A heat pump cycle has 20 bar NH\textsubscript{3} saturated vapor enter the condenser and saturated liquid exit. The evaporator operates at 5 bar; two-phase mixtures enter and exit. Compute the coefficient of performance if all the processes are reversible. What is the condenser specific heat transfer [kJ/kg]?

**EFD:**

![Diagram of heat pump cycle]

**Basic Equations:**

\[
\frac{dm_{sys}}{dt} = \sum_{\text{in}} \dot{m}_{in} - \sum_{\text{out}} \dot{m}_{out}
\]

\[
\frac{dE_{sys}}{dt} = Q - W + \sum_{\text{in}} \dot{m}_{in} (h + ke + pe)_{in} - \sum_{\text{out}} \dot{m}_{out} (h + ke + pe)_{out}
\]

\[
COP_{HP} = \frac{Q_H}{W_{net,in}}
\]

\[
COP_{HP, rev} = \frac{T_H}{T_H - T_C}
\]

**Assumptions:**

1D, uniform flow, uniform state  
SSSF  
neglect ke and pe
Solution:

If all the processes are reversible, then the HP COP equals the reversible HP COP. Assume that the evaporator operates at the cold reservoir temperature and the condenser operates at the hot reservoir temperature.

The condenser operates at 20 bar in the mixture dome, therefore the $T_H=49.351\, \text{degC}$.

The evaporator operates at 5 bar in the mixture dome, therefore $T_C=4.1396\, \text{degC}$.

$COP_{HP} = COP_{HP, rev} = \frac{T_H}{T_H - T_C} = \frac{(49.351\, \text{degC} + 273) \, K}{(49.351\, \text{degC} + 273)\, K - (4.1396\, \text{degC} + 273)\, K} = 7.13$

What is $q_H \left[ \frac{kJ}{kg} \right]$?

System 2 (NH3 in condenser):

$$\frac{dm_{sys}}{dt} = \sum_{in} \dot{m}_{in} - \sum_{out} \dot{m}_{out}$$

$$\dot{m}_2 = \dot{m}_3 = \dot{m}$$

$$\frac{dE_{sys}}{dt} = Q - W + \sum_{in} \dot{m}_{in} (h + ke + pe)_{in} - \sum_{out} \dot{m}_{out} (h + ke + pe)_{out}$$

$$\dot{q}_H = \frac{Q_H}{\dot{m}} = h_3 - h_2$$

$h_2 (x = 1.20\, \text{bar}) = 1471.9 \, \frac{kJ}{kg}$

$h_3 (x = 0.20\, \text{bar}) = 418.17 \, \frac{kJ}{kg}$

$$\dot{q}_H = \frac{Q_H}{\dot{m}} = h_3 - h_2 = 1471.9 \, \frac{kJ}{kg} - 418.17 \, \frac{kJ}{kg} = 1053.7 \, \frac{kJ}{kg}$$
A Carnot vapor power cycle uses water as its working fluid. The boiler pressure is 150 bar; saturated liquid enters and saturated vapor exits. The condenser pressure is 0.1 bar, with 2-phase mixtures entering and exiting. Calculate the thermal efficiency. What is the specific heat transfer for water passing through the boiler [kJ/kg]?

**EFD:**

**Basic Equations:**

\[
\frac{dm_{sys}}{dt} = \sum_{in} m_{in} - \sum_{out} m_{out}
\]

\[
\frac{dE_{sys}}{dt} = Q - W + \sum_{in} m_{in} (h + \text{ke} + \text{pe})_{in} - \sum_{out} m_{out} (h + \text{ke} + \text{pe})_{out}
\]

\[
\eta_{th} = \frac{W_{net, out}}{Q_{in}}
\]

\[
\eta_{th, rev} = 1 - \frac{T_L}{T_H}
\]

**Assumptions:**

1D, uniform flow, uniform state
SSSF
neglect ke and pe
Solution:

Since the power cycle is carnot cycle, it is reversible. This means we can use the reversible thermal efficiency.

The boiler operates at 150 bar in the mixture dome, therefore the $T_H=342.16$ degC.
The evaporator operates at 0.1 bar in the mixture dome, therefore $T_C=45.81$ degC.

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{(45.81 \text{degC} + 273)K}{(342.16 \text{degC} + 273)K} = 48.2\%$$

What is $Q_{in}$?

