K

At 0.08 bar (p_2) : $h_3 = h_{f(p_2)} = 173.88$ kJ/kg,

$s_3 = s_{f(p_2)} = 0.5926$ kJ/kg-K

$h_{fg(p_2)} = 2403.1$ kJ/kg, $s_{g(p_2)} = 8.2287$ kJ/kg-K

$v_{f(p_2)} = 0.001008$ m³/kg $\therefore$ $s_{fg(p_2)} = 7.6361$ kJ/kg-K

$$s_1 = s_2$$

$$6.9917 = s_{f(p_2)} + x_2\, s_{fg(p_2)} = 0.5926 + x_2 \times 7.6361$$

$$x_2 = \frac{0.69917 - 0.5926}{7.6361} = 0.838$$

$$\therefore \qquad h_2 = h_{f(p_2)} + x_2\, h_{fg(p_2)}$$

$$= 173.88 + 0.838 \times 2403.1 = 2187.68 \text{ kJ/kg.}$$

Net work, W_{net} :

$$W_{net} = W_{turbine} - W_{pump}$$

$$W_{pump} = h_{f_4} - h_{f(p_2)} \ (= h_{f_3}) = v_{f(p_2)} \ (p_1 - p_2)$$

$$= 0.00108 \ (\text{m}^3/\text{kg}) \times (20 - 0.08) \times 100 \ \text{kN/m}^2$$

$$= 2.008 \ \text{kJ/kg}$$

[and $h_{f_4} = 2.008 + h_{f(p_2)} = 2.008 + 173.88 = 175.89$ kJ/kg]

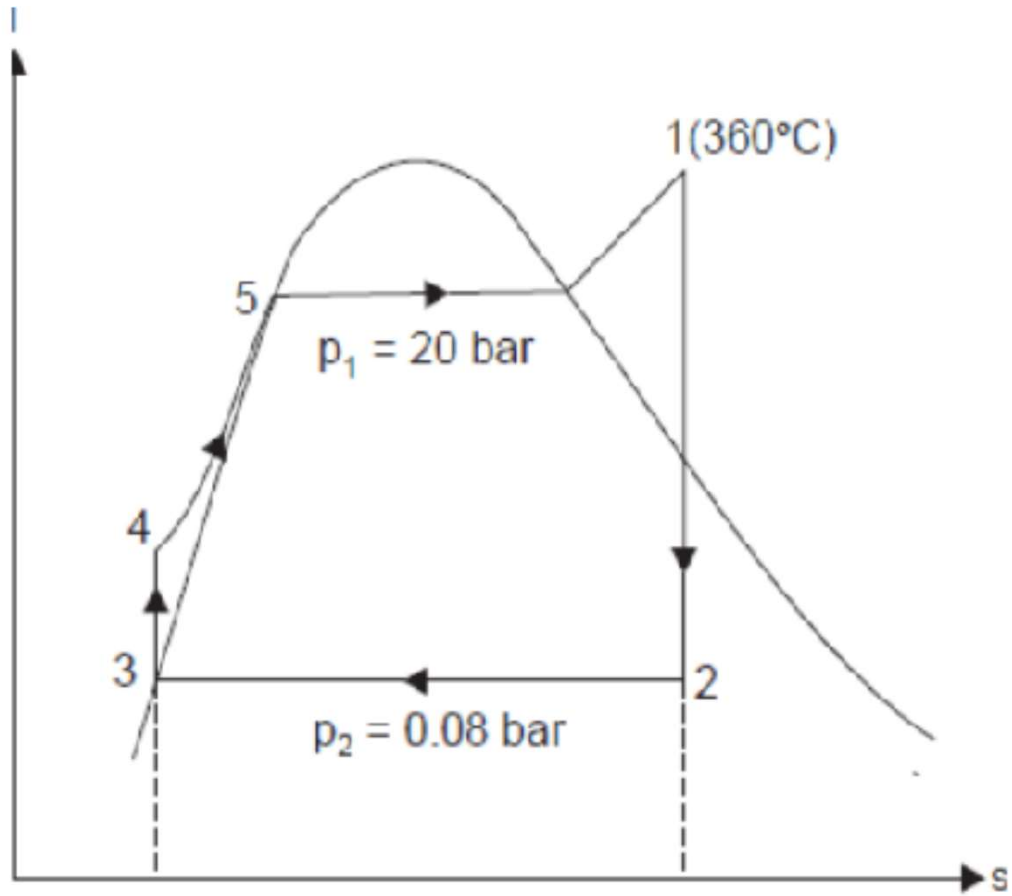
$$W_{turbine} = h_1 - h_2 = 3159.3 - 2187.68 = 971.62 \ \text{kJ/kg}$$

$W_{net} = 971.62 - 2.008 =$ **969.61 kJ/kg. (Ans.)**

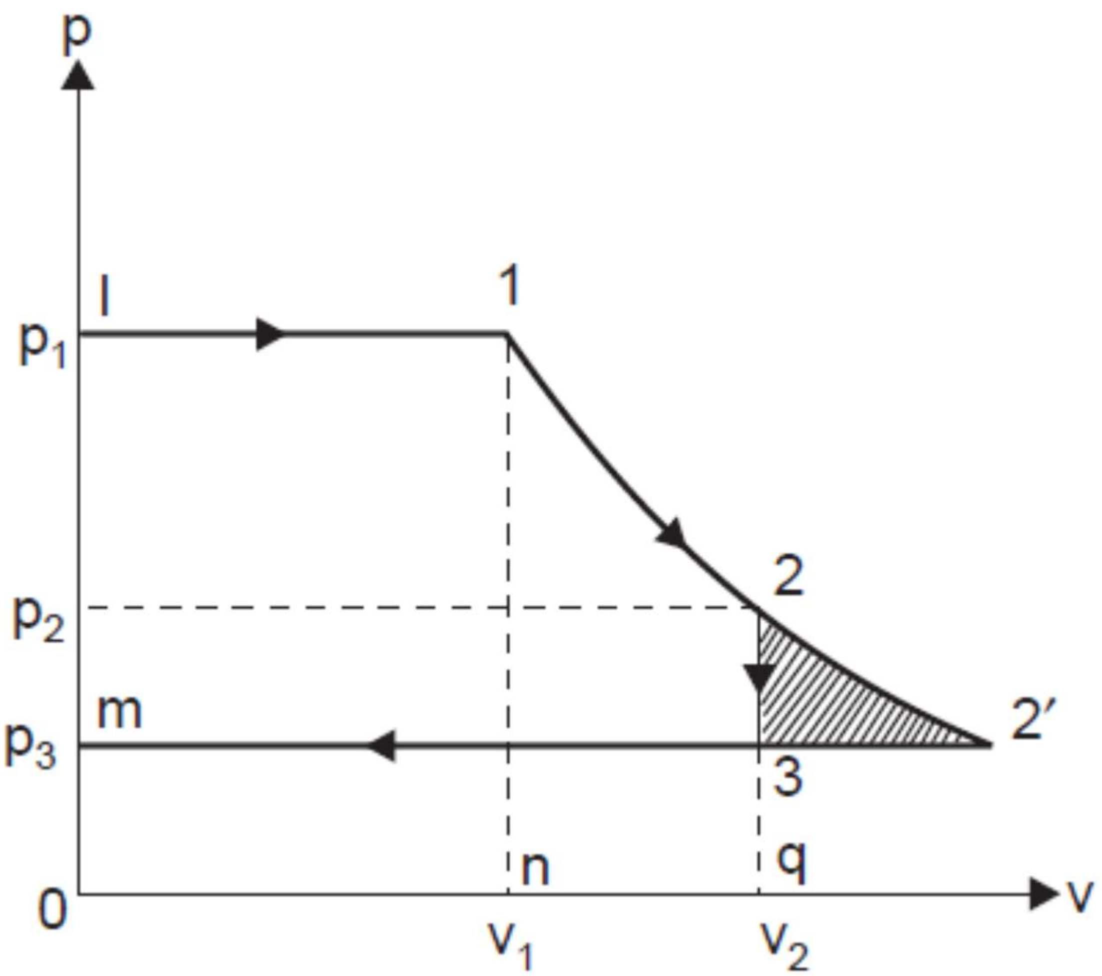
Cycle efficiency, η_{cycle} :

