(b) states 2 and $02$ are the actual and stagnation states of the fluid leaving the diffuser.

(4) The velocity coefficient $C_v$ is defined:

\[ C_v = \frac{\text{Actual velocity at nozzle exit}}{\text{Velocity at nozzle exit with isentropic flow and same exit pressure}} \]

### REVIEW PROBLEMS

**PROBLEM 1**

Determine the final equilibrium state in English units when 2 lbm of saturated liquid mercury at 1 psia is mixed with 4 lbm of mercury vapor at 1 psia and 1,400°F. During the process the pressure in the cylinder is kept constant and no energy is lost between the cylinder and mercury.

![Figure 34. (a) The control mass](image)

![Figure 34. (b) The process representation](image)

**SOLUTION**

Since the amount of liquid might change during the process, the liquid or only the vapor cannot be taken as the control mass. Instead, take the entire 6 lbm of mercury. By assumption, no energy transfer as heat occurs, but the volume is expected to change, resulting in an energy transfer as work. The only energy stored within the control mass is the internal energy of the mercury; the energy balance, made over the time for the process to take place, is therefore (Figures 34 and 35)

\[ W = \Delta U \]

energy + input = increase in energy storage

where \( \Delta U = U_2 - U_1 \)
The work calculation is made easy by the fact that the pressure is constant. When the piston moves an amount $dx$, the energy transfer as work from the environment to the control mass is

$$dW = PADx = -PdV.$$ Integrating,

$$W = \int_{1}^{2} -PdV = P(V_1 - V_2).$$

Combining with the energy balance obtain

$$U_2 + PV_2 = U_1 + PV_1 \tag{1}$$

<table>
<thead>
<tr>
<th>TABLE 3</th>
<th>PROPERTIES OF SATURATED MERCURY</th>
</tr>
</thead>
<tbody>
<tr>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>0.010</td>
<td>233.57</td>
</tr>
<tr>
<td>0.020</td>
<td>259.88</td>
</tr>
<tr>
<td>0.030</td>
<td>276.22</td>
</tr>
<tr>
<td>0.050</td>
<td>297.97</td>
</tr>
<tr>
<td>0.100</td>
<td>329.73</td>
</tr>
<tr>
<td>0.200</td>
<td>364.25</td>
</tr>
<tr>
<td>0.300</td>
<td>385.92</td>
</tr>
<tr>
<td>0.400</td>
<td>401.98</td>
</tr>
<tr>
<td>0.500</td>
<td>415.00</td>
</tr>
<tr>
<td>0.600</td>
<td>425.82</td>
</tr>
<tr>
<td>0.800</td>
<td>443.50</td>
</tr>
<tr>
<td>1.00</td>
<td>457.72</td>
</tr>
<tr>
<td>2.00</td>
<td>504.93</td>
</tr>
<tr>
<td>3.00</td>
<td>535.25</td>
</tr>
<tr>
<td>5.00</td>
<td>575.70</td>
</tr>
</tbody>
</table>
Figure 35. Thermodynamic properties of mercury

To evaluate the initial terms assume that the liquid is in an equilibrium state and the vapor is in an equilibrium state, even though they are not in equilibrium with one another. The graphical and tabular equations
of state, Figure 35 and Table 3 for the thermodynamic properties of saturated mercury, may then be employed for each phase. Since the available equation-of-state information is in terms of the enthalpy property, express the right-hand side of equation (1) as

\[ U_1 + PV_1 = M_i u_{i_l} + M_{v_i} u_{v_i} + P(M_i v_{i_l} + M_{v_i} v_{v_i}) \]

\[ = M_i h_{i_l} + M_{v_i} h_{v_i} \]

Now, from the tables, the initial liquid enthalpy is (saturated liquid at 1 psia)

\[ h_{i_l} = 13.96 \text{ Btu/lbm} \]

\[ T_1 = 457.7^\circ F \]

The initial vapor enthalpy is found from Figure 35 as

\[ h_{v_i} = 164 \text{ Btu/lbm}. \]

Substituting the numbers,

\[ U_1 + PV_1 = 2 \times 13.96 + 4 \times 164 = 684 \text{ Btu}. \]

The final state is a state of equilibrium, for which

\[ U_2 + PV_2 = M(u + P v) = Mh_2. \]

The enthalpy in the final state is therefore

\[ h_2 = \frac{684 \text{ Btu}}{6 \text{ lbm}} = 114 \text{ Btu/lbm}. \]

The final pressure and enthalpy may be used to fix the final state. Upon inspection of Figure 35, the final state is a mixture of saturated liquid and vapor at 1 psia and the "moisture" \((1 - x)\) is about 21 percent (0.79 quality). Alternatively, the information in Table 1, could have been used.

\[ 114 = (1 - x_2) \times 13.96 + x_2 \times 140.7 \]

\[ x_2 = 0.79 \]

**PROBLEM 2**

The gauge pressure in an automobile tire when measured during winter at 32°F was 30 N/m². The same tire was used during the summer, and
and

\[ Q = 0.5(2,804.8 - 1,444.6) + 91.0 = 771.1 \text{ kJ} \]

**PROBLEM 4**

Steam at 3 MPa, 300°C leaves the boiler and enters the high-pressure turbine (in a reheating cycle) and is expanded to 300 kPa. The steam is then reheated to 300°C and expanded in the second stage turbine to 10 kPa. What is the efficiency of the cycle if it is assumed to be internally reversible?

![Figure 36. Schematic of heating cycle](image-url)

![Figure 37. T-s diagram for heating cycle](image-url)
**SOLUTION**

The efficiency $\eta$ can be obtained from the following equation:

$$\eta = \frac{\dot{W}_t + \dot{W}_s - \dot{W}_p}{Q_b - Q_r} \quad (1)$$

To calculate $\dot{W}_t$, assume that the turbine is adiabatic and neglect kinetic and potential energy changes. Applying the first law to the turbine,

$$\dot{W}_t = m(h_2 - h_3).$$

From the steam tables,

$$h_2 = 2,993.5 \text{ kJ/kg} \quad s_2 = 6.5390 \text{ kJ/kg} - K$$

To find $h_3$ for the internally reversible adiabatic process $2 \rightarrow 3$:

