Multi Stage Vapour compression Systems

Dr. M. D. Atrey

INOX Chair Professor

Department of Mechanical Engineering

Indian Institute of Technology Bombay

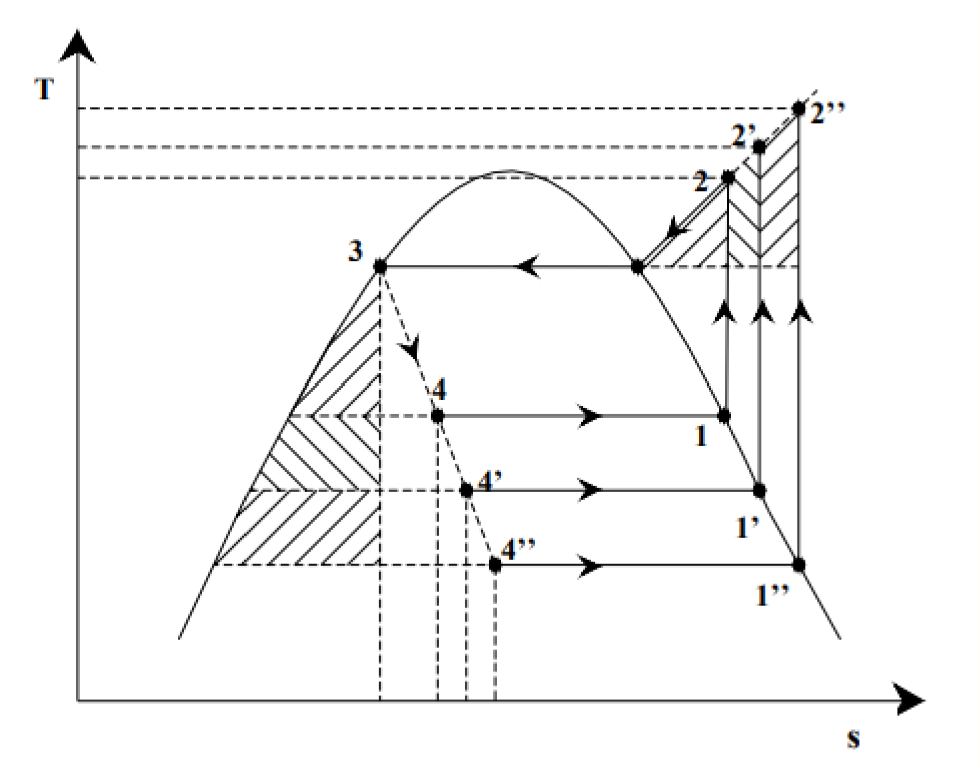
Mumbai – 400076

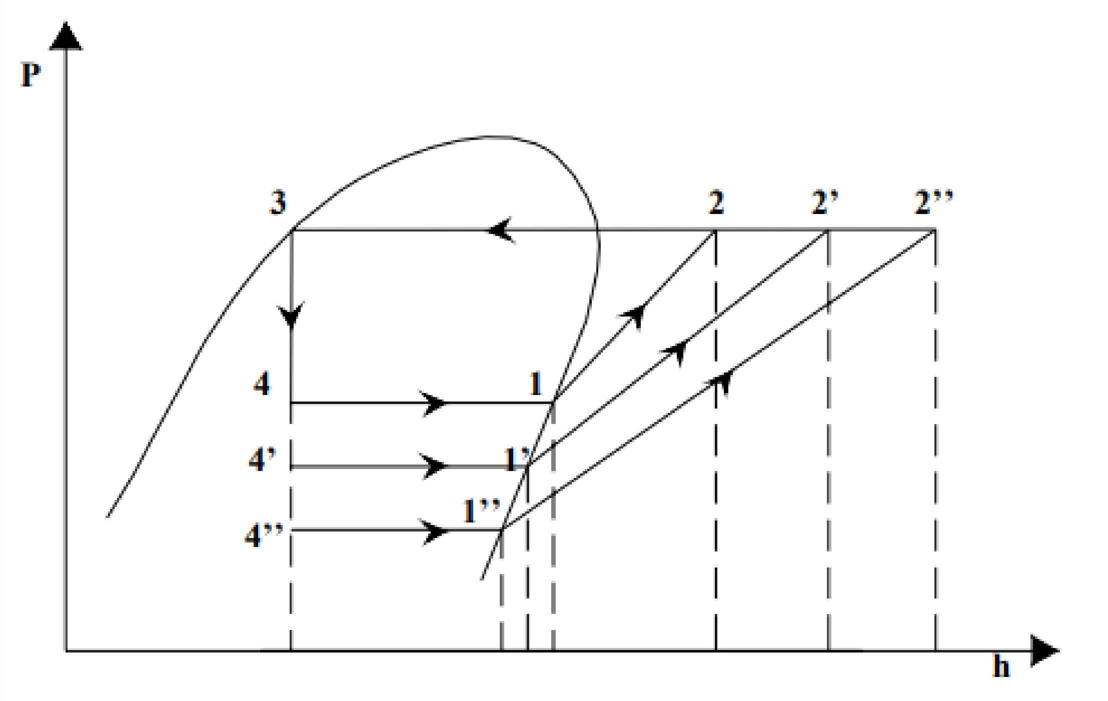
INDIA

Introduction

- Single stage systems are adequate as long as the temperature difference between evaporator and condenser is small. Many applications high temperature lift.
- The temperature lift can become large either due to the requirement of very low evaporator temperatures and/or due to very high condensing temperatures.
- Frozen food industries: -40°C or lower; Chemical industries: temperatures as low as -150°C for liquefaction of gases etc
- High condensing temperatures are required if the refrigeration system is used as a heat pump for heating applications such as process heating, drying etc.

Effect of evaporator temperature – As T_e decreases





Effect of evaporator temperature

- As temperature lift increases, single stage systems become inefficient.

- For a given T_c, as T_e decreases:

    Throttling and superheat losses increase

    Compressor exit temperature increases

    Amount of vapour at evaporator inlet increases

    Specific volume at compressor inlet increases

- COP, refrigeration capacity and life of compressor decrease rapidly

Effect of evaporator temperature

- Performance also degrades as condenser temperature increases
- Hence, single stage systems are not recommended when evaporator temperature becomes very low and/or condenser temperature becomes high
- In such cases multi-stage systems are used in practice

Multistage Refrigeration Systems

- A single stage system is used up to an evaporator temperature of -30°C
- A two-stage system is used up to -60°C
- A three-stage system is used for temperatures below -60°C
- Multi-stage systems are also used in applications requiring refrigeration at different temperatures

Multistage requirement

- Applications requiring refrigeration at different temperatures
- Example: in a dairy plant refrigeration may be required at -30°C for making ice cream and at 2°C for chilling milk
- In such cases it may be advantageous to use a multi-evaporator system with the low temperature evaporator operating at -30°C and the high temperature evaporator operating at 2°C

Multistage VCRS

- A multi-stage system is a refrigeration system with two or more low-side pressures

- Multi-stage systems can be classified into:

  a) Multi-compression systems

  b) Multi-evaporator systems

  c) Cascade systems, etc.

Two Concepts

- Flash Gas Removal
- Intercooling

Flash gas

- Flash gas is the vapour formed during throttling of refrigerant liquid in expansion device.

