Thermodynamics and Heat Transfer Assignment Week 5
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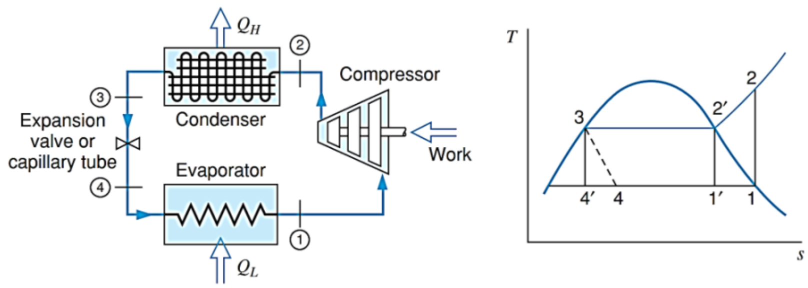
LE4: Part 2- Refrigeration Cycles (50 points)

Problem 1: A refrigerator with R-134a as the working fluid has a minimum temperature of −10°C and a maximum pressure of 1 MPa. Assume an ideal refrigeration cycle, as in Fig. 1. Find the specific heat transfer from the cold space and that to the hot space, and the COP. Compare the results with R410a (15 points).



Exercise 1:

The refrigeration cycle is ideal

According to the graph : $T_1 = -10°C$ and $P_2 = P_3 = 1$ MPa

The working fluids:

R-134a

- At condensor:

  Saturated liquid, $P_3 = 1$ MPa $\Rightarrow h_3 = 255.5$ kJ/kg

- At evaporator

  Saturated vapor, $T_1 = -10°C$ $\Rightarrow h_1 = 392.28$ kJ/kg, $s_1 = 1.7319$ kJ/kgK

- At compressor

  $s_2 = s_1 = 1.7319$ kJ/kgK, $P_2 = 1$ MPa $\Rightarrow h_2 = 425.681$ kJ/kg

- At evaporator

  $h_3 = h_4$, $q_L = h_1 - h_4 = h_1 - h_3$

  $\Rightarrow q_L = 392.28 - 255.5 = 136.78$ kJ/kg

- At condensor

  $q_H = h_2 - h_3 = 425.681 - 255.5 = 170.181$ kJ/kg

- $COP = \frac{q_L}{(q_H - q_L)} = \frac{136.78}{170.181 - 136.78} = 4.095$

R-410a

- At condensor

  Saturated liquid, $P_3 = 1$ MPa $\Rightarrow h_3 = 68.06$ kJ/kg

- At evaporator

  Saturated vapor, $T_1 = -10°C$ $\Rightarrow h_1 = 275.78$ kJ/kg, $S_1 = 1.0567$ kJ/kgK

- At compressor

  $S_2 = S_1 = 1.0567$ kJ/kgK, $P_2 = 1$ MPa $\Rightarrow h_2 = 290.81$ kJ/kg

- At evaporator

  $h_3 = h_4$, $q_L = h_1 - h_4 = h_1 - h_3$

  $\Rightarrow q_L = 275.78 - 68.06 = 207.69$ kJ/kg

- At condensor

  $q_H = h_2 - h_3 = 290.81 - 68.06 = 222.75$ kJ/kg

- $COP = \frac{q_L}{q_H - q_L} = \frac{207.69}{222.75 - 207.69} = 13.79$

$\Rightarrow$ The working fluid R-410a is much more efficient than R-134a

Problem 2: Consider an ideal refrigeration cycle that has a condenser temperature of 45°C and an evaporator temperature of −15°C. Determine the COP of this refrigerator for the working fluids R-134a and R-410a (10 points).

Exercise 2:

The refridgeration cycle is ideal

According to the graph in Ex 1. $\Rightarrow T_1 = -15°C$, $T_3 = 45°C$

The working fluids

R-134a

- At evaporator

Saturated vapor, $T_1 = -15°C$ $\Rightarrow$ $h_1 = 389.2\ kJ/kg$, $s_1 = 1.7354\ kJ/kgK$

- At condensor

Saturated liquid, $T_3 = 45°C$ $\Rightarrow$ $h_3 = 264.11\ kJ/kg$

- At compressor

$s_2 = s_1 = 1.7354\ kJ/kgK \Rightarrow h_2 = 429.8\ kJ/kg$

$\Rightarrow T_2 = 51.7°C$, $P_2 = 1.16\ MPa$

- At evaporator

$q_L = h_1 - h_3 = 389.2 - 264.11$
$= 125.09\ kJ/kg$

- At condensor

$q_H = h_2 - h_3 = 429.8 - 264.11$
$= 165.69\ kJ/kg$

- $COP = \dfrac{q_L}{q_H - q_L} = \dfrac{125.09}{165.69 - 125.09} = 3.08$ (answer)

R-410a

- At evaporator

Saturated vapor, $T_1 = -15°C$ $\Rightarrow$ $h_1 = 273.9\ kJ/kg$, $s_1 = 1.0671\ kJ/kgK$