$$Q_1 = h_1 - h_{f_4} = 3159.3 - 175.89 = 2983.41 \ \text{kJ/kg}$$

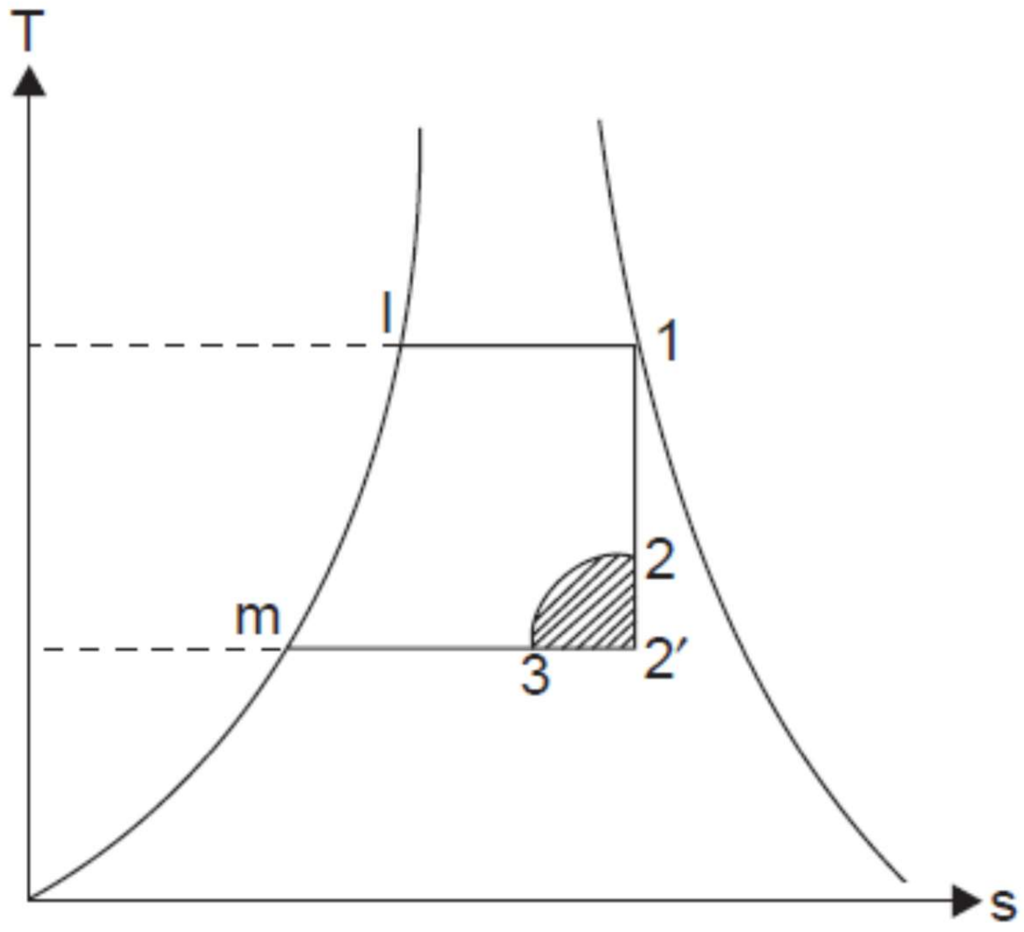
$\eta_{cycle} = \dfrac{W_{net}}{Q_1} = \dfrac{969.61}{2983.41} =$ **0.325 or 32.5%. (Ans.)**



MODIFIED RANKINE CYCLE



p-V diagram of Modified Rankine Cycle.

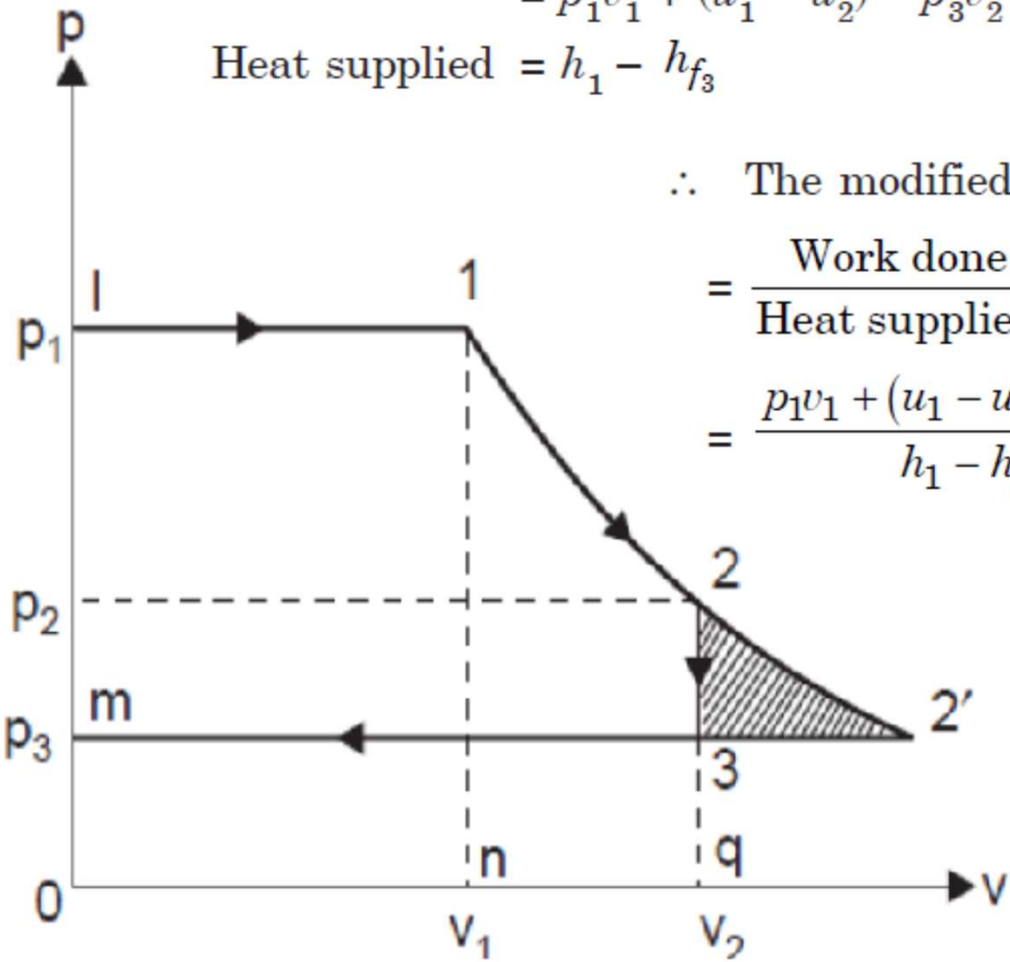


T-s diagram of Modified Rankine cycle.

Work done during the cycle/kg of steam

$$= \text{area } l\text{-}1\text{-}2\text{-}3\text{-}m$$
$$= \text{area } `o\text{-}l\text{-}1\text{-}n\text{'} + \text{area } `1\text{-}2\text{-}q\text{-}n\text{'} - \text{area } `o\text{-}m\text{-}3\text{-}q\text{'}$$
$$= p_1v_1 + (u_1 - u_2) - p_3v_2$$

Heat supplied $= h_1 - h_{f_3}$



$\therefore$ The modified Rankine efficiency

$$= \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{p_1v_1 + (u_1 - u_2) - p_3v_2}{h_1 - h_{f_3}}$$

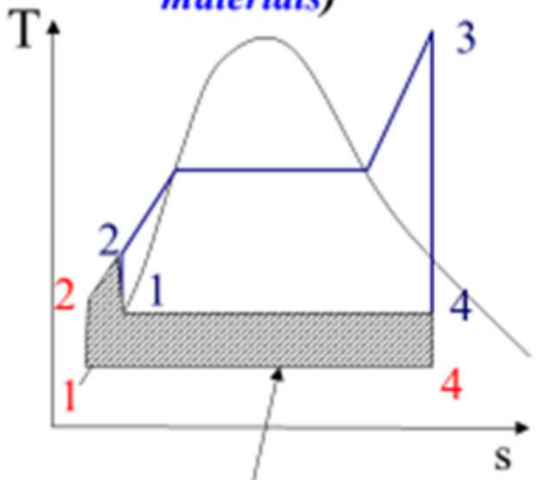
Thermal Efficiency – How to enhance it?

Thermal efficiency can be improved by manipulating the temperatures and/or pressures in various components

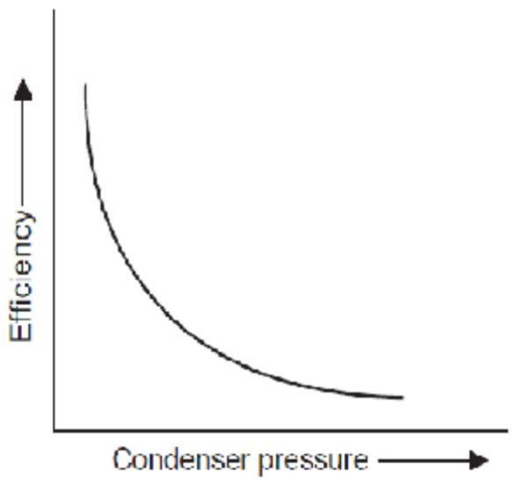
(a) Lowering the condensing pressure (***lowers T_L, but decreases quality, x_4***)

(b) Superheating the steam to a ***higher temperature (increases T_H but requires higher temp materials***)

(c) Increasing the boiler pressure (***increases T_H but requires higher temp/press materials)***



(a) lower pressure(temp)



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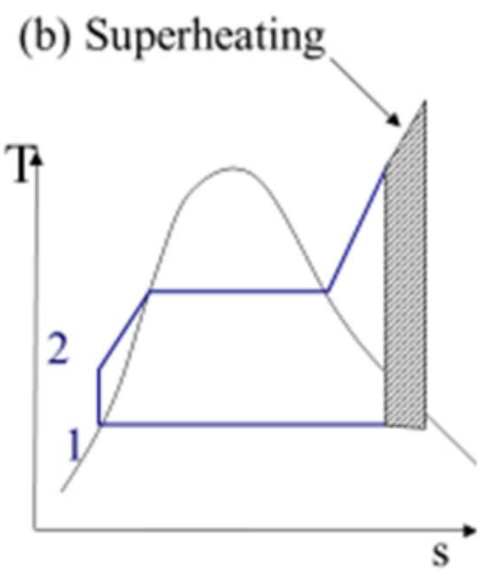