- The flash gas:

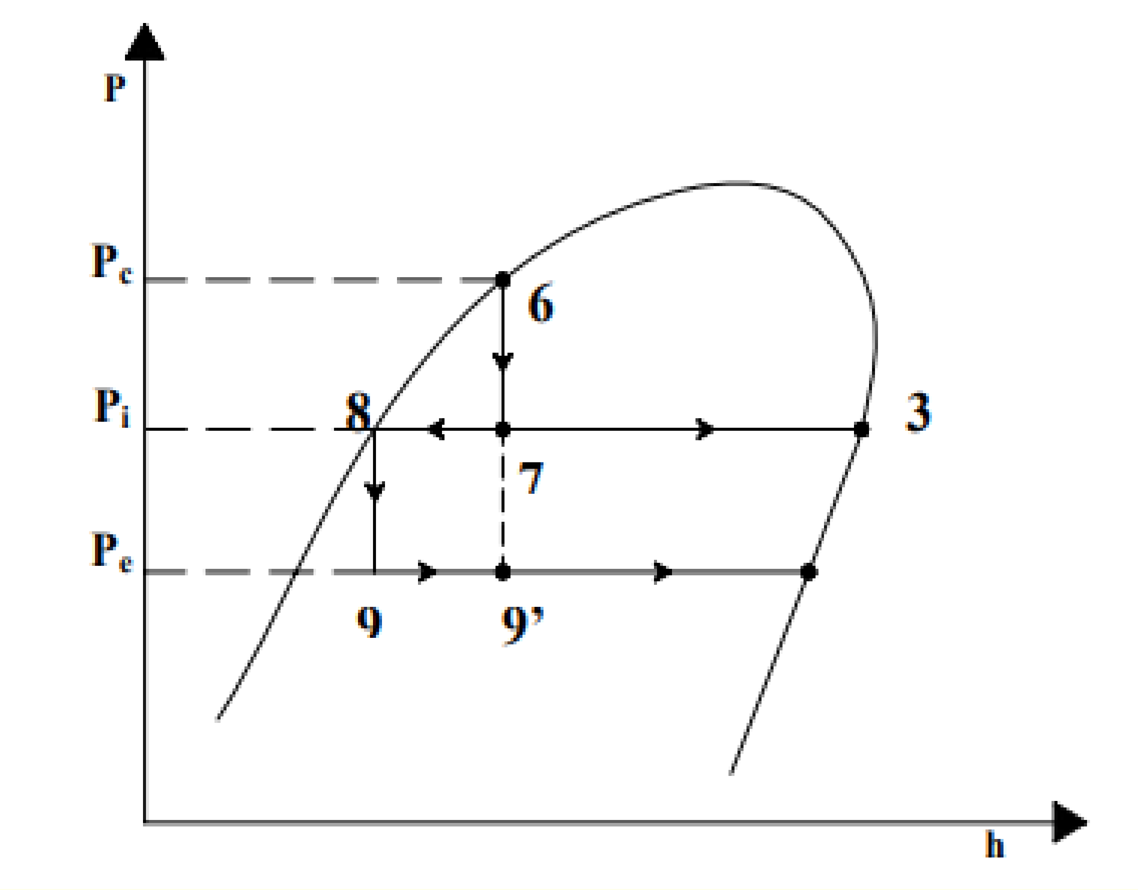
  a) Has to be compressed to condenser pressure

  b) It does not contribute to the refrigeration effect as it is already a vapour, and

