University of Jordan
Chemical Engineering Department
Chemical Engineering Thermodynamics 905322

Dr. Ali Khalaf Al-Matar
aalmatar@ju.edu.jo

Final Exam Solution
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1 Refrigeration & Inventor's Claim

This problem is solved by direct application of the coefficient of performance for a Carnot's refrigeration cycle i.e.,

$$COP = \frac{1}{\frac{T_H}{T_C} - 1} = \frac{1}{\frac{298}{275} - 1} = 11.96.$$

The claim of the inventor states that the COP is 13.5 which is higher than the COP of a Carnot engine. From Carnot's theorem, we know that the Carnot's engine is the most efficient. Consequently, no engine can have a COP greater than 11.96 for the heat source and sink we have. Therefore, we can safely conclude that the claim is false.

2 Steam Throttling & Entropy Generation

The expansion in a throttling valve is Joule-Thompson expansion (isoenthalpic). Therefore, the outlet enthalpy must be the same as the inlet enthalpy.

$$H(600°\text{C}, 700 \text{ bar}) = H(T, 10 \text{ bar}) \approx 3063 \text{ kJ/kg}.$$

Get the rest of properties from Mollier diagram.

	Inlet	**Outlet**
T (°C)	600	308
P (bar)	700	10
H (kJ/kg)	3063	3063
S (kJ/kg.K)	5.522	7.145

The entropy balance yields that the generation is equal to the difference in flow streams i.e.,

$$S_{gen} = (S_{out} - S_{in}) = 7.145 - 5.522 = 1.623 \text{ kJ/kg.K}.$$

3 Heat Exchanger Balance

The energy balance for each side of the exchange yields

$$Q = m_w C_{P,w} \Delta T_w = m_a C_{P,a} \Delta T_a.$$

Subscript w is used for water, while subscript a is used for air. Rearrange this equation to have the ratio of mass flow rates of air and water on one side

$$\frac{m_a}{m_w} = \frac{C_{P,w} \Delta T_w}{C_{P,a} \Delta T_a}.$$

The temperature differences on both sides are given. However, the heat capacities are not. Water is very common and the heat capacity is 4.184 kJ/kg.K. Air at these conditions may be assumed to be an ideal (diatomic) gas with a heat capacity of $3.5R$ J/mol.K. Convert this value into consistent units with that of water

$$C_{P,a} = \frac{7}{2}(8.314)\frac{1}{29} = 1.0034 \text{ kJ/kg.K.}$$

Consequently,

$$\frac{m_a}{m_w} = \frac{(4.184)(20)}{(1.0034)(25)} = 3.3359 \text{ kg air/kg water.}$$

Notice that at the same temperature rise and drop fro both streams, the ratio of heat capacities is really what determines the ratio of mass flow rates.

4 Heat of Combustion of n-Octane

This problem is a direct application of the use of the stoichiometry and heat of formation. The balances combustion reaction for n-octane is

$$C_8H_{18,(g)} + \frac{25}{2}O_{2,(g)} \rightarrow 8CO_{2,(g)} + 9H_2O_{(l)}$$

Component	ν_i	$\Delta H^\circ_{f,i}$(kJ/mol)	$\nu_i \Delta H^\circ_{f,i}$(kJ/mol)
$C_8H_{18,(g)}$	-1	-208.75	208.75
$O_{2,(g)}$	$-\frac{25}{2}$	0	0
$CO_{2,(g)}$	8	-393.509	-3148.1
$H_2O_{(l)}$	9	-285.830	-2572.5
		$\sum$(kJ/mol)	-5511.9

The heat of combustion is the net sum of stoichiometric coefficient times the heats of formation i.e.,

$$\Delta H^\circ_C = \sum \nu_i \Delta H^\circ_{f,i} = -5511.9 \text{ kJ/mol.}$$

5 Rankine Cycle Analysis

Appropriate balances are applied directly to each unit in the Rankine cycle. Start with the turbine inlet since this is the point at which all conditions are known.

