Analysis of Vapour Compression Refrigeration Cycle

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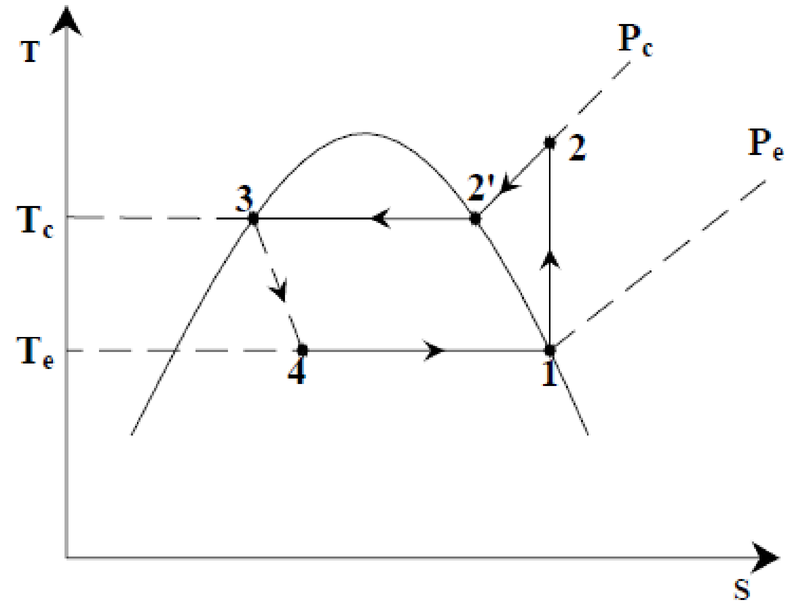
Assumptions:

a) Steady flow; b) negligible kinetic and potential energy changes across each component, and c) no heat transfer in connecting pipe lines

The steady flow energy equation is applied to each of the four components.



Evaporator: Heat transfer rate at evaporator or *refrigeration capacity* is given by

$$\dot{Q}_e = \dot{m}_r (h_1 - h_4)$$

Where $\dot{m}_r$ is the refrigerant mass flow rate in kg/s, h_1 and h_4 are the specific enthalpies (kJ/kg) at the exit and inlet to the evaporator, respectively. $(h_1 - h_4)$ is known as specific refrigeration effect or simply *refrigeration effect*, which is equal to the heat transferred at the evaporator per kilogram of refrigerant.

The evaporator pressure P_e is the saturation pressure corresponding to evaporator temperature T_e, i.e.,

$$P_e = P_{sat}(T_e)$$

Compressor: Power input to the compressor is given by

$$\dot{W}_c = \dot{m}_r (h_2 - h_1)$$

Where h_2 and h_1 are the specific enthalpies (kJ/kg) at the exit and inlet to the compressor respectively. $(h_2 – h_1)$ is known as specific work of compression or simply *work of compression*, which is equal to the work input to the compressor per kilogram of refrigerant.

Condenser: Heat transfer at condenser is given by

$$\dot{Q}_c = \dot{m}_r (h_2 - h_3)$$

Where h_3 and h_2 are the specific enthalpies (kJ/kg) at the exit and inlet to the condenser respectively.

The condenser pressure P_c is the saturation pressure corresponding to evaporator temperature, T_e. i.e.

$$P_c = P_{sat}(T_c)$$

Expansion Device: For the **isenthalpic expansion process**, the kinetic energy change across the expansion device could be considerable, however, well downstream of the expansion device the kinetic energy gets dissipated due to viscous effects, and

$$h_3 = h_4$$

The exit condition of the expansion device lies in the two-pahse region, hence applying the definition of quality or dryness fraction, we can write

$$h_4 = (1 - x_4)h_{f,e} + x_4 h_{g,e} = h_f + x_4 h_{fg}$$

Where x_4 is the quality of refrigerant at point 4, $h_{f,e}$, $h_{g.e}$, h_{fg} are the saturated liquid enthalpy, saturated vapour enthalpy and latent heat of vapourization at evaporator pressure, respectivley

The COP of the system is given by:

$$COP = \left(\frac{\dot{Q}_e}{\dot{W}_c}\right) = \left(\frac{\dot{m}_r (h_1 - h_4)}{\dot{m}_r (h_2 - h_1)}\right) = \frac{(h_1 - h_4)}{(h_2 - h_1)}$$

At any point in the cycle, the mass flow rate of refrigerant $\dot{m}_r$ can be written in terms of volumetric flow rate and specific volume at that point, i.e.,

$$\dot{m}_r = \dot{V}/v$$

applying this equation to the inlet condition of the compressor,

$$\dot{m}_r = \dot{V}_1/v_1$$

where $\dot{V}_1$ is the volumetric flow rate at compressor inlet and v_1 is the specific volume at compressor inlet.