$$s_2 = s_3 = 6.5390 \text{ kJ/kg} - K$$

At state 3,

$$s_{f_3} = 1.6718 \text{ kJ/kg} - K \quad h_{f_3} = 561.47 \text{ kJ/kg}$$

$$s_{fg_3} = 5.3201 \text{ kJ/kg} - K \quad h_{fg_3} = 2,163.8 \text{ kJ/kg}$$

$$s_{g_3} = 6.9919 \text{ kJ/kg} - K \quad h_{g_3} = 2,725.3 \text{ kJ/kg}$$

$$s_2 = s_3 = s_{f_3} + x_3 s_{fg_3}$$

$$6.5390 = 1.6718 + x_3(5.3201)$$

$$x_3 = 0.915$$

$$h_3 = h_{f_3} + x_3 h_{fg_3}$$

$$= 561.47 + 0.915(2,163.8)$$

$$= 2,542 \text{ kJ/kg}$$

$$\dot{W}_t = h_2 - h_3$$

$$= 2,993.5 - 2542$$

$$= 452 \text{ kJ/kg}$$
Similarly, to find $\dot{W}_{t2}$

$$\dot{W}_{t2} = m(h_4 - h_5)$$

From the steam tables,

$$h_4 = 3,069.3 \text{ kJ/kg}$$
$$s_4 = 7.7022 \text{ kJ/kg} - \text{K}$$

To find $h_5$, note that

$$s_4 = s_5$$

At state 5,

$$s_{f_5} = 0.6493 \text{ kJ/kg} - \text{K}$$
$$h_{f_5} = 191.83 \text{ kJ/kg}$$
$$s_{f_{g5}} = 7.5009 \text{ kJ/kg} - \text{K}$$
$$h_{f_{g5}} = 2,392.8 \text{ kJ/kg}$$
$$s_{g_5} = 8.1502 \text{ kJ/kg} - \text{K}$$
$$h_{g_5} = 2,584.7 \text{ kJ/kg}$$
$$s_4 = s_5 = s_{f_5} + x_5 s_{f_{g5}}$$
$$x_5 = 0.949$$
$$h_5 = h_{f_5} + x_5 h_{f_{g5}}$$
$$h_5 = 191.83 + 0.949(2,392.8)$$
$$h_5 = 2,463 \text{ kJ/kg}$$

$$\therefore \frac{\dot{W}_{t2}}{m} = h_4 - h_5$$

$$= 3,069.3 - 2,463$$
$$= 606 \text{ kJ/kg}$$

To obtain $\dot{W}_p$, assume that $\dot{W}_p = m v_6 (p_1 - p_6)$.

From the steam tables,

$$v_6 = v_{f_6}$$
$$= 1.0102 \times 10^{-3} \text{ m}^3/\text{kg}$$
Thus, 

\[
\frac{\dot{W}_p}{m} = 1.0102(30 - 0.1)10^5 \times 10^{-6}
\]

\[= 3.0 \text{ kj/kg}
\]

To obtain \(\dot{Q}_b\), use

\[
\dot{Q}_b = m(h_2 - h_1)
\]

\[
h_1 = h_6 + \frac{\dot{W}_p}{m}
\]

\[= 191.8 + 3.0
\]

\[= 194.8 \text{ kJ/kg}
\]

\[
\dot{Q}_b = 2,993.5 - 194.8
\]

\[= 2,799 \text{ kJ/kg}
\]

To find \(\dot{Q}_r\),

\[
\dot{Q}_r = m(h_4 - h_3)
\]

\[
\dot{Q}_r = 3,069.3 - 2,542
\]

\[= 527 \text{ kJ/kg}
\]

From equation (1) then

\[
\eta = \frac{452 + 606 - 3}{2,799 + 527}
\]

\[= 0.317
\]
PROBLEM 3

A container which has a volume of 0.1 m$^3$ is fitted with a plunger enclosing 0.5 kg of steam at 0.4 MPa. Calculate the amount of heat transferred and the work done when the steam is heated to 300°C at constant pressure.

SOLUTION

For this system changes in kinetic and potential energy are not significant. Therefore,

$$Q = m(u_2 - u_1) + W$$

$$W = \int_1^2 PdV = P\int_1^2 dV = P(V_2 - V_1) = m(P_2v_2 - P_1v_1)$$

Therefore,

$$Q = m(u_2 - u_1) + m(P_2v_2 - P_1v_1) = m(h_2 - h_1)$$

$$v_1 = \frac{V_1}{m} = \frac{0.1}{0.5} = 0.2 = 0.001084 + x_1(0.4614)$$

$$x_1 = \frac{0.1989}{0.4614} = 0.4311$$

Then

$$h_1 = h_f + x_1h_{fg} = 604.74 + 0.4311 \times 2133.8 = 1524.6$$

$$h_2 = 3066.8$$

$$Q = 0.5(3066.8 - 1524.6) = 771.1 \text{ kJ}$$

$$W = mP(v_2 - v_1) = 0.5 \times 400(0.6548 - 0.2) = 91.0 \text{ kJ}$$

Therefore,

$$U_2 - U_1 = Q-W = 771.1 - 91.0 = 680.1 \text{ kJ}.$$  

The heat transfer can be calculated from $u_1$ and $u_2$ by using

$$Q = m(u_2 - u_1) + W$$

$$u_1 = u_f + x_1u_{fg} = 604.31 + 0.4311 \times 1949.3 = 1444.6$$

$$u_2 = 2804.8$$
PROBLEM 5

Steam leaves the boiler in a steam turbine plant at 2 MPa, 300°C and is expanded to 3.5 kPa before entering the condenser. Compare the following four cycles:

(1) A superheated Rankine cycle.

(2) A reheat cycle, with steam reheated to 300°C at the pressure when it becomes saturated vapor.

(3) A regenerative cycle, with an open feedwater heater operating at the pressure where steam becomes saturated vapor.

(4) A regenerative cycle, with a closed feedwater heater operating at the pressure where steam becomes saturated vapor.

Figure 38. Rankine cycle

SOLUTION

(1) Referring to Figure 38, the steam tables show that

\[ h_4 = 3.025 \text{ kJ/kg} \]
\[ s_4 = 6.768 \text{ kJ/kg} - \text{K} \]

At \( P = 3.5 \text{ kPa} \),

\[ s_g = 8.521 \text{ kJ/kg} - \text{K} \]
\[ s_f = 0.391 \text{ kJ/kg} - \text{K} \]
Since $s_5 = s_4$, steam at 5 is a mixture of liquid and vapor. The quality is found as

$$x_5 = \frac{s_5 - s_f}{s_{fg}}$$

$$= \frac{6.768 - 0.391}{8.130}$$

$$= 0.785$$

Therefore,

$$h_5 = h_f + x_5 h_{fg}$$

$$= 112 + 0.785(2,438)$$

$$= 2,023 \text{ kJ/kg}$$

hence

$$w_{45} = h_4 - h_5$$

$$= 3,025 - 2,023$$

$$= 1,002 \text{ kJ/kg}$$

Now

$$w_{12} = h_1 - h_2$$

$$= v_f(p_1 - p_2)$$

$$= 0.0010(0.0035 - 2) \times 10^3 \text{ kJ/kg}$$

$$= -2 \text{ kJ/kg}$$

Therefore, the net work output is

$$w = w_{45} + w_{12} = 1,000 \text{ kJ/kg}$$

Heat input is

$$q_{42} = h_4 - h_2$$

But

$$h_2 = h_1 - w_{12} = 112 + 2 = 114 \text{ kJ/kg}$$

therefore,

$$q_{42} = 3,025 - 114 = 2,911 \text{ kJ/kg}$$

Thus,

$$\eta = \frac{w}{q_{42}} = \frac{1,000}{2,911} = 0.344$$
Also

Specific Steam Consumption = \frac{3,600}{w} = \frac{3,600}{1,000} = 3.6 \text{ kg/kWh}

\[ \text{Figure 39. Reheat cycle} \]