System 1 (water in boiler):

$$\frac{dm_{sys}}{dt} = \sum_{in} m_{in} - \sum_{out} m_{out}$$

$m_4 = m_1 = \dot{m}$

$$\frac{dE_{sys}}{dt} = Q - W + \sum_{in} \dot{m}_{in} (h + ke + pe)_{in} - \sum_{out} \dot{m}_{out} (h + ke + pe)_{out}$$

$$q_{in} = \frac{Q_{in}}{\dot{m}} = h_1 - h_4$$

$h_4 (x = 0.150 \text{bar}) = 1610.2 \frac{kJ}{kg}$

$h_1 (x = 1.150 \text{bar}) = 2610.7 \frac{kJ}{kg}$

$q_{in} = \frac{Q_{in}}{\dot{m}} = h_1 - h_4 = 2610.7 \frac{kJ}{kg} - 1610.2 \frac{kJ}{kg} = 1000.5 \frac{kJ}{kg}$
In a real heat pump, the condenser temperature is not constant because a superheated vapor enters. This renders the Carnot expression inaccurate.

Be that as it may, the Carnot expression will still serve as an upper bound on the cycle thermal efficiency, as long as we can find an effective upper T. We’ll do that by choosing that effective T to lie between that of the condenser outlet and condenser inlet. Choose a value and use it to compute the coefficient of performance using the Carnot expression. Use NH$_3$ as the working fluid with an evaporator temperature corresponding to 5 bar. The condenser exit temperature corresponds to 20 bar. The compressor exit temperature is 10°C above the condenser exit temperature.

**EFD:**

![Diagram of a heat pump cycle](image)

**Basic Equations:**

\[
\frac{dm_{sys}}{dt} = \sum_{in} \dot{m}_{in} - \sum_{out} \dot{m}_{out}
\]

\[
\frac{dE_{sys}}{dt} = Q - W + \sum_{in} \dot{m}_{in} (h + ke + pe)_{in} - \sum_{out} \dot{m}_{out} (h + ke + pe)_{out}
\]

\[
COP_{HP,rev} = \frac{T_H}{T_H - T_C}
\]

**Assumptions:**

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1D, uniform flow, uniform state
SSSF
neglect ke and pe

Solution:

Choose a value and use it to compute the coefficient of performance using the Carnot expression.
The inlet of the condenser is 59.351degC and the outlet of the condenser is 49.351degC. Taking the mean of the inlet and outlet of the condenser is about 54degC.

The evaporator operates at 5 bar in the mixture dome, therefore \( T_c = 4.1396 \)degC.

\[
COP_{HP} = COP_{HP,rev} = \frac{T_H}{T_H - T_C} = \frac{(54 \text{ degC} + 273) K}{(54 \text{ degC} + 273) K - (4.1396 \text{degC} + 273) K} = 6.56
\]

As any value for \( T_H \) between 59.351degC and 49.351degC is generally acceptable, we can take any range between 6.02 and 7.13.

\[
COP_{HP} = COP_{HP,rev} = \frac{T_H}{T_H - T_C} = \frac{(49.351 \text{ degC} + 273) K}{(49.351 \text{degC} + 273) K - (4.1396 \text{degC} + 273) K} = 7.13
\]

\[
COP_{HP} = COP_{HP,rev} = \frac{T_H}{T_H - T_C} = \frac{(59.351 \text{ degC} + 273) K}{(59.351 \text{degC} + 273) K - (4.1396 \text{degC} + 273) K} = 6.02
\]
SP24—Due by 4:30 pm EST on Friday 10 March to your division Gradescope site

Return to SP22a. Calculate the entropy for each of the four states. Which component has the largest entropy increase? Are they all positive? If not, does this concern you? Why or why not?

EFD:

Assume:

SSSF

Assuming that the throttle is reversible and adiabatic
Assuming that the compressor is reversible and adiabatic

Solution:

Find $s_2$ using $P_2$ and $x_2$.

Find $s_3$ using $P_3$ and $x_3$.

Assuming that the throttle is reversible and adiabatic. Therefore $s_4=s_3$.

Assuming that the compressor is reversible and adiabatic, therefore $s_1=s_2$.

<table>
<thead>
<tr>
<th>State</th>
<th>Entropy ($kJ/kg/K$)</th>
<th>delta$_s$ ($kJ/kg/K$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5023</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1.5023</td>
<td>3.2674</td>
</tr>
<tr>
<td>3</td>
<td>4.7697</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>4.7697</td>
<td>-3.2674</td>
</tr>
</tbody>
</table>
The changes in entropy are not all positive. It is ok to have a negative change in entropy because this decrease in entropy is caused by the heat transferred out of the system. A negative change in entropy does NOT mean entropy is destroyed which is impossible.