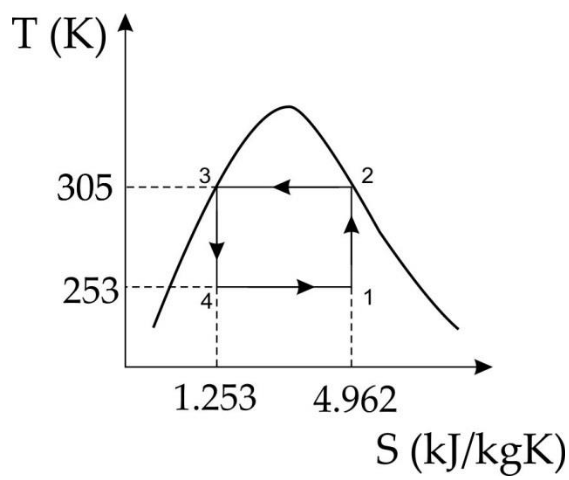
Example 10

Pressure in the evaporator of an ammonia refrigerator is 1.902bar and the pressure in the condenser is 12.37bar. Calculate the refrigerating effect per unit mass of refrigerant and the COP_{ref} for the following cycles;

i. Ideal reversed Carnot cycle
ii. Dry saturated vapor delivered to the condenser after isentropic compression, and no intercooling of the condensed liquid
iii. Dry saturated vapor delivered to the compressor where it is compressed isentropically, and no intercooling of the condensed liquid
iv. Dry saturated vapor delivered to the compressor, and the liquid after condensation undercooled by 10K
v. Recalculate (iv) for a cycle between the same saturation temperature using Refrigerant ® 134a instead of ammonia
vi. Mass flow rate required of ammonia and R134a, and the indicated power of the compressor per kilowatt of refrigerating capacity

i.



T_1 = -20°C is the saturation temperature corresponding to the evaporator pressure of 1.902 bar

T_2 = 32°C the saturation temperature corresponding to the condenser pressure of 12.37bar.

$$COP_{ref} = \frac{T_1}{T_2 - T_1} = \frac{305}{305 - 253} = \frac{253}{52} = 4.86$$

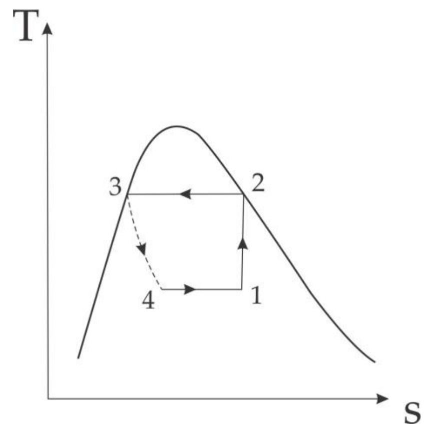
Refrigerating effect, Q_1,

$$q_1 = T_1(s_1 - s_4) = T_1(s_2 - s_3)$$

From table

$$s_2 = s_{g@at12.37bar} = 4.9519 kJ/kgK$$
$$s_3 = s_{f@at12.37bar} = 1.2306 kJ/kgK$$
$$q_1 = 253(4.9519 - 1.2306) = 948.32 kJ/kg$$

ii.



At 12.37bar

$h_2 = h_g = 1466.95 kJ/kg$ and $h_3 = h_f = 331.81 kJ/kg$

At 12.37bar,

$h_4 = h_3 = 331.81 kJ/kg$

Process 1 - 2 is isentropic,

$s_1 = s_2 = s_g$ at 12.37bar $= 4.9519 kJ/kg/K$

Therefore,

$$s_1 = s_{f,1} + xs_{fg,1}$$
$$4.9519 = 0.3635 + x_1(5.6151 - 0.3635)$$
$$x_1 = 0.8737$$