At a given compressor speed, V_1 is an indication of the size of the compressor

The refrigeration capacity in terms of volumetric flow rate,

$$\dot{Q}_e = \dot{m}_r(h_1 - h_4) = \dot{V}_1\left(\frac{h_1 - h_4}{v_1}\right)$$

where $\left(\frac{h_1 - h_4}{v_1}\right)$ is called as *volumetric refrigeration effect* (kJ/m^3 of refrigerant).

Problem Solving Technique

Type of refrigerant, required refrigeration capacity, evaporator and condenser temperatures are known

1.

From the condenser and evaporator temperatures, find the condenser and evaporator pressures and enthalpies at the exit of evaporator and condenser (saturated vapour enthalpy at evaporator pressure and saturated liquid enthalpy at condenser pressure)

2.

The exit condition of the compressor is in the superheated region, two independent properties are required to fix the state of refrigerant at this point

One of these independent properties could be the condenser pressure, which is already known

Since the compression process is isentropic, the entropy at the exit to the compressor is same as the entropy at the inlet, s_1 which is the saturated vapour entropy at evaporator pressure (known).

From the known pressure and entropy, the enthalpy at exit state of the compressor

$$h_2 = h(P_c, s_2) = h(P_c, s_1)$$

$$s_1 = s_2$$

3.

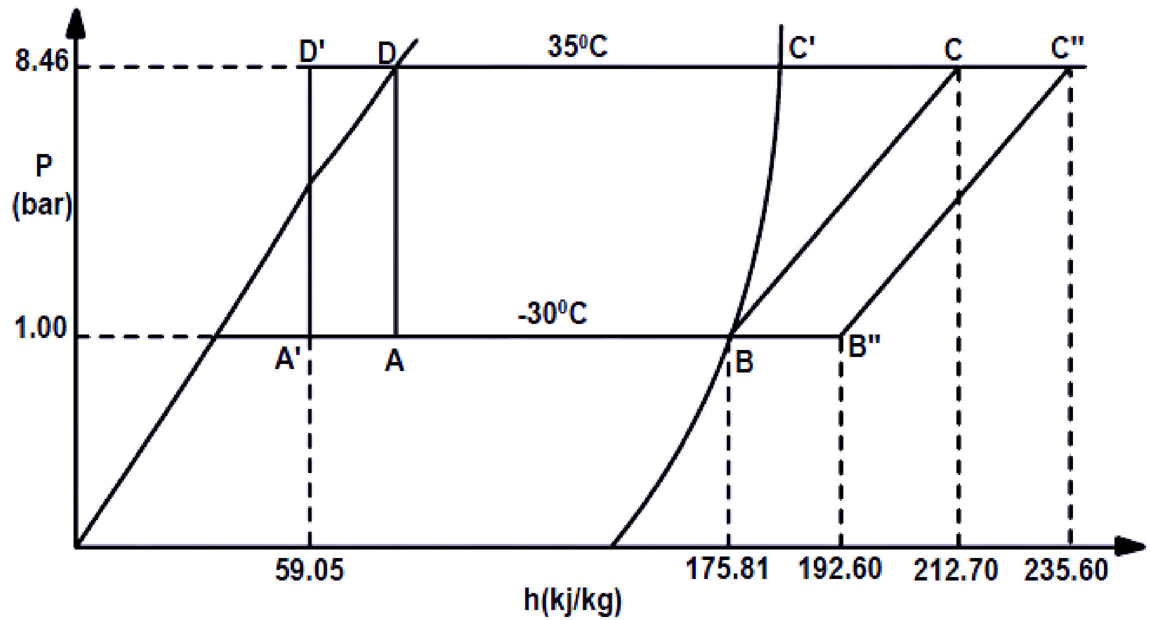
The quantity of refrigerant at the inlet to the evaporator (x_4) could be obtained from the known values of h_3, $h_{f,e}$ and $h_{g,e}$

Factors Affecting the Performance of Vapor Compression Refrigeration System

(a) Sub-cooling of Liquids:

$$(h_B - h'_A) > (h_B - h_A)$$

net refrigeration effect is increased



(b) Superheating of Vapour:

$$(h''_B - h_A) > (h_B - h_A)$$

$$(h''_C - h''_B) > (h_C - h_B)$$

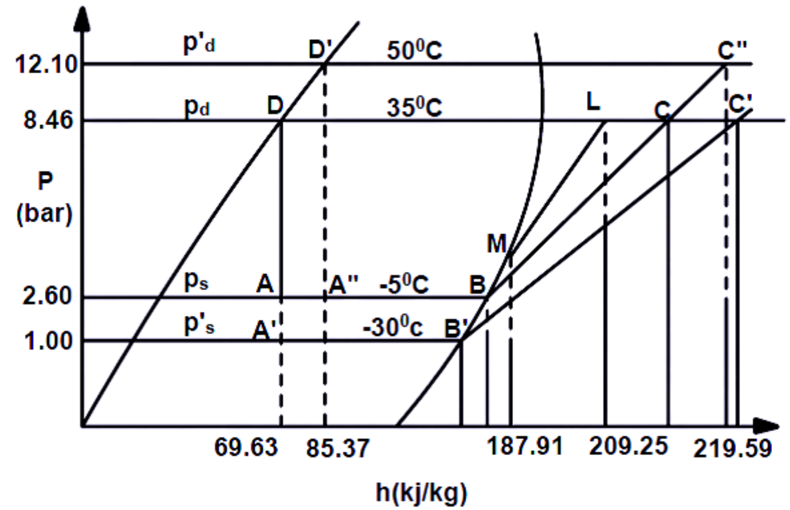
increases both the refrigeration effect as well as the work of compression.

COP (ratio of refrigeration effect and work of compression) may or may not increase with superheat, depending mainly upon the nature of the working fluid.

Even though useful superheating may or may not increase the COP of the system, a minimum amount of superheat is desirable as it prevents the entry of liquid droplets into the compressor.

(c) Change in evaporator and condenser pressure

Let the suction pressure or the evaporating pressure in a simple refrigeration cycle be reduced from P_S to P'_S.



The refrigerating effect is reduced to:

$$(h'_B - h'_A) < (h_B - h_A)$$

The work of compression is increased to

$$(h'_C - h'_B) > (h_C - h_B)$$

decrease in suction pressure decreases the refrigeration effect and at the same time increases the work of compression. But, both the effects tend to decrease the COP

let us assume that the pressure at the discharge or the condensing pressure is increased from P_d to P'_d.

The compressor work requirement is increased to: $(h''_C - h_B) > (h_C - h_B)$

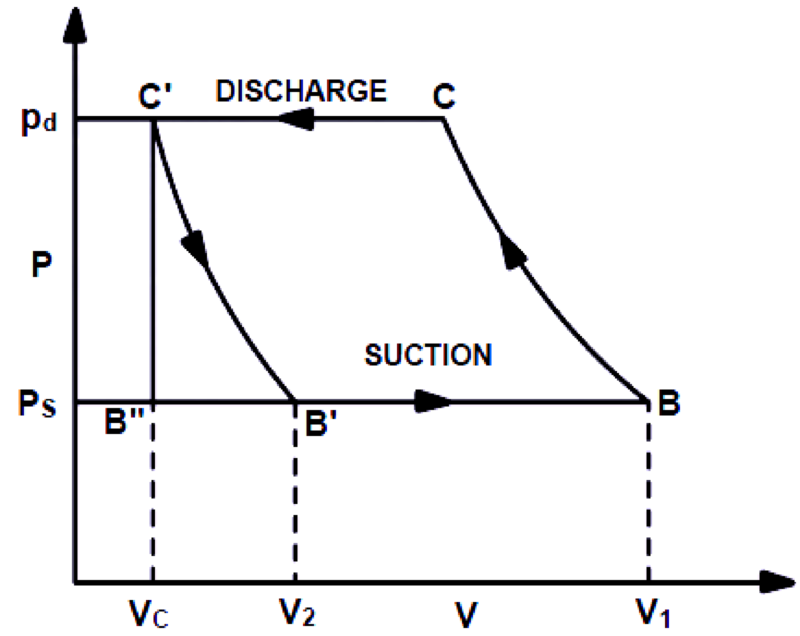
The refrigerating effect is reduced to: $(h_B - h''_A) < (h_B - h_A)$

increase in discharge pressure results in lower COP

Hence, the discharge pressure should be kept as low as possible depending upon the temperature of the cooling medium available

(e) Effect of Volumetric Efficiency of Compressor:

The factors like clearance volume, pressure drop through discharge and suction valves, leakage of vapour along the piston and superheating of cold vapour due to contact with hot cylinder walls, affects the volume of the vapour actually pumped by the compressor.



The volumetric efficiency of a compressor is defined as;

$$\eta_{vol} = \frac{\text{Actual mass of vapor drawn at suction conditions}}{\text{Theoritical mass that can be filled in the displacement volume}}$$

during suction stroke B"–B, the vapor filled in clearance space at pressure P_d expands along C'-B' and the suction valve opens only when the pressure has dropped down to P_S. Therefore, the actual amount of vapour sucked during the suction stroke is $(v_1 - v_2)$ while the stroke volume is $(v_1 - v_c)$.

decrease Volumetric efficiency decreases the refrigeration effect