(2) Refer to Figure 39, and note that since

\[ s_5 = s_{sat} = s_4 = 6.768 \text{ kJ/kg - K} \]

the pressure at reheat point 5 can be found using the steam tables. Interpolating between 0.55 MPa and 0.6 MPa gives

\[ P_5 = 0.588 \text{ MPa}. \]

Then

\[ h_5 = \frac{2,753 + \frac{0.588 - 0.55}{0.60 - 0.55}(2,757 - 2,753)}{0.038 + \frac{0.05}{0.05} \times 4} = 2,753 + \frac{0.588 - 0.55}{0.60 - 0.55}(2,757 - 2,753) \]

\[ = 2,753 + \frac{0.588 - 0.55}{0.60 - 0.55}(2,757 - 2,753) \]

\[ = 2,756 \text{ kJ/kg} \]

As 6 and 5 are on the same isobar, by interpolation
\[ h_6 = 3,065 + \frac{0.588 - 0.5}{0.60 - 0.5} (3,062 - 3,065) \]
\[ = 3,065 + \frac{0.088}{0.1} (-3) \]
\[ = 3,062.4 \text{ kJ/kg} \]
\[ s_6 = 7.460 + 0.88(7.373 - 7.460) \]
\[ = 7.460 + 0.88(-0.087) \]
\[ = 7.384 \text{ kJ/kg} - \text{K} \]

At \( P = 3.5 \text{ kPa}, \)
\[ s_g = 8.521 \text{ kJ/kg} - \text{K} \]
\[ s_f = 0.391 \text{ kJ/kg} - \text{K} \]

Since \( s_f = s_6, \) the quality at 7 is found as
\[ x_f = \frac{7.384 - 0.391}{8.130} = 0.86. \]

Then
\[ h_f = 112 + 0.86(2,438) \]
\[ = 112 + 2,095 = 2,207 \text{ kJ/kg} \]

The net work output is given by
\[ w = w_{45} + w_{67} + w_{12} \]
\[ = (3,025 - 2,765) + (3,062.4 - 2,207) - 2 \]
\[ = 1,122.4 \]

The heat input is
\[ q = q_{42} + q_{65} \]
\[ = 2,911 + (h_6 - h_5) \]
\[ = 2,911 + (3,062.4 - 2,756) \]
\[ = 3,217.4 \]

Therefore,
\[ \eta = \frac{1,122.4}{3,217.4} = 0.349 \]
and

\[ s.s.c. = \frac{3,600}{\dot{w}} = \frac{3,600}{1,122.4} = 3.2 \text{ kg/kWh}. \]

Figure 40. (a) Equipment schematic for regenerative cycle

\[ T \]

\[ s \]

Figure 40. (b) Regenerative cycle

(3) Refer to Figures 40 (a) and 40 (b). The work is as in (b)

\[ w_{45} = 269 \text{ kJ/kg} \]

Next determine the amount of steam bled off at 5. Consider an energy balance for the open feedwater heater with

\[ h_2' = yh_s - (1 - y)h_2 \]

which gives
\[ y = \frac{h_2' - h_2}{h_5 - h_2} \]

To find the value for \( h_2' \), enter the steam tables. At 5 the pressure is known \((P = 0.588 \text{ MPa})\) and the state of the steam is given as saturated vapor. Therefore, by interpolating between the values of 0.5 MPa and 0.6 MPa, obtain

\[
h_2' = 656 + \frac{0.588 - 0.55}{0.60 - 0.55} (670 - 656)
\]
\[= 656 + \frac{0.038}{0.05} \times 14\]
\[= 656.6 \text{ kJ/kg}\]

Then

\[
y = \frac{666.6 - 114}{2,756 - 114}
\]
\[= \frac{552.6}{2,642}\]
\[= 0.209\]

Hence,

\[
w_{56} = (1 - y)(h_5 - h_6)
\]
\[= 0.791(2,756 - 2,023)\]
\[= 580 \text{ kJ/kg}\]

also

\[
w_{22'} = \nu_j(P_2' - P_2)
\]
\[= 0.0011(0.588 - 2) \times 10^3\]
\[= -1.1 \times 1.412\]
\[= -1.55 \text{ kJ/kg}\]

Therefore,

\[
w = w_{45} + w_{56} + w_{12} + w_{22'}
\]
\[= 269 + 580 - 0.791 \times 2 - 1.55\]
\[= 845.87 \text{ kJ/kg}\]

The heat input is
\[ q_{42'} = 3025 - (666.6 + 1.55) \]
\[ = 2356.8 \text{ kJ/kg} \]

The efficiency of this cycle is

\[ \eta = \frac{w}{q_{42''}} = \frac{845.87}{2356.8} = 0.3595 \]

and

\[ \text{s.s.c.} = \frac{3600}{w} = \frac{3600}{845.9} = 4.25 \text{ kg/k Wh.} \]

Figure 41. (a) Equipment diagram including closed heater

Figure 41. (b) A regenerative cycle with closed heater
(4) Refer to Figures 41 (a) and 41 (b). The work is as in part (b).

\[ w_{45} = 269 \text{ kJ/kg} \]

Heat balance for the heater as a closed system gives

\[ h_{21} = yh_5 - (1 - y)h_2 \]

giving

\[ y = \frac{h_{11} - h_2}{h_5 - h_9} \]

Now in finding the enthalpies in the feed line, it is usual to make the following assumptions:

i. Neglect the feed pump term.

ii. Assume the enthalpy of the compressed liquid to be the same as that of the saturated liquid at the same temperature.

iii. Assume the states of the condensate extracted from the turbine, before and after throttling, to be the same as that of the saturated liquid at the lower pressure of the throttled liquid.

Using these assumptions

\[ h_2 = h_1 \]
\[ h_{11} = h_3 \]
\[ h_9 = h_{10} = h_1 \]

whence

\[ y = \frac{h_8 - h_1}{h_5 - h_1} \]

\[ = \frac{666.6 - 112}{2,756 - 112} = 0.209 \text{ kJ/kg} \]

Also,

\[ w_{56} = 580 \text{ kJ/kg}. \]

Therefore,

\[ w = w_{45} + w_{56} + w_{12} \]
\[ = 269 + 580 - 2 = 847 \text{ kJ/kg} \]
Heat input $q_{411} = 2,358.4$ kJ/kg.