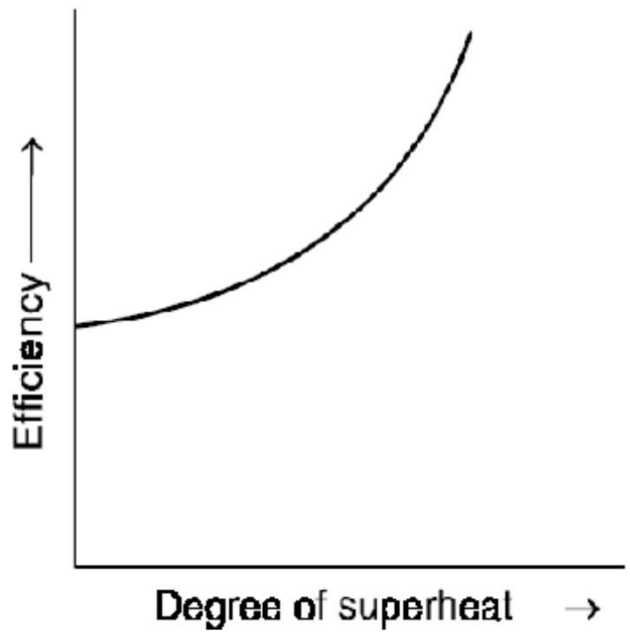

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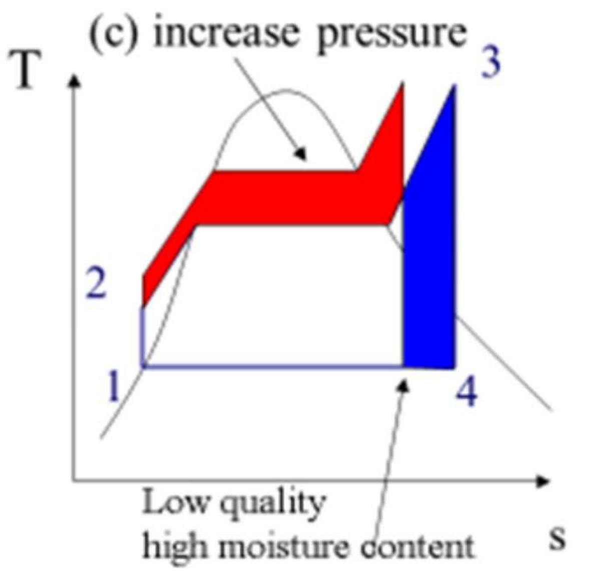
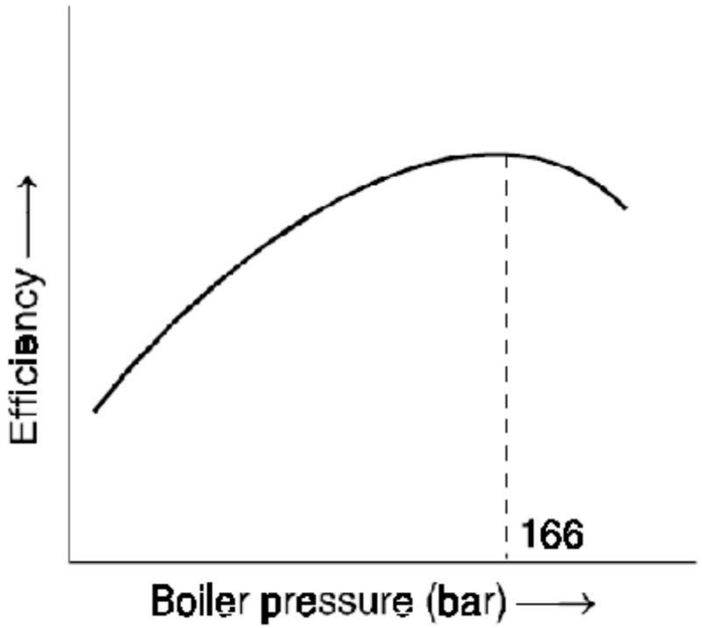
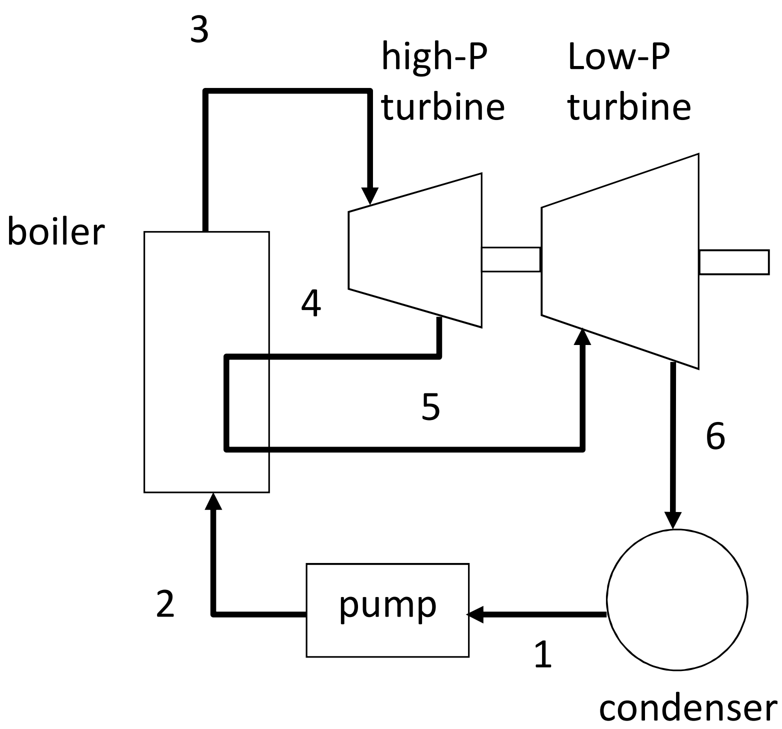


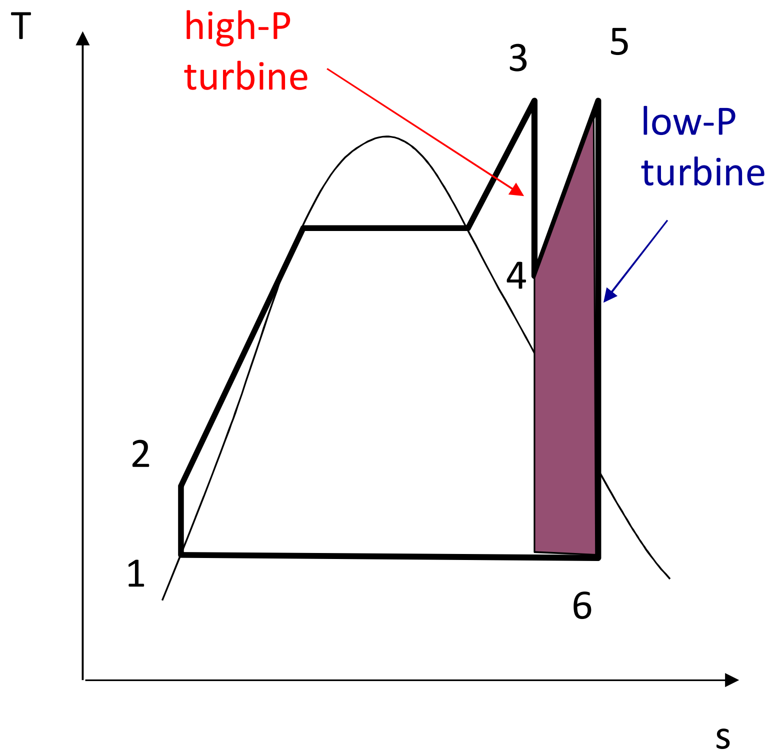
Red area = increase in W net
Blue area = decrease in W net