  c) It increases the pressure drop in the evaporator

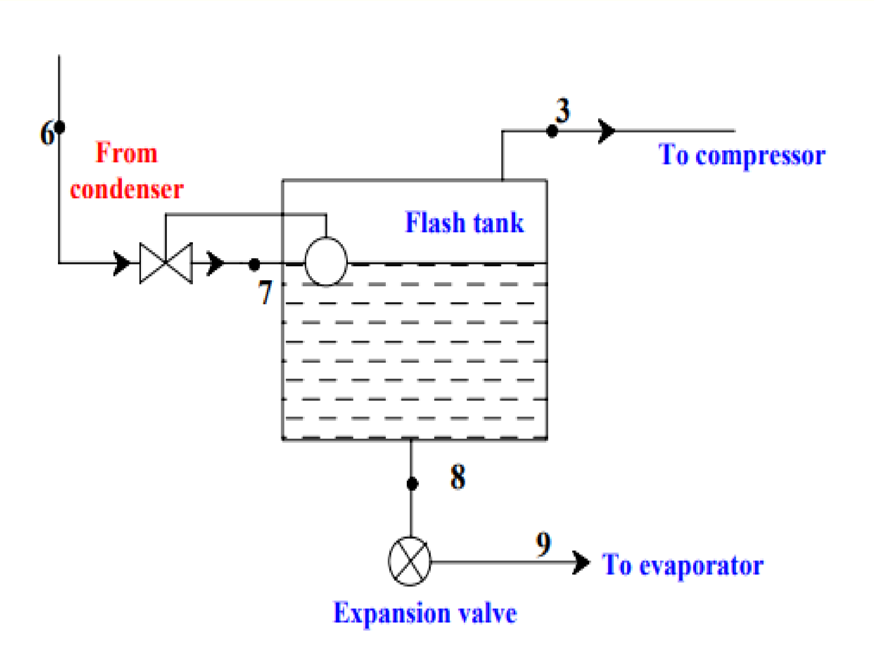
Flash gas removal

- Performance can be improved if the flash gas is removed as soon as it is formed and recompressed to condenser pressure
- However, continuous removal of flash gas as soon as it is formed and recompressing it immediately is difficult in practice.
- A practical way is to remove the flash gas at an intermediate pressure using a flash tank



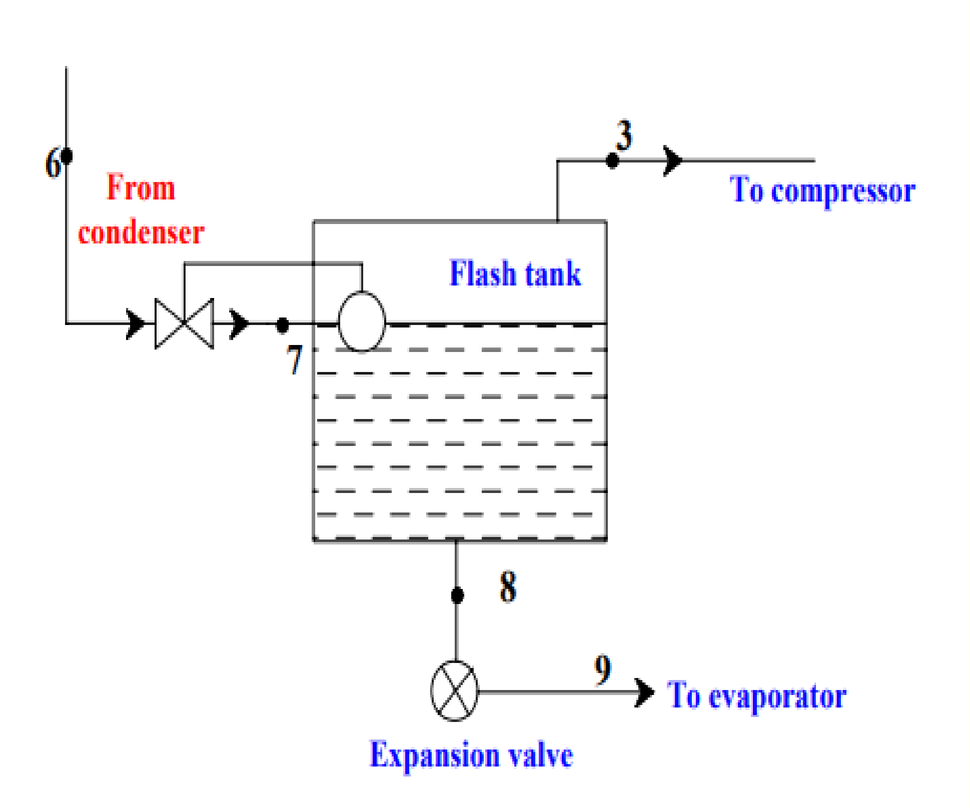
Flash gas removal – Flash tank

- A flash tank is a pressure vessel in which the refrigerant liquid and vapour are separated at an intermediate pressure
- Refrigerant from condenser is first expanded to an intermediate flash tank pressure using a low side float valve
- Upward velocity of refrigerant vapour in flash tank should be low (< 1 m/s) to avoid liquid droplet carry-over.