Then

$$\eta = \frac{w}{q_{411}} = \frac{847}{2,358.4} = 0.360$$

and

$$s.s.c. = \frac{3,600}{w} = \frac{3,600}{847} = 4.25 \text{ kg/k Wh.}$$

**PROBLEM 6**

(1) One kilogram of air at 101.35 kPa, 21°C is compressed in an Otto cycle with a compression ratio of 7 to 1. During the combustion process, 953.66 kJ of heat is added to the air. Compute (a) the specific volume, pressure, and temperature at the four points in the cycle, (b) the air standard efficiency, and (c) the mep (mean effective pressure) and hp of the engine, if it uses 1 kg/min of air.

(2) Calculate the efficiency for a Carnot cycle operating between the maximum and minimum temperatures of the Otto cycle (Figure 42).

![Figure 42. Otto cycle](image)

**SOLUTION**

(1) (a) At state 1,

$$P_1 = 101.35 \text{ kPa}$$

$$T_1 = 294 \text{ K}$$
\[ \frac{V_A}{V_B} = 8 \]
\[ P_A = 100 \text{ kPa} \]
\[ q_{BC} = +800 \text{ kJ/kg} \]
\[ C_p = \frac{7}{2} R \]

AB: reversible, adiabatic
BC: isochoric
CD: reversible, adiabatic
dA: isochoric

<table>
<thead>
<tr>
<th></th>
<th>T (K)</th>
<th>P (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>290</td>
<td>100</td>
</tr>
<tr>
<td>B</td>
<td>662</td>
<td>1838</td>
</tr>
<tr>
<td>C</td>
<td>1782</td>
<td>4918</td>
</tr>
<tr>
<td>D</td>
<td>776</td>
<td>268</td>
</tr>
</tbody>
</table>
Adiabatic compression

\[
\frac{dS}{dt} = \sum \text{Int Perf} \dot{S} + \dot{Q} + \dot{S}_{\text{gen}}
\]

\[
\dot{S}_A = \dot{S}_B
\]

\[
\Delta S(P, V) = 0 = C_p \ln \frac{V_B}{V_A} + C_v \ln \frac{P_B}{P_A}
\]

\[
\frac{P_B}{P_A} = \left( \frac{\rho_A}{\rho_B} \right)^{C_p/C_v}
\]

\[
P_B = P_A \left( \frac{8}{5} \right)^{5/2} = 100 \left( \frac{8}{5} \right)^{7/5}
\]

Also,

\[
\Delta S(T, V) = 0 \Rightarrow T_B = \left( \frac{V_A}{V_B} \right)^{(C_p - C_v) / C_v} \frac{(C_p - C_v)}{C_v}
\]

\[
T_B = (290k) \left( \frac{8}{5} \right)^{7/5} - 1
\]

\[
T_B = 666.2 \text{ K}
\]
Balance from $B \rightarrow C$

$$\frac{dm}{dt} = \sum_{\text{me}} \dot{m}_{\text{in}} + \dot{Q} + \dot{\mathcal{G}}$$

$$\dot{m}(\hat{u}_C - \hat{u}_B) = \dot{Q}$$

$$\frac{\dot{Q}}{\dot{m}} = \hat{u}_C - \hat{u}_B = c_v(T_C - T_B)$$

$$T_C = \frac{\dot{Q}}{\dot{m}c_v} + T_B$$

$$= \frac{800 \text{ kJ/kg} \cdot 2981 \text{ K}}{(5/2)(8.31 \text{ J/mol} \cdot \text{K})} \cdot \frac{1000 \text{ g}}{1 \text{ kg}} + 666.2 \text{ K}$$

$$T_C = 1782.4 \text{ K}$$

$$\frac{P_C \sqrt{v_C}}{T_C} = \frac{P_B \sqrt{v_B}}{T_B}$$

$$P_C = P_0 \left( \frac{T_C}{T_B} \right)^{1 \text{ (150 choric)}} \left( \frac{v_B}{v_C} \right)$$
\[ P_c = (1838 \text{ kPa}) \left( \frac{1782.4}{666.2} \right) \]

\[ P_c = 4917.5 \text{ kPa} \]

As before during adiabatic compression,

\[ \frac{P_D}{P_c} = \left( \frac{V_c}{V_D} \right)^{\frac{C_p}{C_v}} \]

\[ \frac{T_D}{T_c} = \left( \frac{V_c}{V_D} \right)^{\frac{C_p - C_v}{C_v}} \]

\[ V_D = V_A \]

\[ V_B = V_c \]

\[ P_D = P_c \left( \frac{V_B}{V_A} \right)^{\frac{C_p}{C_v}} \]

\[ = 4917.5 \text{ kPa} \left( \frac{1}{8} \right)^{7/5} \]

\[ P_D = 267.6 \text{ kPa} \]
\[ T_D = T_C \left( \frac{V_{MB}}{V_A} \right) \left( \frac{C_P - C_V}{C_V} \right) \]
\[ = 1782.4 \left( \frac{1}{8} \right) \left( \frac{7/5 - 1}{1} \right) \]
\[ T_D = 775.8K \]

**Overall Balance**

\[ \frac{dH}{dt} = \sum \dot{m} \Delta H + Q + \dot{W}_{net} \]

- \( \dot{W}_{net} = Q_{in} + Q_{out} \)

**Need \( Q_{out} \)**

**Balance around last isochoric step**

\[ \frac{dH}{dt} = \sum \dot{m} \Delta H + \dot{Q}_{out} \left( 45^\circ \right) \]

\[ \dot{m}(\hat{u}_A - \hat{u}_D) = \dot{Q}_{out} \]
\[
\dot{Q}_{\text{out}} = -\frac{C_v}{\dot{m}} (T_A - T_D)
\]

\[
\dot{Q}_{\text{out}} = \frac{5}{2} \left( \frac{8.314 \, \text{J/mol} \cdot \text{K}}{29 \, \text{g/mol}} \right) \cdot \frac{\text{J}}{\text{g}} \cdot \frac{\text{KJ}}{1000 \, \text{J}} \left( 290 - 775.8 \right)
\]

\[
\dot{Q}_{\text{out}} = -348.2 \, \text{KJ/kg}
\]

\[
-\dot{W}_{\text{net}} = 800 - 348.2
\]

\[
-\dot{W}_{\text{net}} = 451.8 \, \text{KJ/kg}
\]

\[
-\frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{451.8}{800} \Rightarrow \eta = 0.565
\]
Process Thermodynamics

First Law

Example 1

A gas is confined in a cylinder by a piston. It is taken from state A to state B along the path ACB as shown on the PV diagram below. The process from A to C is constant pressure, and the system receives 50 J of work and gives up 25 J of heat to the surroundings. The process from C to B is constant volume and the system receives 75 J of heat. The return path from B to A is adiabatic. How much work is exchanged with the surroundings for the adiabatic path? Assume all processes are reversible.