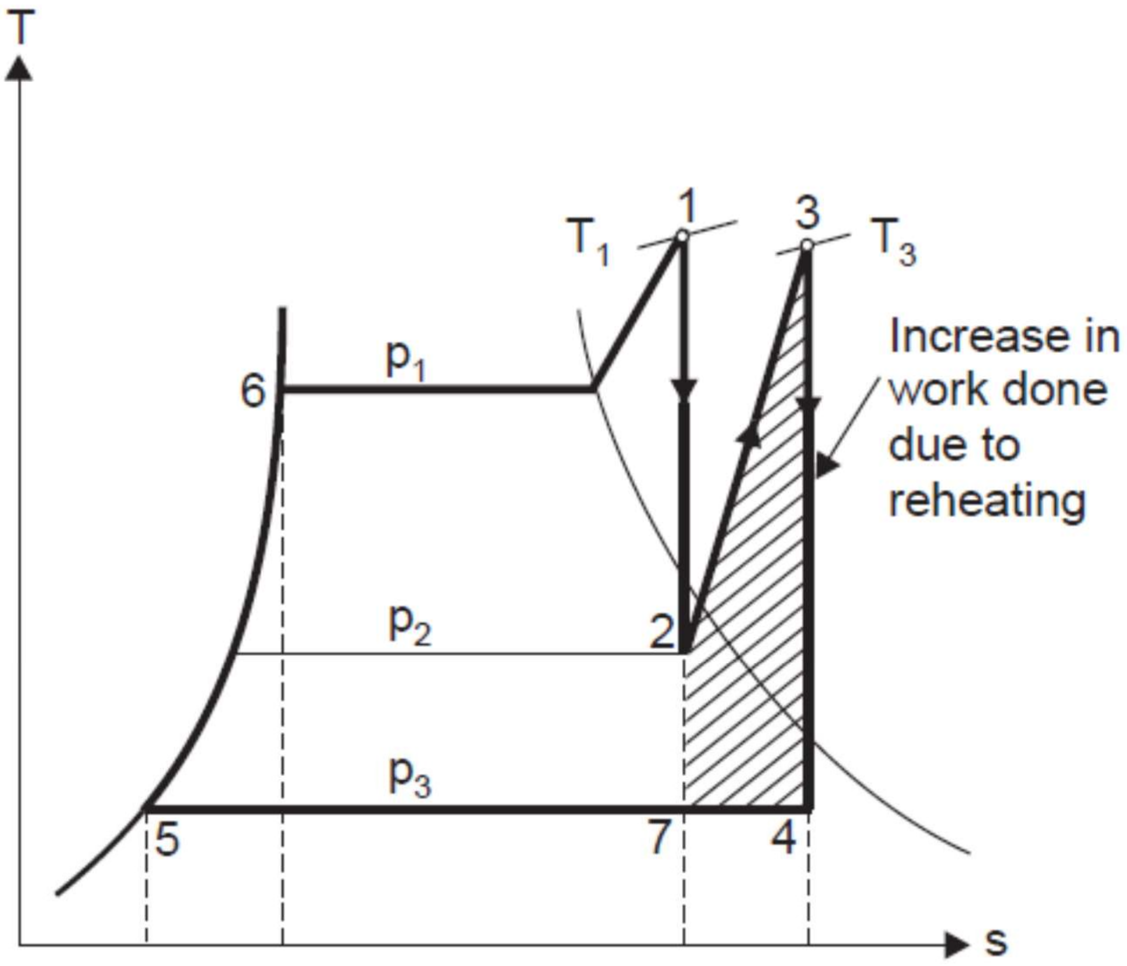


Reheating

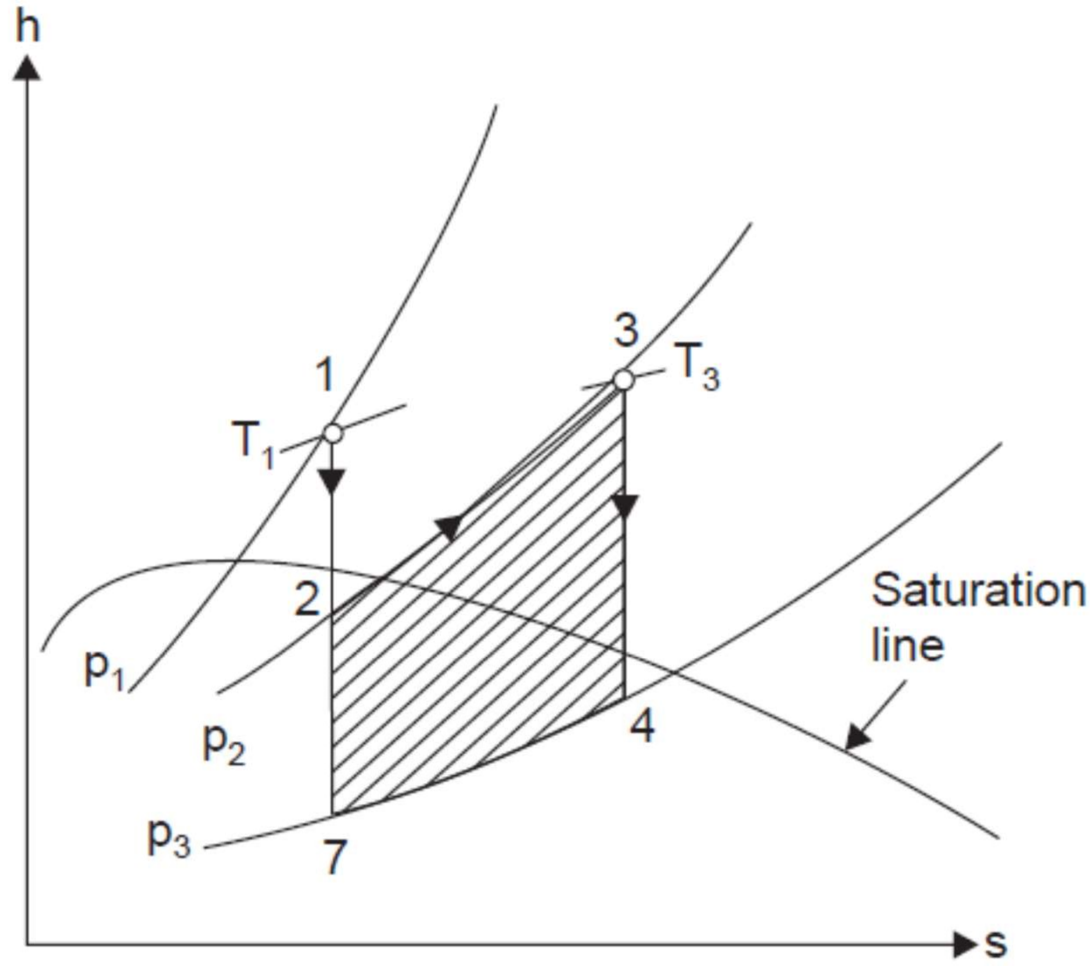
- The optimal way of increasing the boiler pressure *without increasing the moisture content* in the exiting vapor is to ***reheat*** the vapor after it exits from a first-stage turbine and ***redirect this reheated vapor into a second turbine***.







T
s
1
3
T_1
T_3
p_1
p_2
p_3
6
2
5
7
4
Increase in work done due to reheating



h
s
1
3
T_1
T_3
2
4
7
p_1
p_2
p_3
Saturation line

Reheat Rankine Cycle

- Reheating allows one to increase the boiler pressure without increasing the moisture content in the vapor exiting from the turbine.
- By reheating, the average temperature of the vapor entering the turbine is increased, thus, it increases the thermal efficiency of the cycle.
- Multistage reheating is possible but not practical. One major reason is because the vapor exiting will be superheated vapor at higher temperature, thus, decrease the thermal efficiency. *Why*?
- Energy analysis: Heat transfer and work output both change

$$q_{in} = q_{primary} + q_{reheat} = (h_3-h_2) + (h_5-h_4)$$

$$W_{out} = W_{turbine1} + W_{turbine2} = (h_3-h_4) + (h_5-h_6)$$

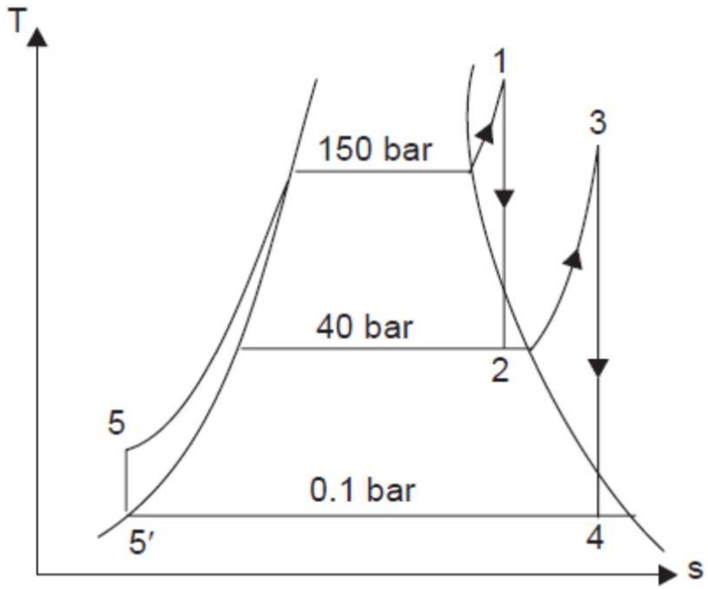
In a 15 MW steam power plant operating on ideal reheat cycle, steam enters the H.P. turbine at 150 bar and 600°C. The condenser is maintained at a pressure of 0.1 bar. If the moisture content at the exit of the L.P. turbine is 10.4%, determine :

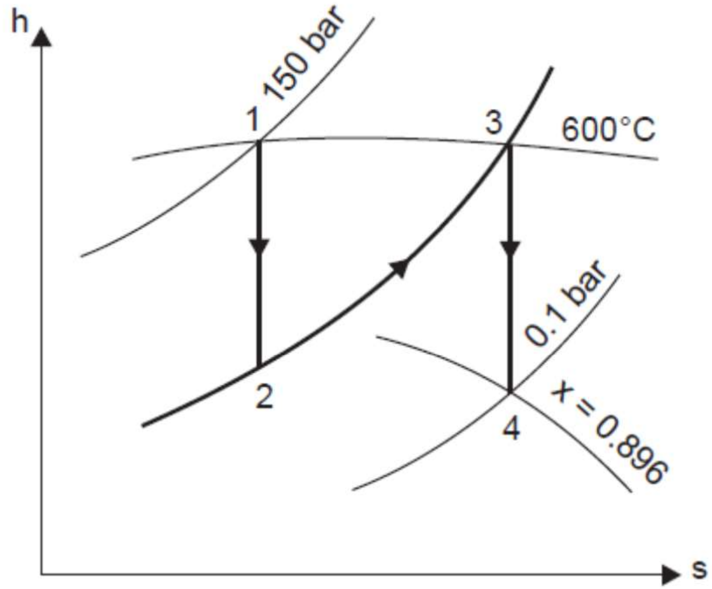
Reheat pressure ; (ii) Thermal efficiency ; (iii) Specific steam consumption ; and (iv) Rate of pump work in kW. Assume steam to be reheated to the initial temperature.