- At condensor

Saturated liquid, $T_3 = 45°C$ $\Rightarrow$ $h_3 = 133.61\ kJ/kg$

- At compressor

$s_2 = s_1 = 1.0671\ kJ/kgK \Rightarrow h_2 = 322.7\ kJ/kg$

$\Rightarrow T_2 = 71.4°C$, $P_2 = 2.72\ MPa$

- At evaporator

$q_L = h_1 - h_3 = 273.9 - 133.61$
$= 140.29\ kJ/kg$

- At condensor

$q_H = h_2 - h_3 = 322.7 - 133.61$
$= 189.09\ kJ/kg$

- $COP = \dfrac{q_L}{q_H - q_L} = \dfrac{140.29}{189.09 - 140.29} = 2.87$ (answer)

Problem 3: A heat pump uses R410a with a high pressure of 3000 kPa and an evaporator operating at −10°C, so it can absorb energy from underground water layers at 4°C. Find the COP and the temperature at which it can deliver energy (10 points).

Exercise 3:

$T_1 = -10°C$, $P_2 = P_3 = 3 MPa$

- First state:

  Saturated vapor, $T_1 = -10°C$ $\Rightarrow$ $h_1 = 275.78 \, kJ/kg$, $s_1 = 1.0567 \, kJ/kg\,K$

- Second state

  $s_2 = s_1 = 1.0567 \, kJ/kgK$, $P_2 = 3 MPa$ $\Rightarrow$ $h_2 = 322.4 \, kJ/kg$

- Third state

  Saturated liquid, $P_3 = 3 MPa$ $\Rightarrow$ $T_3 \approx 49°C$, $h_3 = 141.7 \, kJ/kg$

$$\Rightarrow COP = \frac{q_H}{w_C} = \frac{h_2 - h_3}{h_2 - h_1} = \frac{322.4 - 141.7}{322.4 - 275.78} = 3.876 \text{ (answer)}$$

The temperature it can deliver energy at is about 49°C as the cycle is not perfect.
If heat transfer is not taken into account, $T_{deliverable} > 49°C$

Problem 4: A refrigerator using R-134a is located in a 20°C room. Consider the cycle to be ideal, except that the compressor is neither adiabatic nor reversible. Saturated vapor at −20°C enters the compressor, and the R-134a exits the compressor at 50°C. The condenser temperature is 40°C. The mass flow rate of refrigerant around the cycle is 0.2 kg/s, and the COP is measured and found to be 2.3. Find the power input to the compressor and the rate of entropy generation in the compressor process (15 points).

Exercise 4:

The refrigeration cycle is ideal and working fluid is R-134a

The compressor is not adiabatic nor reversible

According to graph in Ex 1. $\Rightarrow T_1 = -20°C,\ T_2 = 50°C,\ T_3 = 40°C$

- At compressor

$\left.\begin{array}{l}\text{Saturated vapor}\\ T_1 = -20°C\end{array}\right\} \Rightarrow \begin{array}{l} s_1 = 1.7395\ kJ/kg\,K \\ h_1 = 386.08\ kJ/kg\end{array}$

- At condensor

$\left.\begin{array}{l}\text{Saturated liquid}\\ T_3 = 40°C\end{array}\right\} \Rightarrow \begin{array}{l} h_3 = 256.54\ kJ/kg = h_4 \\ P_3 = 1017\ kPa\end{array}$

- Inside compressor

$\left.\begin{array}{l}\text{Saturated liquid}\\ P_3 = 1017\ kPa\end{array}\right\} \Rightarrow \begin{array}{l} s_2 = 1.747\ kJ/kg\,K \\ h_2 = 430.87\ kJ/kg\end{array}$

- $COP = 2.3 \Rightarrow \frac{q_L}{w_C} = 2.3 \Rightarrow \frac{h_1 - h_4}{w_C} = 2.3 \Rightarrow \frac{386.08 - 256.54}{w_C} = 2.3$

$\Rightarrow w_C = 56.322\ kJ/kg$

$\Rightarrow$ Power input to the compressor: $\dot{W}_C = \dot{m} w_C = 0.2\,kg/s \times 56.322\,kJ/kg$
$= 11.2643\ kW$ (answer)

* Enthalpy balance at the compressor: $h_1 + q_{in} + w_C = h_2$

$\Rightarrow q_{in} = h_2 - h_1 - w_C = 430.87 - 386.08 - 56.322 = -11.532\ kJ/kg$

- The entropy generation

$s_{generate} = s_2 - s_1 - \Delta s = s_2 - s_1 - \frac{q_{in}}{T_{room}} = 1.747 - 1.7395 + \frac{11.532}{(20 + 273.15)K}$

$\Rightarrow s_{generate} = 0.04688\ kJ/kgK$

$\Rightarrow$ Rate of entropy generation: $\dot{S}_{generate} = \dot{m} s_{generate} = 0.2\,kg/s \times 0.04688$
$= 9.367 \times 10^{-3}\ kW/K$ (answer)