\[ \Delta U + \Delta E_p + \Delta E_k = Q + W \]
\[ \Delta U = Q + W \]

\[ \Delta U_{BA} = Q_{BA} + W_{BA} \]
\[ \Delta U = 0 = \Delta U_{AC} + \Delta U_{CB} + \Delta U_{BA} \]
\[ -\Delta U_{AB} = \Delta U_{BA} = -\Delta U_{AC} - \Delta U_{CB} \]

System: gas in cylinder

Known:
\[ Q_{AC} = -25 \text{ J} \]
\[ W_{AC} = 50 \text{ J} \]
\[ Q_{CB} = 75 \text{ J} \]
\[ Q_{BA} = 0 \]
\[ \Delta U_{BA} = \Delta U_{AB} \]

Assume: reversible (details to follow, of course) (i.e. frictionless)

\[ \Delta U \] is a state function, we know that we can get same \( \Delta U \) by following different path
$$\Delta U_{AC} = q_{AC} + W_{AC}$$
$$= -25J + 50J$$
$$= 25J$$

$$\Delta U_{CB} = q_{CB} + W_{CB}$$
$$= 75J + W_{CB}$$

$$W_{CB} = \int_{V_C}^{V_B} p \, dV$$
$$= 0$$

$$\Delta U_{BA} = -\Delta U_{AC} - \Delta U_{CB}$$
$$= -25J - 75J$$
$$= -100J$$

$$W_{BA} = -100J$$  work done by system
Water at 200 °F is pumped from a storage tank at the rate of 50 gal min⁻¹. The motor for the pump supplies work at the rate of 2 hp. The water goes through a heat exchanger, giving up heat at the rate of 40,000 Btu min⁻¹, and is delivered to a second storage tank at an elevation 50 ft above the first tank. What is the temperature of the water delivered to the second tank? The density of water at 200 °F is 60.1 lbm ft⁻³.
Energy Balance

\[ \Delta H + \frac{u_2^2 - U_1^2}{2} + g \left( z_2 - z_1 \right) = \dot{Q} + \dot{W}_s \]

\[ \Delta \hat{H} = \hat{H}_2 - \hat{H}_1 = \dot{Q} + \dot{W}_s - g \Delta z \]

\[ \hat{H}_2 = \hat{H}_1 + \dot{Q} + \dot{W}_s - g \Delta z \]

Use steam tables to get \( \hat{H}_1 \)

Enthalpy of liquid \( H_2O \) at 200°F

\[ \hat{H}_1 = 168.09 \text{ Btu/lbm} \]

\[ \hat{H}_2 = (168.09 \text{ Btu/lbm}) + \left( -40000 \frac{\text{Btu}}{\text{min}} \right) \left( \frac{\text{min}}{52.8 \text{gal}} \right) \left( \frac{52.8 \text{ gal}}{60.1 \text{ lbm}} \right) \left( \frac{7.48 \text{ gal}}{4 \text{ ft}^3} \right) \]

\[ + (2 \text{ hp}) \left( \frac{1424.1 \text{ Btu/min}}{1 \text{ hp}} \right) \left( \frac{1}{50} \right) \left( \frac{7.48 \text{ gal}}{60.1 \text{ lbm}} \right) \left( \frac{4 \text{ ft}^3}{52.8 \text{ gal}} \right) \]

\[ = 68.74 \text{ Btu/lbm} \]

From steam tables, we see that \( T_2 \) is between 100° and 102°F

Interpolate to get \( T_2 = 100.74°F \)

Note that \( \dot{W}_s \) is negligible in comparison to \( \dot{Q} \) and could have been neglected.
Air at 1 bar and 298.15 K is compressed to 5 bar and 298.15 K by two different frictionless (reversible) processes:

(a) Cooling at constant pressure followed by heating at constant volume
(b) Heating at constant volume followed by cooling at constant pressure

Calculate the heat and work requirements and the change in internal energy and enthalpy of the air for each path. Assume that air is an ideal gas, regardless of the changes it undergoes and that $C_p = C_v + R$. At 298.15 K and 1 bar the molar volume of air is 0.02479 m³ mol⁻¹.

\[ P_A = 1 \text{ bar} \]
\[ P_C = 5 \text{ bar} \]
\[ T_A = T_C = 298.15 \text{ K} \]
\[ V(T_A, P_A) = 0.02479 \text{ m}^3/\text{mol} \]
\[ W_S = 0 \] (work)

Assume: | PBD | (wait)
\[ \Delta E_p = \Delta E_k = 0 \]

(a) First Step (A → B)  
Closed system changing \( V \)

\[ \Delta H + \Delta E_p + \Delta E_k = Q + W_s \]  (add to known)

\[ \Delta H = Q \]

\[ \Delta H_{AB} = Q_{AB} \]

\[ \Delta H_{AB} = Q_{AB} = \int_{T_A}^{T_B} C_P \, dT \]  (need \( C_P \) & \( T_B \))

\[ = \int_{T_A}^{T_B} a + bT + cT^2 + dT^3 \]

\[ = a(T_B - T_A) + b\left(\frac{T_B^2 - T_A^2}{2}\right) + c\left(\frac{T_B^3 - T_A^3}{3}\right) + d\left(\frac{T_B^4 - T_A^4}{4}\right) \]
\[ PV = RT \]
\[
\frac{P_a V_a}{T_a} = \text{constant} \]

\[
\frac{P_a V_a}{T_a} = \frac{P_b V_b}{T_b} \]
\[
P_A = P_B \]

\[
T_B = \frac{V_B}{V_A} \cdot T_A \quad \text{Need but} \quad V_B = V_C \]

\[
T_B = \frac{V_C}{V_A} \cdot T_A \quad \text{Need} \]

We also know
\[
\frac{P_A V_A}{T_A} = \frac{P_C V_C}{T_C} \quad \text{and} \quad T_A = T_C \]

\[
V_C = \frac{P_A}{P_C} \cdot V_A \]

\[
T_B = \frac{P_A}{P_C} \cdot T_A \]

\[
T_B = \left( \frac{1 \text{bar}}{5 \text{bar}} \right) (298.15 \text{K}) \]
\[= 59.63 \text{K}\]