The cycle is shown on T-s and h-s diagrams in Figs.

The following values are read from the Mollier diagram :

$$h_1 = 3580 \text{ kJ/kg}, \ h_2 = 3140 \text{ kJ/kg}, \ h_3 = 3675 \text{ kJ/kg, and } h_4 = 2335 \text{ kJ/kg}$$

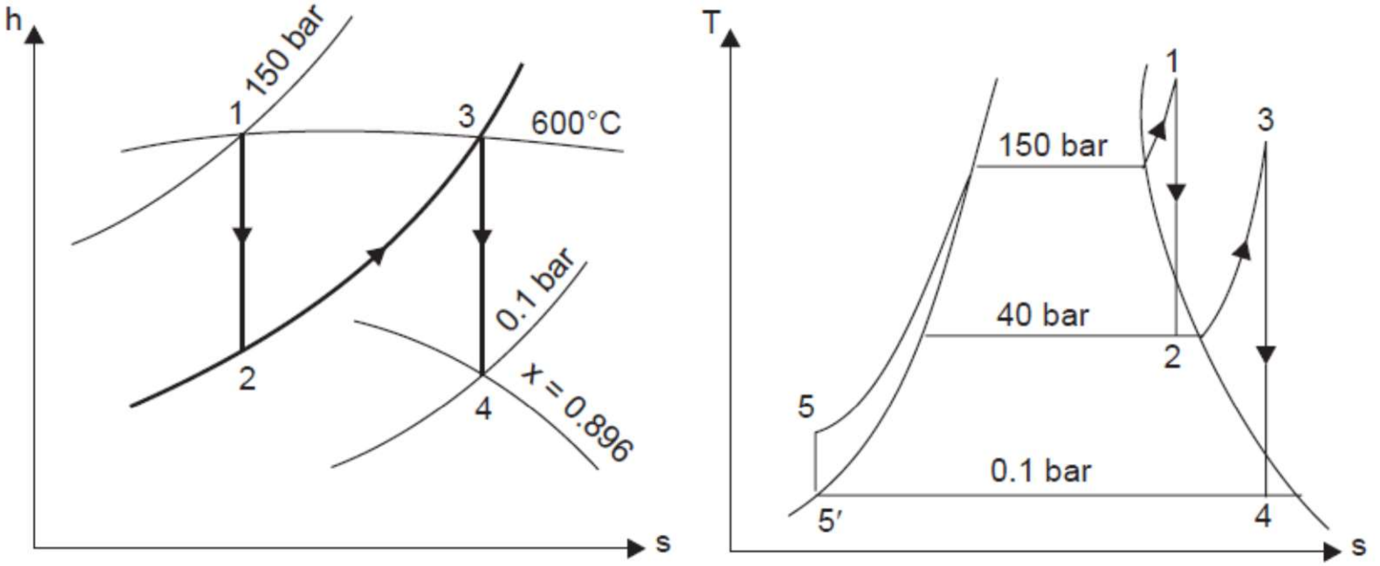




Moisture contents in exit from L.P. turbine = 10.4%

$$x_4 = 1 - 0.104 = 0.896$$

(*i*) **Reheat pressure :** From the Mollier diagram, the **reheat pressure is 40 bar.**



Turbine work $= (h_1 - h_2) + (h_3 - h_4) = (3580 - 3140) + (3675 - 2335) = 1780$ kJ/kg.

$Q_{input} = (h_1 - h_5) + (h_3 - h_2)$ $\boxed{\text{pump work may be neglected in computing of } \eta_{th}}$

$= (3580 - 191.8) + (3675 - 3140) = 3923.2$ kJ/kg

Thermal efficiency, $\% \eta_{th} = \dfrac{1780}{3923.2} \times 100 = \mathbf{45.37\%}$. **(Ans.)**

Steam consumption $= \dfrac{15 \times 10^3}{1780} = 8.427$ kg/s

Specific steam consumption $= \dfrac{8.427 \times 3600}{15 \times 10^3} = \mathbf{2.0225}$ **kg/kWh. (Ans.)**

(*iv*) **Rate of pump work :**

Rate of pump work $= 8.427 \times 0.15 =$ **1.26 kW. (Ans.)**

Advantages of 'Reheating' :

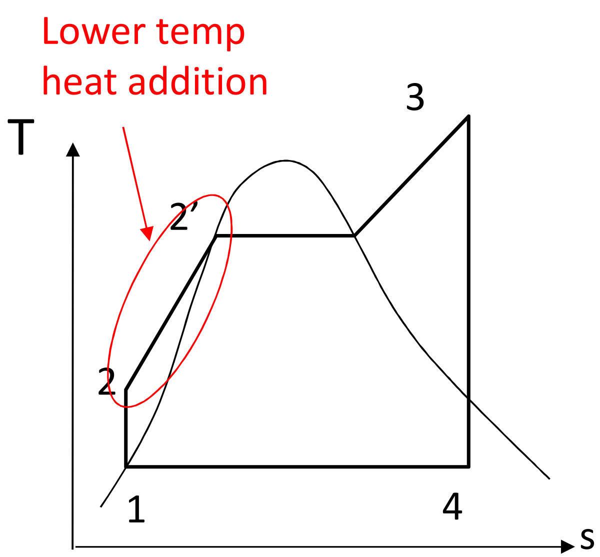
1. There is an increased output of the turbine.
2. Erosion and corrosion problems in the steam turbine are eliminated/avoided.
3. There is an improvement in the thermal efficiency of the turbines
4. Final dryness fraction of steam is improved.
5. There is an increase in the nozzle and blade efficiencies.

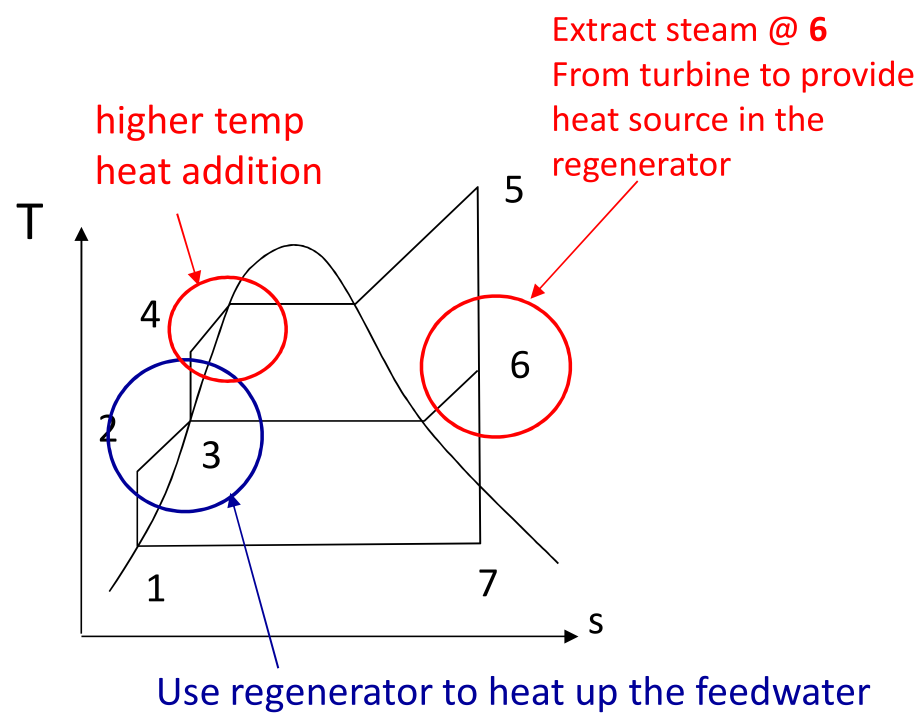
Disadvantages :

1. Reheating requires more maintenance.
2. The increase in thermal efficiency is not appreciable in comparison to the expenditure incurred in reheating.

Regeneration

- From 2-2', the average temperature is very low, therefore, the heat addition process is at a lower temperature and therefore, the thermal efficiency is lower. Why?
- Use a ***regenerator*** to heat the liquid (feedwater) leaving the pump before sending it to the boiler. This increases the average temperature during heat addition in the boiler, hence it increases efficiency.