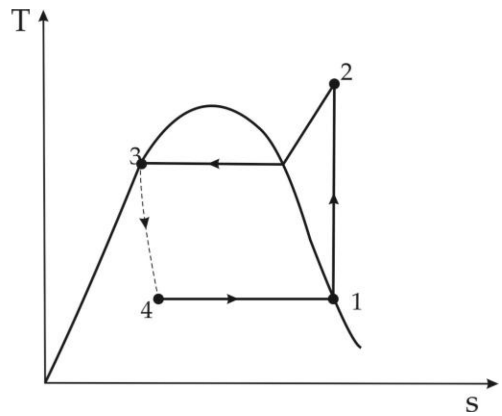
$$h_1 = h_{f,1} + xh_{fg,1}$$
$$= 89.528 + [0.8737(1417.726 - 89.528)] = 1249.97 kJ/kg$$

$$\text{Refrigerating effect} = q_L = h_1 - h_4 = 1249.97 - 331.81 = 918.16 \text{kJ/kg}$$

$$W_{in} = h_2 - h_1 = 1466.95 - 1249.97 = 216.98 \text{kJ/kg}$$

$$COP_{ref} = \frac{Q_1}{\sum W} = \frac{918.16}{216.98} = 4.2315$$

iii.



At 1.902 bar,

$h_1 = h_g = 1417.73 \text{kJ/kg}$

$h_3 = h_4 = 331.81 \text{kJ/kg}$

$s_1 = s_g = s_2 = 5.6152 \text{kJ/kg}$

At 12.37 bar, $s_g = 4.952 \text{kJ/kgK}$

Refrigerant is superheated at state 2.

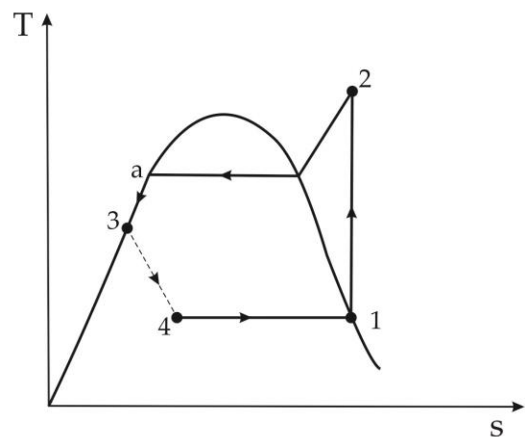
$\Rightarrow h_2 = 1694.786 \text{kJ/kg}$

$$\text{Refrigerating effect}, q_1 = h_1 - h_4 = 1417.73 - 331.81 = 1085.92 \text{kJ/kg}$$

$$W_{in} = h_2 - h_1 = 1694.786 - 1417.73 = 277.056 \text{kJ/kg}$$

$$COP_{ref} = \frac{Q_1}{\sum W} = \frac{1085.92}{277.056} = 3.92$$

iv.



h_1 and h_2 are as determined

$h_3 = h_4$ can be found by assuming that the undercooling takes place along the saturated liquid line,

Therefore, $h_3 = h_f$ at T_3.

Another way of obtaining h_3 is by assuming a constant specific heat, c, for the ammonia liquid and then,

$$h_3 = (h_f \text{ at } T_a) - c(T_a - T_3)$$

$$h_3 = h_{f@ \text{at} T_3 = 295K} = 283.84 kJ/kg$$

$$\text{Refrigerating effect}, q_1 = h_1 - h_4$$
$$= 1417.73 - 283.84 = 1133.89 kJ/kg$$

$$COP_{ref} = \frac{Q_1}{\sum W} \frac{1133.89}{277.056} = 4.092$$

v. R134a (derived from properties of the ICI refrigerant KLEA 134a)

Saturation pressure in the evaporator is that corresponding to -20°C, i.e. 1.3299bar

$$h_1 = h_{g1@-20°C} = 283.03 kJ/kg$$

$$h_3 = h_{f3@22°C} = 129.708 kJ/kg$$

Also,

$$s_1 = s_{g1} = s_2 = 1.7273 kJ/kgK$$

Saturation temperature in the condenser is 32°C, hence using a double interpolating to find h_2.