For \( \Delta u \),
\[
\Delta u = u + PV \]
\[
\Delta H = \Delta u + \Delta (PV) \]
\[
\Delta u_{AB} = \Delta H_{AB} - \Delta (PV)_{AB} \]
\[
\Delta u_{AB} = \Delta H_{AB} - P_A (V_B - V_A) \quad \text{and} \quad V_B = V_C = \frac{P_A}{P_C} \cdot V_A \quad (\text{above}) \]
\[
= \Delta H_{AB} - P_A \left( \frac{P_A}{P_C} \cdot V_A - V_A \right) \]
\[
= \Delta H_{AB} - P_A (V_A - V_A) \]
\[
= \Delta H_{AB} - P_A \cdot 0 \]
\[= \Delta H_{AB} \]
Second step - closed system at const. V (B → C)

\[ \Delta U_{BS} + \Delta E_p + \Delta E_K = Q + W^E \text{ (const. V)} \]

\[ \Delta U_{BC} = Q_{BC} = \int_{T_B}^{T_C} C_v dT \quad ; \quad C_v = C_p - R \]

\[ = \int_{T_B}^{T_C} C_p - R = (a - R)(T_C - T_B) + \frac{1}{2} (T_C^2 - T_B^2) + \frac{C}{3} (T_C^3 - T_B^3) \]

\[ + \frac{d}{4} (T_C^4 - T_B^4) \]

**Entire process**

\[ Q_T = Q_{AB} + Q_{BC} \]

\[ \Delta U_T = \Delta U_{AB} + \Delta U_{BC} \]

\[ \Delta H_T = \Delta H_{AB} + \Delta H_{BC} \]

\[ = \Delta U + \Delta (C_v) = \Delta U + \Delta (PV) \]

**Extensive properties are additive**

**Overall Balance**

\[ \Delta U^0 = Q + W \]

\[ W = -Q \]

**Final Values**

\[ \Delta H_{AB} = Q_{AB} = -6820 \text{ J/MOL} \]

\[ \Delta U_{AB} = -4837 \text{ J} \]

\[ \Delta U_{BC} = Q_{BC} = 4837 \text{ J} \]

\[ Q_T = -1983 \text{ J} \]

\[ \Delta U_T = 0 \]

\[ \Delta H_T = 0 \]

\[ W = 1983 \text{ J} \]

Recall that \( W = f(T) \) for Ig
(2) In a similar fashion, for path (1b)

\[ A \rightarrow D \]

\[ \frac{P_A V_A}{T_A} = \frac{P_D V_D}{T_D} \quad \Rightarrow \quad V_A = V_D \quad ; \quad P_D = P_c \]

\[ T_D = \frac{P_c}{P_A} T_A \]

\[ = 149075 \text{ K} \]

\[ \Phi_{AD} = \Delta U_{AD} = \int_{T_A}^{T_D} C_v \, dT \]

\[ = (a-R)(T_D-T_A) + \frac{\ell}{2}(T_D^2-T_A^2) + \frac{c}{3}(T_D^3-T_A^3) \]

\[ + \frac{d}{4}(T_D^4-T_A^4) \]

\[ D \rightarrow C \]

\[ \Phi_{DC} = \Delta U_{DC} = \int_{T_D}^{T_C} C_v \, dT \]

\[ = a(T_C-T_D) + \frac{\ell}{2}(T_C^2-T_D^2) + \frac{c}{3}(T_C^3-T_D^3) \]

\[ + \frac{d}{4}(T_C^4-T_D^4) \]

\[ \Delta U_{DC} = \Delta H_{DC} - \Delta (PV)_{DC} \]

\[ = \Delta H_{DC} - P_c (V_C-V_D) \quad \frac{V_D}{V_A} = \frac{V_C}{V_A} \]

\[ \frac{T_A}{T_C} = \frac{T_A}{T_C} \]

\[ \frac{P_A}{P_C} V_A = \frac{P_C}{P_A} \frac{V_C}{V_A} \]

\[ V_C = \frac{P_A}{P_C} V_A \]

\[ = \Delta H_{DC} - P_c V_A \left( \frac{P_A}{P_C} - 1 \right) \]
Entire Process

\[ Q_T = Q_{AB} + Q_{DC} \]
\[ \Delta W = \Delta U_{AD} + \Delta U_{DC} \]
\[ \Delta H_T = \Delta H_{AD} + \Delta H_{DC} \]

Overall Balance

\[ \Delta U = Q + W \]
\[ W = -Q \]

Final Values

\[ \Delta H_{DC} = Q_{DC} = -38,435 \text{ J} \]
\[ \Delta U_{DC} = \underline{28,520} \text{ J} \]
\[ Q_{AD} = \Delta U_{AD} = 28,520 \text{ J} \]
\[ Q_T = -9915 \text{ J} \]
\[ \Delta W = \Delta H_T = 0 \]
\[ W = 9915 \text{ J} \]

Note that the property changes \( \Delta U \) & \( \Delta H \) are the same for both paths, but \( Q \) & \( W \) are path-dependent.
A well-insulated storage tank of 60 m$^3$ contains 200 L of liquid water at 75 °C. The rest of the tank contains steam in equilibrium with the water. Spent process steam at 2 bar and 90% quality enters the storage tank until the pressure in the tank reaches 2 bar. Assuming that the heat losses from the system to the tank and the environment are negligible, calculate the total amount of steam that enters the tank during the filling process and the fraction of liquid water present at the end of the process.

\[
\begin{align*}
\text{Initial} & \\
V & = 60 \text{ m}^3 \\
Q & = 0 \\
W & = 0 \\
T & = 75^\circ \text{C} \\
\text{Sat.} & \\
\hat{V}_L & = 1.026 \times 10^{-3} \text{ m}^3/\text{kg} \\
\hat{V}_V & = 4.131 \text{ m}^3/\text{kg} \\
\hat{u}_L & = 313.9 \text{ kJ/kg} \\
\hat{u}_V & = 2475.9 \text{ kJ/kg} \\
\hat{h}_L & = 504.49 \text{ kJ/kg} \\
\hat{h}_V & = 2529.5 \text{ kJ/kg} \\
\hat{h}_{L,in} & = 504.49 \text{ kJ/kg} \\
\hat{h}_{V,in} & = 2529.5 \text{ kJ/kg} \\
\end{align*}
\]

\[
\begin{align*}
\Delta m & = \frac{\Delta E_k}{\Delta p} \\
\Delta m & = \text{total mass of steam introduced} \\
m_L + m_V & = m_i \\
m_L = \frac{V_L}{\hat{V}_L} = \frac{200 \text{ L}}{1.026 \times 10^{-3} \text{ m}^3/\text{kg}} \times \left( \frac{\text{m}^3}{1000 \text{L}} \right) = 194.932 \text{ kg} \\
m_V = \frac{V_V}{\hat{V}_V} = \frac{60 \text{ m}^3 - 200 \text{ L} \left( \frac{\text{m}^3}{1000 \text{L}} \right)}{4.131 \text{ m}^3/\text{kg}} = 14.476 \text{ kg} \\
m_i = 209.41 \text{ kg} \\
\end{align*}
\]
Energy Balance

\[ \frac{d\hat{u}}{dt} = \dot{m}_\text{in}(\hat{H}_\text{in}) + \dot{Q} + \dot{Q}_0 \quad (1) \]