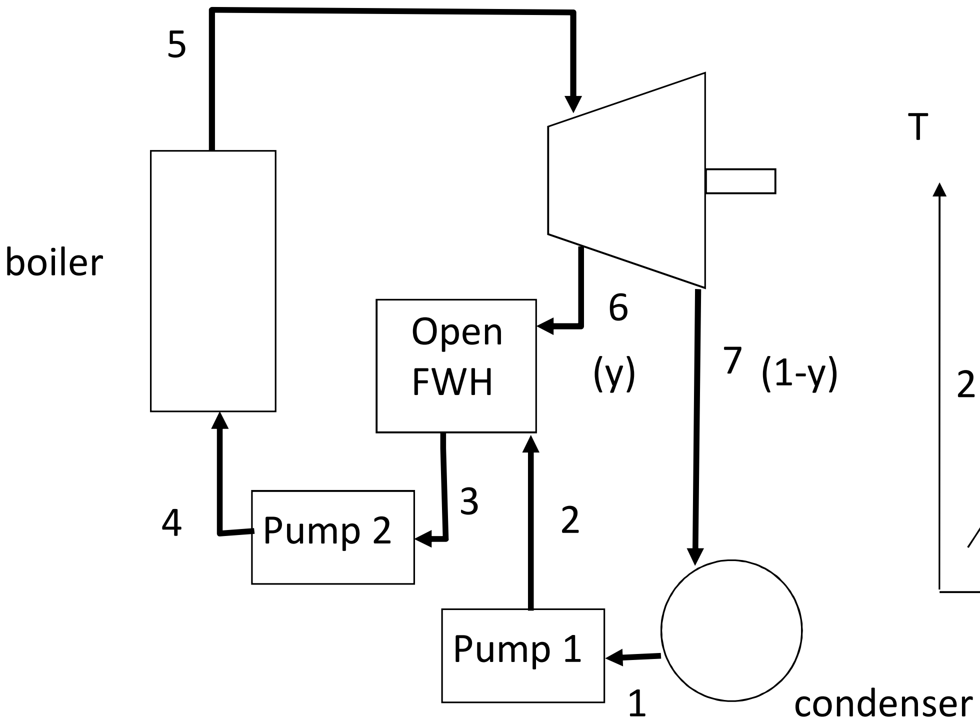


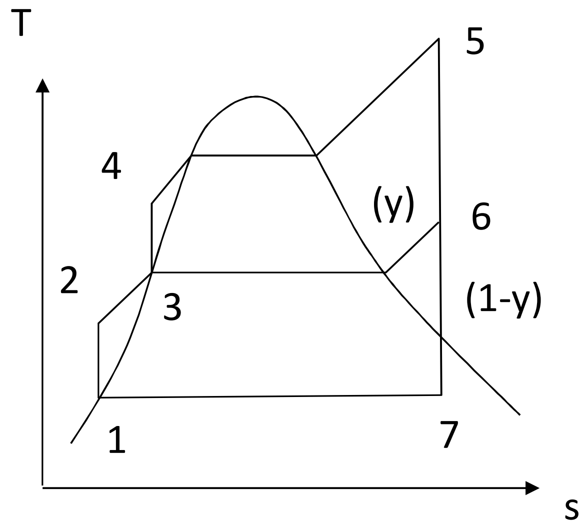


Regenerative Cycle

- Improve efficiency by increasing feedwater temperature before it enters the boiler.
- Two Options:
  - **Open feedwater** : Mix steam with the feedwater in a mixing chamber.
  - **Closed feedwater**: No mixing.

Open FWH





Advantages of Regenerative cycle over Simple Rankine cycle :

1. The heating process in the boiler tends to become reversible.
2. The thermal stresses set up in the boiler are minimised. This is due to the fact that temperature ranges in the boiler are reduced.
3. The thermal efficiency is improved because the average temperature of heat addition to the cycle is increased.
4. Heat rate is reduced.
5. The blade height is less due to the reduced amount of steam passed through the low pressure stages.
6. Due to many extractions there is an improvement in the turbine drainage and it reduces erosion due to moisture.
7. A small size condenser is required.

Disadvantages :

1. The plant becomes more complicated.
2. Because of addition of heaters greater maintenance is required.
3. For given power a large capacity boiler is required.
4. The heaters are costly and the gain in thermal efficiency is not much in comparison to the heavier costs.

Regenerative Cycle - Analysis

- Assume ***y*** percent of steam is extracted from the turbine and is directed into open feedwater heater.

- Energy analysis:

  $q_{in} = h_5 - h_4$, $\quad q_{out} = (1-y)(h_7 - h_1)$,

  $W_{turbine,\ out} = (h_5 - h_6) + (1-y)(h_6 - h_7)$

  $$\begin{aligned} W_{pump,\ in} &= (1-y)W_{pump1} + W_{pump2} \\ &= (1-y)(h_2 - h_1) + (h_4 - h_3) \\ &= (1-y)v_1(P_2 - P_1) + v_3(P_4 - P_3) \end{aligned}$$

- In general, more feedwater heaters result in higher cycle efficiencies.

$$\text{Efficiency of the cycle} = \frac{\text{Net Power output}}{\text{Rate of Heat addition}}$$

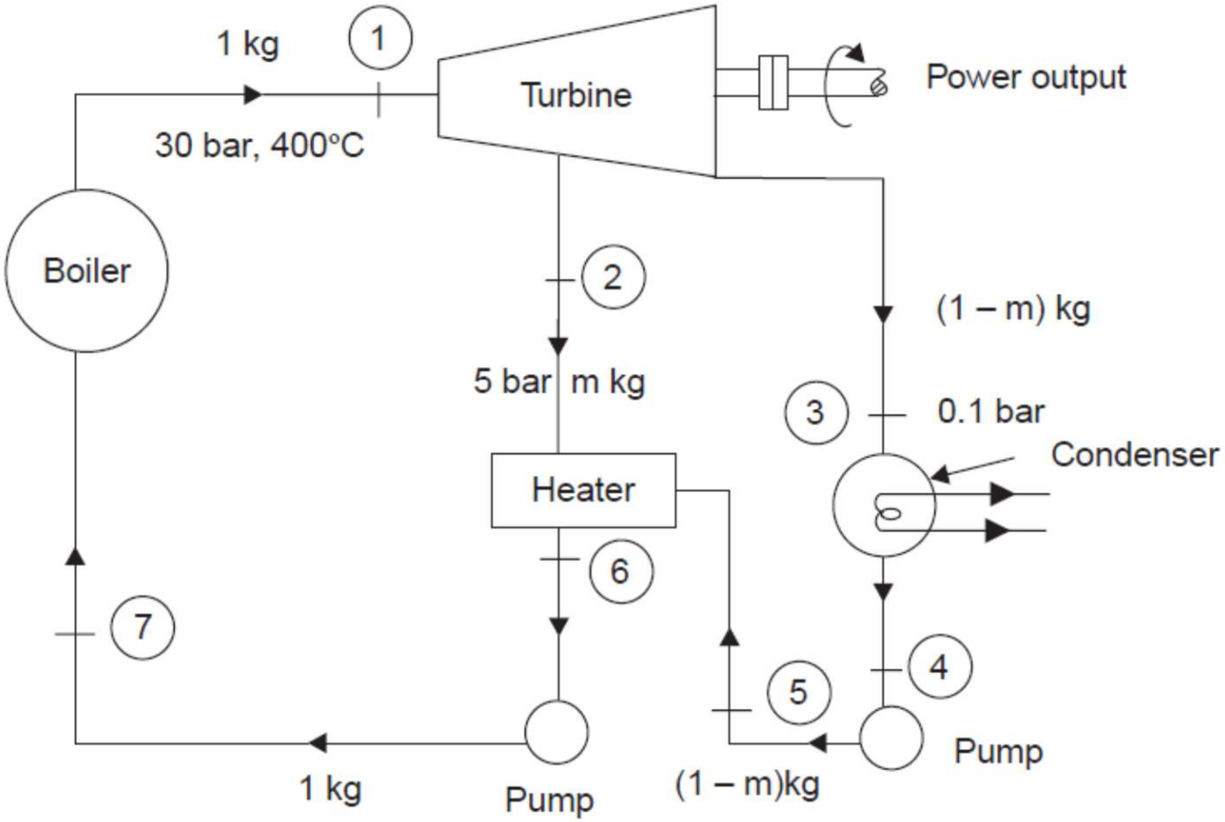
In a single-heater regenerative cycle the steam enters the turbine at 30 bar, 400°C and the exhaust pressure is 0.10 bar. The feed water heater is a direct contact type which operates at 5 bar. Find :