5.1 Turbine Analysis (2→3)

Get the desired enthalpy and entropy from the steam tables at the inlet conditions. Use the assumption of the turbine being isentropic to get the properties at the outlet

$$S_3 = S_2 = 7.1873 \text{ kJ/kg.K}$$

	Inlet (2)	**Outlet (3)**
T (°C)	500	81.4
P (kPa)	3300	50
H (kJ/kg)	3452.8	2500.8
S (kJ/kg.K)	7.1873	7.1873
x (-)	1.0	0.937

The quality at the outlet of the turbine is found by the relation

$$x = \frac{S_3 - S_{\text{sat liquid}}}{S_{\text{sat vapor}} - S_{\text{sat liquid}}} = \frac{7.1873 - 1.0912}{7.5947 - 1.0912} = 0.937$$

Knowing the quality enables us to find the enthalpy at the outlet of the turbine

$$\begin{aligned} H_3 &= xH_{\text{sat vapor}} + (1-x)H_{\text{sat liquid}} \\ &= (0.937)(2646) + (1-0.937)(340.564) = 2500.8 \text{ kJ/kg.} \end{aligned}$$

The work in the turbine is the difference between the outlet and inlet enthalpies

$$W_T = \Delta H = H_3 - H_2 = 2500.8 - 3452.8 = -952.0 \text{ kJ/kg.}$$

5.2 Condenser Analysis (3→4)

The condenser is straightforward. All we need to calculate is the latent heat of vaporization (condensation) of the stream at the pressure of 50 kPa. However, we do not really need to carry out this calculation. All we need to know is that the outlet stream from the condenser is saturated liquid at 50 kPa.

5.3 Pump Analysis (4→1)

The work in the pump is the change of enthalpy in the liquid. Virtually the liquid is not compressible which enables us to calculate the work as the molar volume times the pressure difference. The outlet pressure is 3300 since it is going to be fed to the boiler

	Inlet (4)	**Outlet (1)**
T (°C)	81.4	81.4
P (kPa)	50	3300
H (kJ/kg)	340.6	343.95
V (m^3/kg)	0.00103	0.00103
x (-)	0.0	Compressed

The work for the pump is given as

$$\begin{aligned} W_P &= V(P_1 - P_4) \\ &= 0.00103(3.3 \times 10^6 - 5.0 \times 10^4) = 3.3475 \text{ kJ/kg.} \end{aligned}$$

The outlet enthalpy is the inlet enthalpy and the work

$$H_1 = H_4 + W_P = 340.6 + 3.3475 = 343.\,95 \text{ kJ/kg.}$$

5.4 Boiler Analysis (1→2)

The heat input to the boiler is the difference between the enthalpy of the outlet and inlet stream. We already have these values

$$Q_B = H_2 - H_1 = 3452.8 - 343.95 = 3108.\,9 \text{ kJ/kg.}$$

5.5 Efficiency

The efficiency is the net work we have divided by the heat input to the boiler

$$\begin{aligned} \eta &= \frac{|W_{net}|}{|Q_B|} = \frac{|W_T| - |W_P|}{|Q_B|} \\ &= \frac{952.0 - 3.3475}{3108.9} = 0.305\,14. \end{aligned}$$

5.6 Turbine Efficiency is 80%

If the turbine efficiency is 80%, the only point to be affected is point 3 accounting for a reversible turbine case. The work of the pump as well as the heat input to the boiler remains the same. Consequently,

$$\begin{aligned} \eta &= \frac{|W_{net}|}{|Q_B|} = \frac{|W_T| - |W_P|}{|Q_B|} = \frac{0.8\,|W_{T,\mathrm{rev}}| - |W_P|}{|Q_B|} \\ &= \frac{(0.8)(952.0) - 3.3475}{3108.9} = 0.243\,90. \end{aligned}$$

In general, the coefficient of performance of the cycle has dropped to roughly 80% of the reversible case. This is because $W_P \ll W_T$. So the performance of the cycle is mainly determined by the efficiency of the turbine.

Student Name:

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02	○	○	■	○
03	○	■	○	○
04	■	○	○	○
05	○	○	■	○
06	○	○	■	○
07	○	○	■	○
08	■	○	○	○
09	■	○	○	○
10	○	■	○	○
11	○	○	■	○
12	○	○	■	○
13	○	■	○	○
14	○	○	■	○
15	○	○	■	○
16	○	■	○	○
17	○	○	■	○
18	○	○	○	■
19	○	○	○	■
20	○	○	■	○
21	■	○	○	○
22	○	■	○	○
23	○	○	○	■
24	○	■	○	○
25	○	○	■	○
26	○	■	○	○
27	○	○	■	○
28	○	○	○	■
29	○	■	○	○
30	○	○	■	○

Fill the circles completely.
Don't fill more than one circle for each question. If there are more than one circles filled, you will get a zero for that question.
No answers on the questions sheet will be accepted.
Use a black/blue pen not a pencil.