Integrate from initial to final conditions

\[ \int_{u_i}^{u_f} du = \int_{t_i}^{t_f} \dot{m}_\text{in} \hat{H}_\text{in} \, dt \quad \dot{m}_\text{in} (t) \]

\[ u_f - u_i = (m_f - m_i) \hat{H}_\text{in} \quad (2) \]

\[ u_f = m_f \hat{u}_f \quad (\text{sub into (2)}) \]

\[ m_f \hat{u}_f - m_i \hat{u}_i = (m_f - m_i) \hat{H}_\text{in} \quad (3) \]

Use lever rule for 2-phase mixture

\[ \frac{\hat{u}}{\hat{H}_\text{in}} = \frac{x^I \hat{u}^I + x^II \hat{u}^II}{x^I + x^II} \]

\[ m \hat{u} = m_L \hat{u}_L + m_v \hat{u}_v \quad (\text{sub into (3)}) \]

\[ (m_f \hat{u}_L^f + m_v \hat{u}_v^f) - (m_i \hat{u}_L^i + m_v \hat{u}_v^i) = (m_f - m_i) \hat{H}_\text{in} \quad (4) \]

Analyze & Get variables

\[ \hat{H}_\text{in} \approx 0.1 \hat{H}_\text{L,in} + 0.9 \hat{H}_\text{V,in} \]

\[ m_f = m_L^f + m_v^f \]

We have one eq & two variables — can we solve?

Do we know anything else about the final mass?

\[ \sqrt{v} = m_L^f \hat{v}_L^f + m_v^f \hat{v}_v^f \quad (5) \]

Now solve (4) & (5) simultaneously

\[ 504.19 \, m_L^f + 2529.5 \, m_v^f = 97030.3 = (m_L^f + m_v^f - 269.41) \cdot 2486.5 \quad (4) \]

\[ 9852.7 = 46.1 \, m_L^f - m_v^f \quad (4) \]

\[ 677 = 1.20 \times 10^{-3} \, m_L^f + m_v^f \quad (5) \]

\[ m_L^f = 215.19 \, kg \]

\[ m_v^f = 67.7 \, kg \]

\[ \Delta M = 73.48 \, kg \]

\[ x_L = \frac{m_L^f}{m_L^f + m_v^f} = 0.761 \]
Process Thermodynamics

Engine Efficiency

Example 1

A central power plant, rated at 800,000 kW, generates steam at 585 K and discards heat to a river at 295 K. If the thermal efficiency of the plant is 70% of the maximum possible value, how much heat is discarded to the river at rated power?

\[ \eta_{\text{max}} = 1 - \frac{295}{585} = 0.496 \]

\[ \eta = 0.7 \eta_{\text{max}} = 0.347 \]

Energy Bal

\[ Q_H + Q_c + W = 0 \]

\[ \eta = -\frac{W}{Q_H} \]

\[ Q_c = +W \left( \frac{1}{\eta} - 1 \right) \]

\[ = -800000 \left( \frac{1}{0.347} - 1 \right) \]

\[ Q_c = -1.505 \times 10^6 \text{ kW} \]

Engine Efficiency

Example 2

The following heat engines produce power of 95,000 kW. Determine in each case the rates at which heat is absorbed from the hot reservoir and discarded to the cold reservoir.

1. A Carnot engine operates between heat reservoirs at 750 K and 300 K.
2. A practical engine operates between the same heat reservoirs but with a thermal efficiency \( \eta = 0.35 \).

1. \[ \eta = 1 - \frac{T_c}{T_H} = 1 - \frac{300}{750} \]

\[ \eta = 0.6 \]

\[ Q_c + Q_H + W = 0 \]

\[ Q_c + 1.573 \times 10^8 - 95000 = 0 \]

\[ Q_c = -5.33 \times 10^4 \text{ kW} \]

\[ Q_H = 95000 \text{ kW} \]

\[ \eta = -\frac{W}{Q_H} \]

\[ \frac{Q_H}{0.6} = \frac{95000}{0.6} \]

\[ \boxed{Q_H = 1.583 \times 10^5 \text{ kW}} \]
2. \( \eta = 0.35 \)

\[
Q_w = \frac{-W}{\eta} = \frac{95000}{0.35} \]

\[ Q_w = 2.71 \times 10^5 \text{ kW} \]

\[ Q_c + 2.71 \times 10^5 - 95000 = 0 \]

\[ Q_c = -1.76 \times 10^5 \text{ kW} \]
Process Thermodynamics

Power Cycles
Example 1

Steam generated in a power plant at a pressure of 8000 kPa and a temperature of 500 °C is fed to a turbine. Exhaust from the turbine enters a condenser at 10 kPa, where it is condensed to saturated liquid, which is then pumped to the boiler.

a) What is the thermal efficiency of a Rankine cycle operating at these conditions?

b) What is the thermal efficiency of a practical cycle operating at these conditions if the turbine efficiency and pump efficiency are both 0.75?

c) If the rating of the power cycle of part (b) is 80,000 kW, what is the steam rate and what are the heat-transfer rates in the boiler and condenser?

We can get \( \hat{H}_1 \) & \( \hat{S}_1 \) from steam tables (values in table)

Entropy Bal around turbine

\[ \frac{dS}{dT} = \sum \text{nh} \Delta \hat{S}_{rev} + \frac{\hat{Q}}{T} + \hat{S}_{gen} \Rightarrow \hat{S}_1 = \hat{S}_2 \]
From steam tables at 10 kPa, it is seen that sat. vapor too high of \(\hat{S} \rightarrow \) must be mixture

\[
\hat{S}_2^L = 0.6493, \quad \hat{S}_2^v = 8.1502
\]

\[
\hat{S}_2 = (1-x)\hat{S}_2^L + x\hat{S}_2^v
\]

\[
= \hat{S}_2^L + x(\hat{S}_2^L - \hat{S}_2^v)
\]

Solve for \(x = 0.810\)

\[
\hat{H}_2^v = 21584.7
\]

\[
\hat{H}_2^L = 191.83
\]

\[
\hat{H}_2 = 2130.1 \text{ (Put } \hat{H}_2 \text{ in table)}
\]

Read \(T\) from table (Put \(T_2 = 45.81\) °C in table)

We know condenser isobaric (\(P_3 = 10\) kPa)

\[
\hat{H}_3 = 45.81\text{ °C (Put } T_3 \text{ in table)}
\]

Calculate work of turbine

\[
\frac{d\hat{W}}{dt} = \sum m \hat{H}_k + \Phi + \hat{W}_T
\]

\[
\hat{W}_T = \hat{m}(\hat{H}_2 - \hat{H}_1)
\]

\[
\frac{\hat{W}_T}{\hat{m}} = \hat{H}_2 - \hat{H}_1 = -1268.2 \text{ kJ/kg}
\]