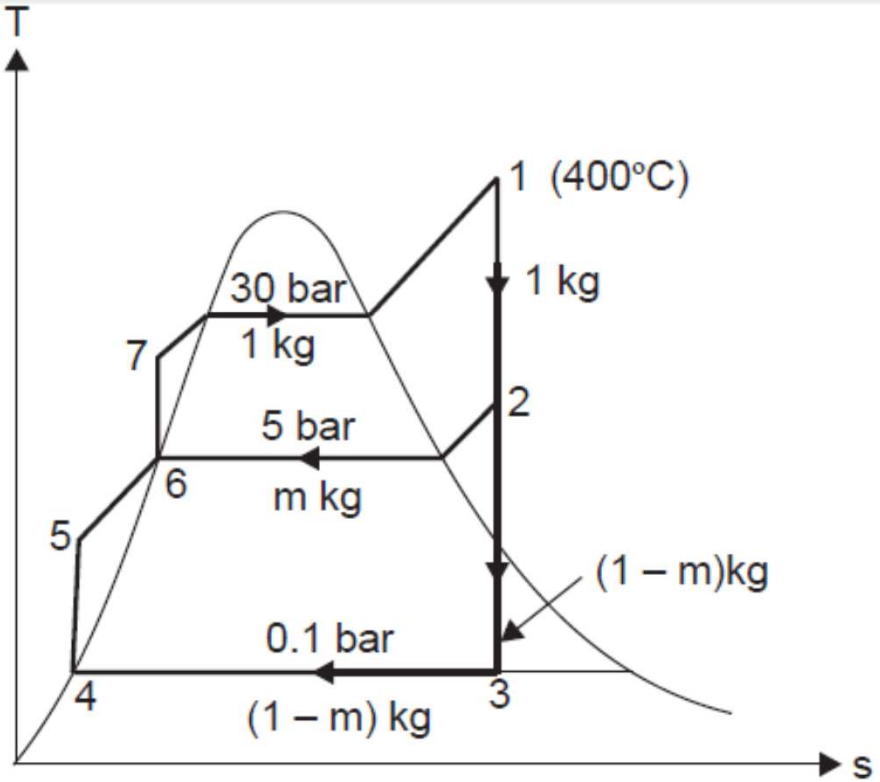
(i) The efficiency and the steam rate of the cycle.

(ii) The increase in mean temperature of heat addition, efficiency and steam rate as compared to the Rankine cycle (without regeneration).

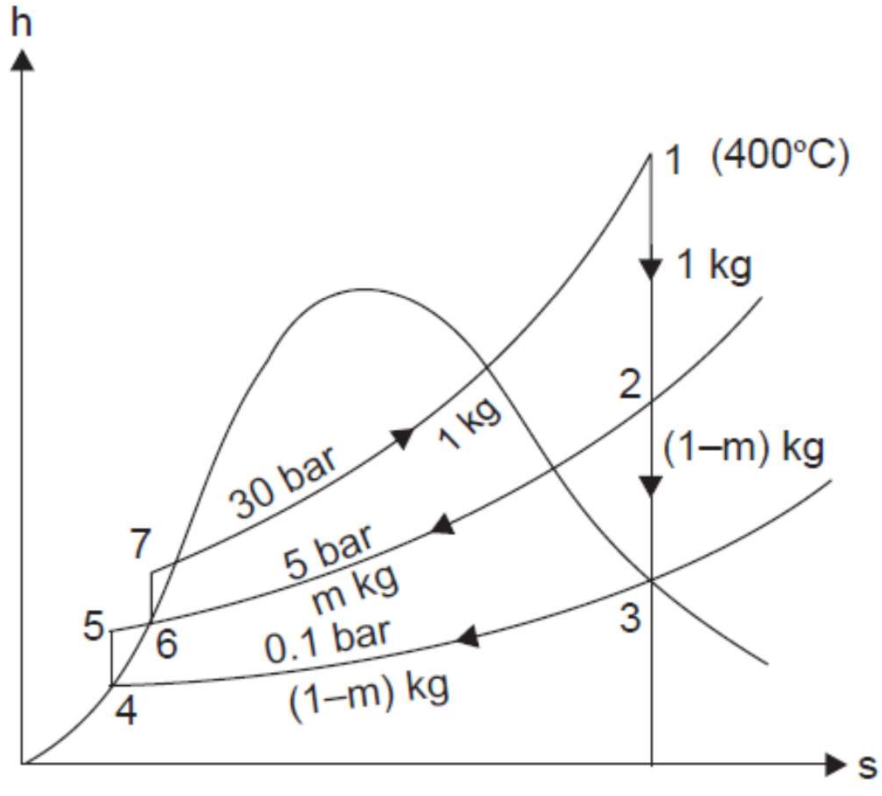
Pump work may be neglected.

Solution. Fig. 12.17 shows the flow, *T-s* and *h-s* diagrams.





(b)



(c)

From steam tables :

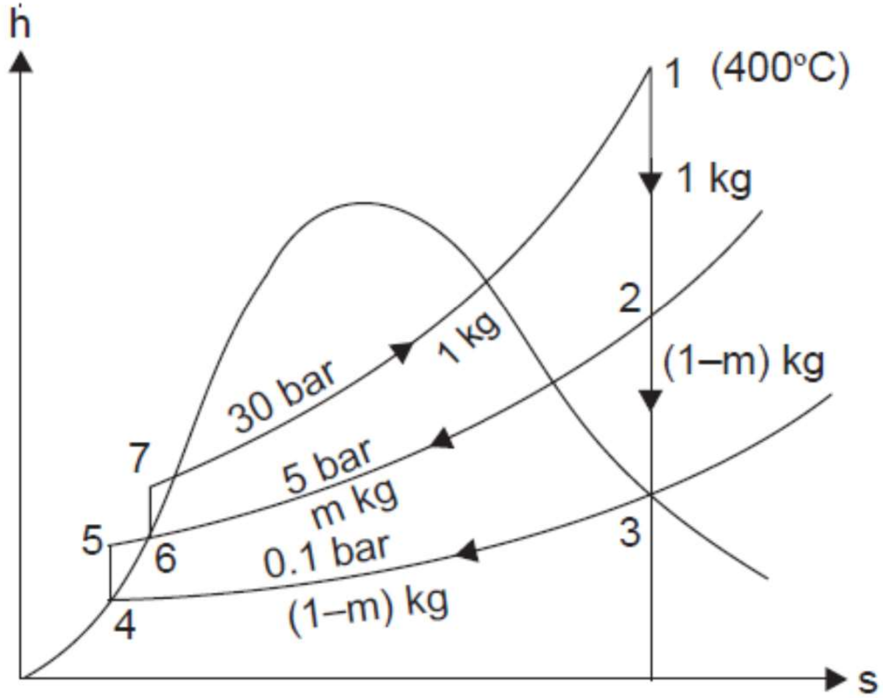
At 30 bar, 400°C : h_1 = 3230.9 kJ/kg, s_1 = 6.921 kJ/kg K = $s_2 = s_3$,

At 5 bar : s_f = 1.8604, s_g = 6.8192 kJ/kg K, h_f = 640.1 kJ/kg

Since $s_2 > s_g$, the state 2 must lie in the superheated region. From the table for superheated steam t_2 = 172°C, h_2 = 2796 kJ/kg.

At 0.1 bar : $s_f = 0.649$, $s_{f_g} = 7.501$, $h_f = 191.8$, $h_{f_g} = 2392.8$

At 0.1 bar : $s_f = 0.649$, $s_{f_g} = 7.501$, $h_f = 191.8$, $h_{f_g} = 2392.8$



$$s_2 = s_3$$

$$6.921 = s_{f_3} + x_3\ s_{fg_3} = 0.649 + x_3 \times 7.501$$

$$x_3 = \frac{6.921 - 0.649}{7.501} = 0.836$$

$$h_3 = h_{f_3} + x_3\ h_{fg_3} = 191.8 + 0.836 \times 2392.8 = 2192.2 \text{ kJ/kg}$$

$\boxed{\text{Since pump work is neglected}}$

$$h_{f_4} = 191.8 \text{ kJ/kg} = h_{f_5}$$

$$h_{f_6} = 640.1 \text{ kJ/kg (at 5 bar)} = h_{f_7}$$

Energy balance for heater gives $m\,(h_2 - h_{f_6}) = (1 - m)\,(h_{f_6} - h_{f_5})$

$$m\,(2796 - 640.1) = (1 - m)\,(640.1 - 191.8) = 448.3\,(1 - m)$$

$$2155.9\ m = 448.3 - 448.3\ m$$

$$m = 0.172 \text{ kg}$$

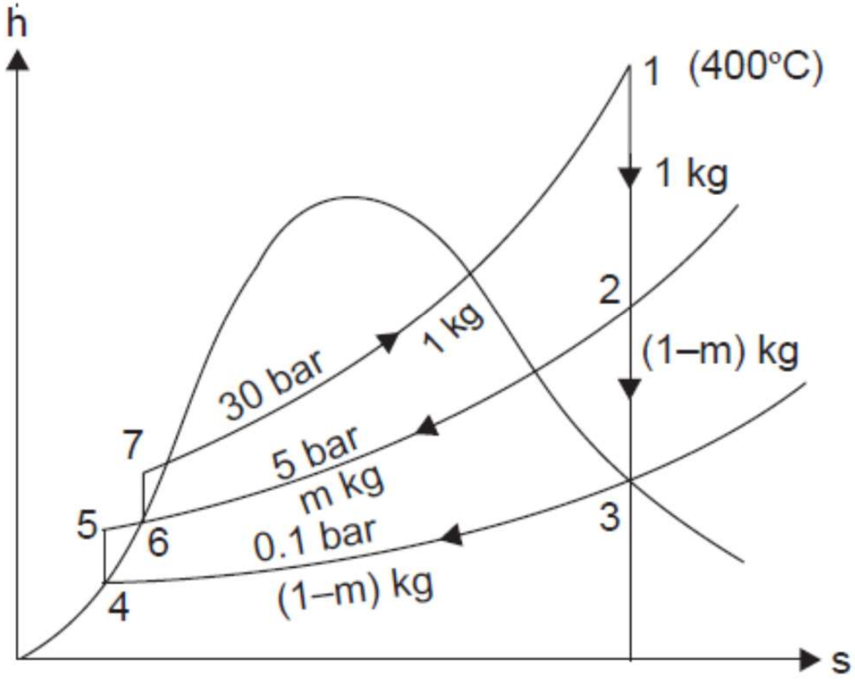
$\therefore$ Turbine work, $W_T = (h_1 - h_2) + (1 - m)\,(h_2 - h_3)$

$$= (3230.9 - 2796) + (1 - 0.172)\,(2796 - 2192.2)$$

$$= 434.9 + 499.9 = 934.8 \text{ kJ/kg}$$

Heat supplied, $Q_1 = h_1 - h_{f_6} = 3230.9 - 640.1 = 2590.8$ kJ/kg.