$$\text{At } 30°C \Rightarrow \left(\frac{h_{2@30°C} - h_{g@30°}}{h_{2@30°C@superheated@10K} - h_{g@30°}}\right) = \left(\frac{s_2 - s_{g@30°}}{s_{superheated@20°@10K} - s_{g@30°}}\right)$$

$$h_{2@30°C} = 311.79 + \left(\frac{1.7273 - 1.7044}{1.7444 - 1.7044}\right)(324.12 - 311.79) = 318.85 kJ/kg$$

$$\text{At } 35°C \Rightarrow \left(\frac{h_{2@35°C} - h_{g@35°}}{h_{2@35°C@superheated@10K} - h_{g@35°}}\right) = \left(\frac{s_2 - s_{g@35°}}{s_{superheated@20°@10K} - s_{g@35°}}\right)$$

$$h_{2@35°C} = 314.47 + \left(\frac{1.7273 - 1.7038}{1.7444 - 1.7038}\right)(327.11 - 314.47) = 321.82 kJ/kg$$

Therefore, at 32°C of saturation temperature in the condenser

$$h_{2@32°C} = 320.04 kJ/kg$$

Refregerating effect, $q_1 = h_1 - h_4 = 283.03 - 129.708 = 153.322 kJ/kg$

(lower compared to 1085.92 kJ/kg for ammonia cycle)

$$COP_{ref} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{283.03 - 129.708}{320.04 - 283.03} = \frac{153.322}{37.01} = 4.14$$

(higher compared to 4.092 for ammonia cycle) vi.

$$\text{Refrigerating effect}_{\text{ammonia}} = q_1 = 1133.89\text{kJ/kg}$$

$$\text{Refrigerating effect}_{\text{R134a}} = q_1 = 153.322\text{kJ/kg}$$

Refrigerating load,

$$\dot{m} = \frac{\text{refrigeration capacity}}{\text{refrigerating effect per unit mass}}$$

refrigeration capacity = 1 kilowatt of refrigeration (according to the requirement)

$$\dot{m}_{\text{ammonia}} = \frac{1}{1133.89} = 8.819 \times 10^{-4}\text{kg/s}$$

$$\dot{m}_{\text{R134a}} = \frac{1}{153.322} = 6.522 \times 10^{-3}\text{kg/s}$$

$$W_{\text{ammonia}} = 277.056\text{kJ/kg}$$

$$P_{\text{ammonia}} = 8.819 \times 10^{-4} \times 277.056 = 0.2443\text{kW}$$

$$W_{\text{R134a}} = 320.04 - 283.03 = 37.01\text{kJ/kg}$$

$$\text{Power}_{\text{R134a}} = 6.522 \times 10^{-3} \times 37.01 = 0.2414\text{kW}$$

It can be seen that

- COP is greater for the cycle using R134a
    - Therefore, the power output required is less for the same capacity.
- Mass flow rate required for R134a is very much greater than for ammonia
- But at the compressor intake, the specific volume of saturated ammonia vapor at the suction pressure is 0.6237m³/kg (refer refrigerant table) compared with a value of me/kg for R134a. Hence, volume flow rate of vapor into the compressor per kilowatt is

$$\dot{\upsilon}_{\text{ammonia}} = \upsilon \times \dot{m} = 0.6237 \times 8.819 \times 10^{-4} = 5.55 \times 10^{-4}\text{m}^3/\text{s}$$

$$\dot{\upsilon}_{\text{R134a}} = \upsilon \times \dot{m} = 0.145 \times 6.522 \times 10^{-3} = 9.457 \times 10^{-4}\text{m}^3/\text{s}$$

Required volume flow rate for R134a is only about 1.6 greater than ammonia, although the mass flow rate is about a factor of 7 times greater. The volume flow rate determines the size of the compressor.