We know condenser isobaric (\(P_3 = 10\) kPa)

\[
\hat{H}_3 = 45.81\text{ °C (Put } T_3, P_3 \text{ in table)}
\]

Because it is sat. liquid \(\hat{H}_3 = \hat{H}_3^L = 191.83 \text{ (Put } \hat{H}_3 \text{ in table)}
\]

Energy Bal around condenser,

\[
\frac{d\hat{H}}{dt} = \sum m \hat{A}_h + \Phi + \hat{W}_T
\]
\[ \Phi_e = m \left( \dot{H}_3 - \dot{H}_2 \right) \]

\[ \dot{Q}_m = \dot{H}_3 - \dot{H}_2 \]

\[ = -1938.3 \text{ kJ/kg} \]

Pump is isentropic (\( \dot{S}_3 = \dot{S}_4 \))

\[ \frac{d\dot{H}}{dt} = \sum m_i \dot{H}_i + \dot{Q} + \dot{W}_p - \frac{d\dot{V}}{dt} \]

\[ \dot{W}_p = \frac{\dot{Q}}{m} \left( \dot{H}_4 - \dot{H}_3 \right) \]

\[ \text{We need to get } \dot{H}_4 - \text{ Recall that typically we would solve entropy balance} \]

\[ \text{cos } S \text{ is isentropic } \rightarrow \text{ no info } \]

\[ \text{...we need to relate } du \text{ in terms of pressure} \]

\[ \text{Note: That we can't get } \dot{H}_4 \text{ from steam Tables since it is subcooled} \]

\[ \text{We know internal energy should increase} \]

\[ d\dot{u} = T dS \quad d\dot{V} \quad \text{relates } S \text{ to } PdV \]

\[ k = u + PV \]

\[ \text{or } d\dot{H} = d\dot{u} + PdV + Vdp \]

\[ \text{combine } \]

\[ d\dot{H} = TdS + Vdp \]

\[ \text{ineatotropic} \]

\[ \frac{\dot{W}_p}{m} = \int \dot{V} dp \]

\[ = \dot{V} (P_4 - P_3) \]

\[ \text{Get } \dot{V} \text{ from steam tables } \]

\[ \dot{V}_L = 1.01 \times 10^{-3} \text{ m}^3/\text{kg} \]
\[ \frac{W_p}{m} = (1.01 \times 10^{-3} \, \text{m}^3/\text{kg}) \left( 8000 - 10 \, \text{kPa} \right) \]
\[ = 8.07 \, \text{kJ/kg} \]

\[ \frac{W_p}{m} = \hat{h}_4 - \hat{h}_3 \quad \text{or} \quad \hat{h}_4 = \frac{W_p}{m} + \hat{h}_3 \]

\[ \hat{h}_4 = 199.9 \quad \text{(Put \: \hat{h}_4 \: \text{in table)} \]

Energy Balance around boiler:
\[ \frac{dU}{dt} = \sum \text{inlet} \hat{h}_m + \dot{Q}_h + \dot{L} \]

\[ \frac{\dot{Q}_4}{m} = \hat{h}_1 - \hat{h}_4 \]

\[ \frac{\dot{Q}_4}{m} = 3198.4 \, \text{kJ/kg} \]

\[ W_S \, \text{(Rankine)} = \text{Net Work} = \frac{\dot{W}_T}{m} + \frac{\dot{W}_p}{m} \]

\[ = -1268.2 + 8.07 \, \text{kJ/kg} \]

\[ = -1260.1 \, \text{kJ/kg} \]

Note \( W_S = (\dot{Q}_4 + \dot{Q}_e) \)

\[ = (3198.4 - 1938.3) \]

\[ = -1260.1 \, \text{kJ/kg} \]

\[ \eta = \frac{1 + \frac{W_S}{\dot{Q}_h}}{\frac{1260.1 \, \text{kJ/kg}}{3198.4 \, \text{kJ/kg}}} \quad \Rightarrow \eta = 0.394 \]
(b) \( \eta_T = \eta_P = 0.75 \)

\[
\eta_T = \frac{\dot{W}_S}{\dot{W}_S \text{ (isentropic)}} = \frac{\Delta H}{(\Delta H)_S}
\]

\[
\Delta H = \eta_T (\Delta H)_S = 0.75 (-1268.2) = -951.1 \text{ kJ/kg}
\]

\[
\hat{h}_2' = \hat{h}_2 + \Delta \hat{h}
\]

\[
= 3398.3 - 957.1
\]

\[
= 2441.2 \text{ (Put in table)}
\]

We see from steam tables that state 2 is also wet

\[
\hat{h}_2 = \hat{h}_2^L + x (\hat{h}_2^U - \hat{h}_2^L)
\]

\[
2447.2 = 191.83 + x (2584.7 - 191.83)
\]

\[
x = 0.94
\]

\[
\hat{s}_2 = \hat{s}_2^L + x (\hat{s}_2^U - \hat{s}_2^L)
\]

\[
= 7.7 \text{ (Put in table)}
\]

\[
\dot{W}_T = \frac{\dot{W}_T}{m} = \hat{h}_2' - \hat{h}_1
\]

\[
= -951.1 \text{ kJ/kg}
\]
\[ \frac{Q_c}{m} = H_3 - H_2 \]
\[ = 191.83 - 2447.2 \]
\[ = -2255.4 \]

\[ \eta_{pump} = \frac{\Delta H_p}{\Delta H} \]
\[ \Delta H = \frac{0.75 (\Delta T)}{0.75} = \frac{8.07}{0.75} \]
\[ = 10.76 \text{ kJ/kg} \]

\[ W_p = \frac{10.76 \text{ kJ/kg}}{m} \]

\[ W_s (\text{Rambach}) = -951.1 + 10.76 \]
\[ = -940.3 \text{ kJ/kg} \]

\[ H_4 = H_3 + \Delta H \]
\[ = 191.83 + 10.76 \]
\[ = 202.59 \text{ kJ/kg} \]

\[ \frac{Q_h}{m} = H_1 - H_4 \]
\[ = 339.53 - 202.59 \]
\[ = 3195.71 \]
(c) $\dot{W}_S = 80000 \text{ kW}$

\[ \dot{W}_S = \dot{m}W_S \]

\[ \dot{m} = \frac{\dot{W}_S}{W_S} = \frac{80000 \text{ kJ/s}}{940.3 \text{ kJ/kg}} \]

\[ \dot{m} = 85.1 \text{ kg/s} \]

\[ \dot{Q}_H = \dot{m}\phi_H = (85.1)(8195.71) \]

\[ \dot{Q}_H = 2.7 \times 10^5 \text{ kJ/s} \]

\[ \dot{Q}_c = \dot{m}Q_c = (85.1)(-2255.4) \]

\[ \dot{Q}_c = -1.9 \times 10^5 \text{ kJ/s} \]