Efficiency of cycle, $\eta_{cycle} = \frac{W_T}{Q_1} = \frac{934.8}{2590.8} = \mathbf{36.08\%}$**.**



Steam rate $= \frac{3600}{934.8} = \mathbf{3.85\ kg/kWh.}$ **(Ans.)**

(*ii*) $T_{m_1} = \frac{h_1 - h_{f_7}}{s_1 - s_7} = \frac{2590.8}{6.921 - 1.8604} = 511.9\text{ K} = 238.9°\text{C}.$

T_{m_1} (without regeneration) $= \frac{h_1 - h_{f_4}}{s_1 - s_4} = \frac{3230.9 - 191.8}{6.921 - 0.649}$

$= \frac{3039.1}{6.272} = 484.5\text{ K} = 211.5°\text{C}.$

Increase in $\mathbf{T_{m_1}}$ **due to regeneration** $= 238.9 - 211.5 = \mathbf{27.4°C.}$ **(Ans.)**

W_T (without regeneration) $= h_1 - h_3 = 3230.9 - 2192.2 = 1038.7$ kJ/kg

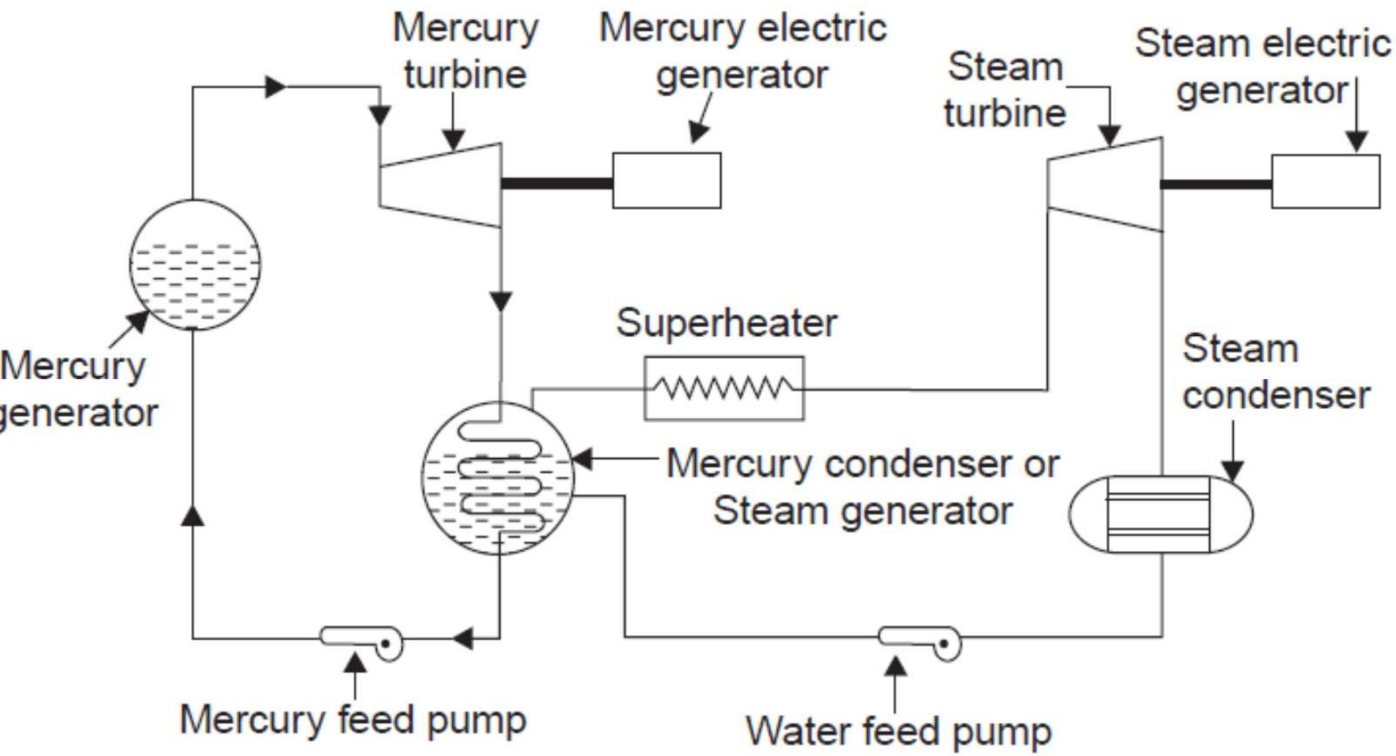
Steam rate without regeneration $= \frac{3600}{1038.7} = 3.46$ kg/kWh

$\therefore$ **Increase in steam rate due to regeneration** $= 3.85 - 3.46 = \mathbf{0.39\ kg/kWh.}$ **(Ans.)**

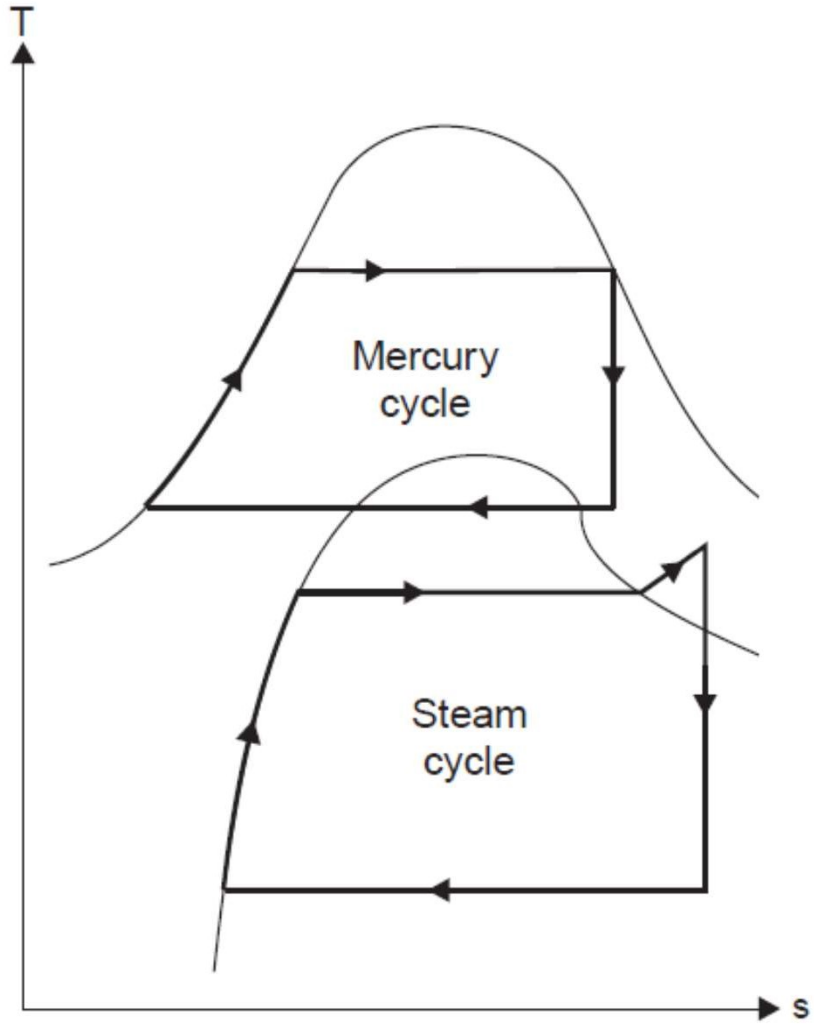
η_{cycle} (without regeneration) $= \frac{h_1 - h_3}{h_1 - h_{f_4}} = \frac{1038.7}{3230.9 - 191.8} = \mathbf{0.3418\ or\ 34.18\%.}$ **(Ans.)**

Increase in cycle efficiency due to regeneration $= 36.08 - 34.18 = \mathbf{1.9\%.}$ **(Ans.)**

BINARY VAPOUR CYCLE



Line diagram of binary vapour cycle.



Binary vapour cycle on T-s diagram.