Flash gas removal – Flash tank

- Float valve maintains a constant liquid level in the flash tank
- Refrigerant liquid and vapour are separated in the flash tank
- Saturated liquid from flash tank is fed to the evaporator after throttling it to the required evaporator pressure



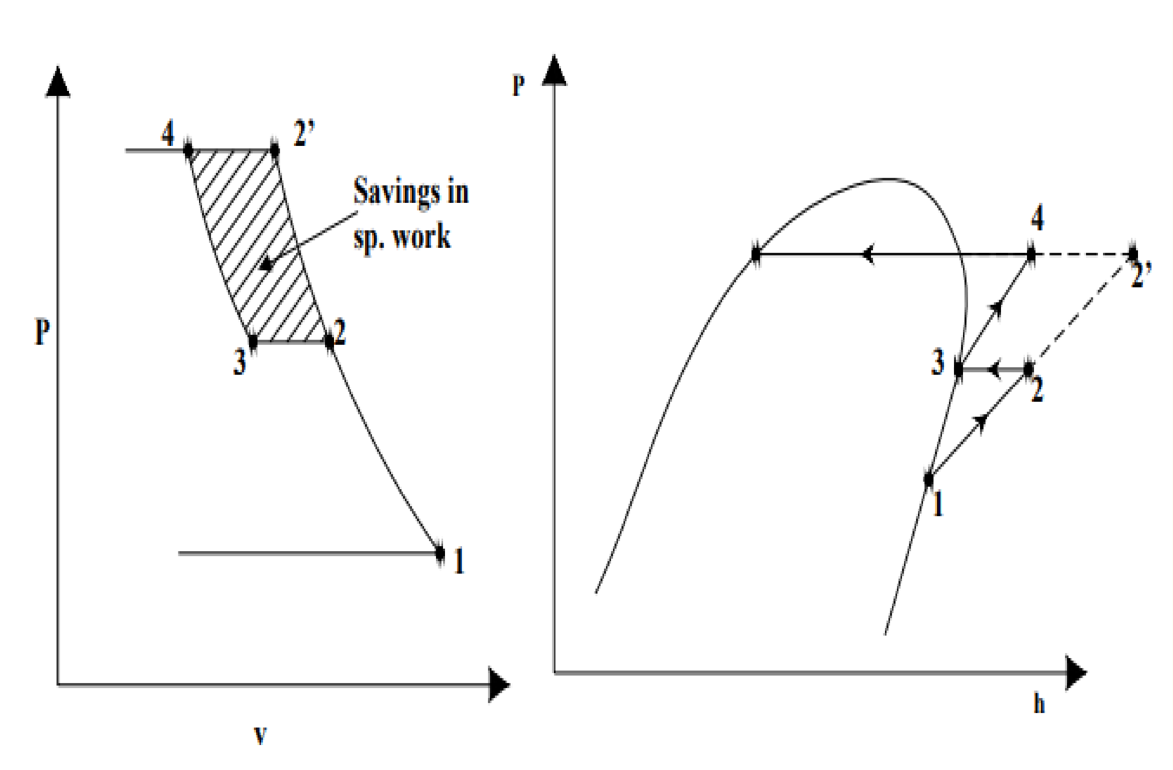
Selection of optimum intermediate pressure

- For two-stage compression of ideal gases with perfect intercooling:

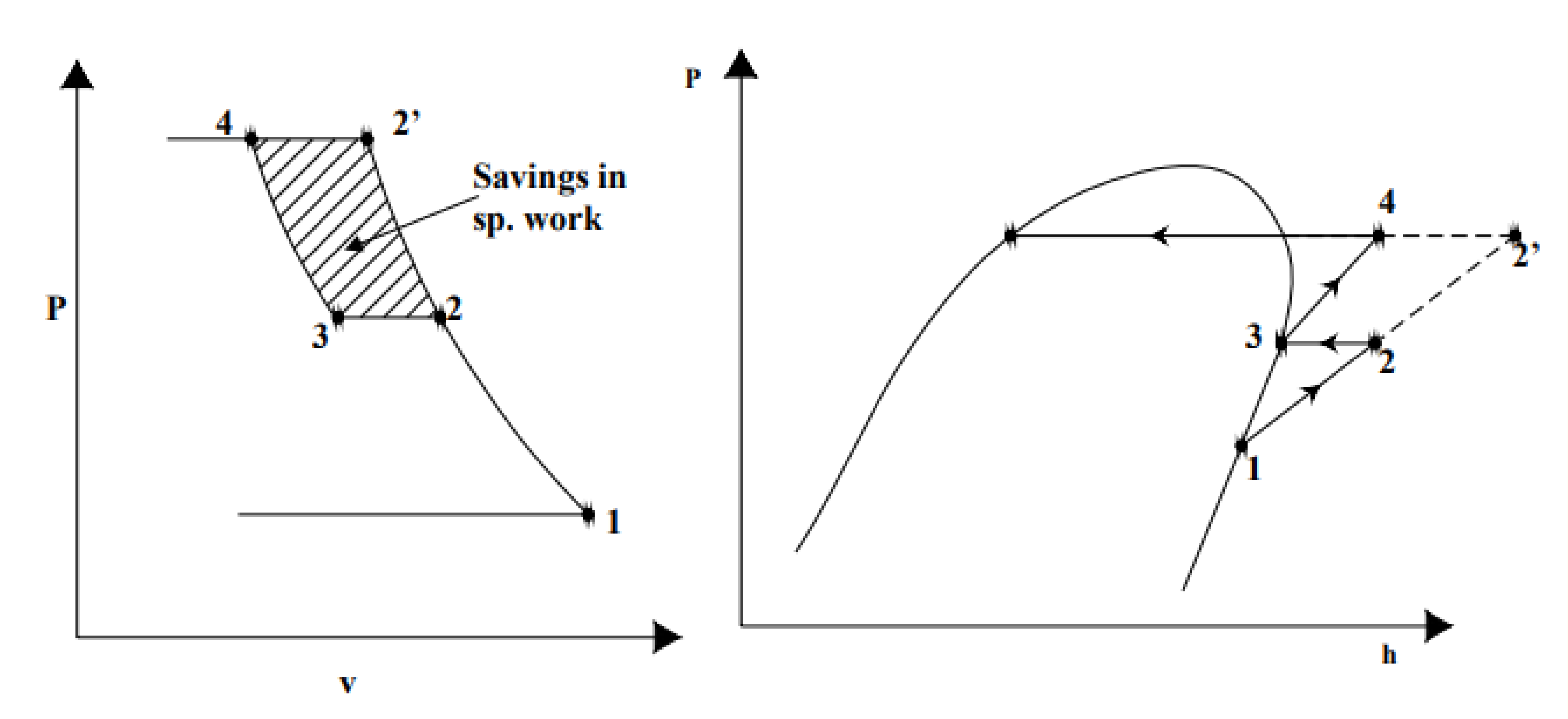
$$P_{i,opt} = \left(P_{low}\, P_{high}\right)^{1/2}$$

- For refrigerant vapours,

$$P_{i,opt} = \left[(P_e P_c).\left(\frac{T_c}{T_e}\right)\right]^{1/2}$$



Intercooling in two stage compression



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Intercooling in multi-stage compression

- The specific work input, w in reversible, polytropic compression is given by

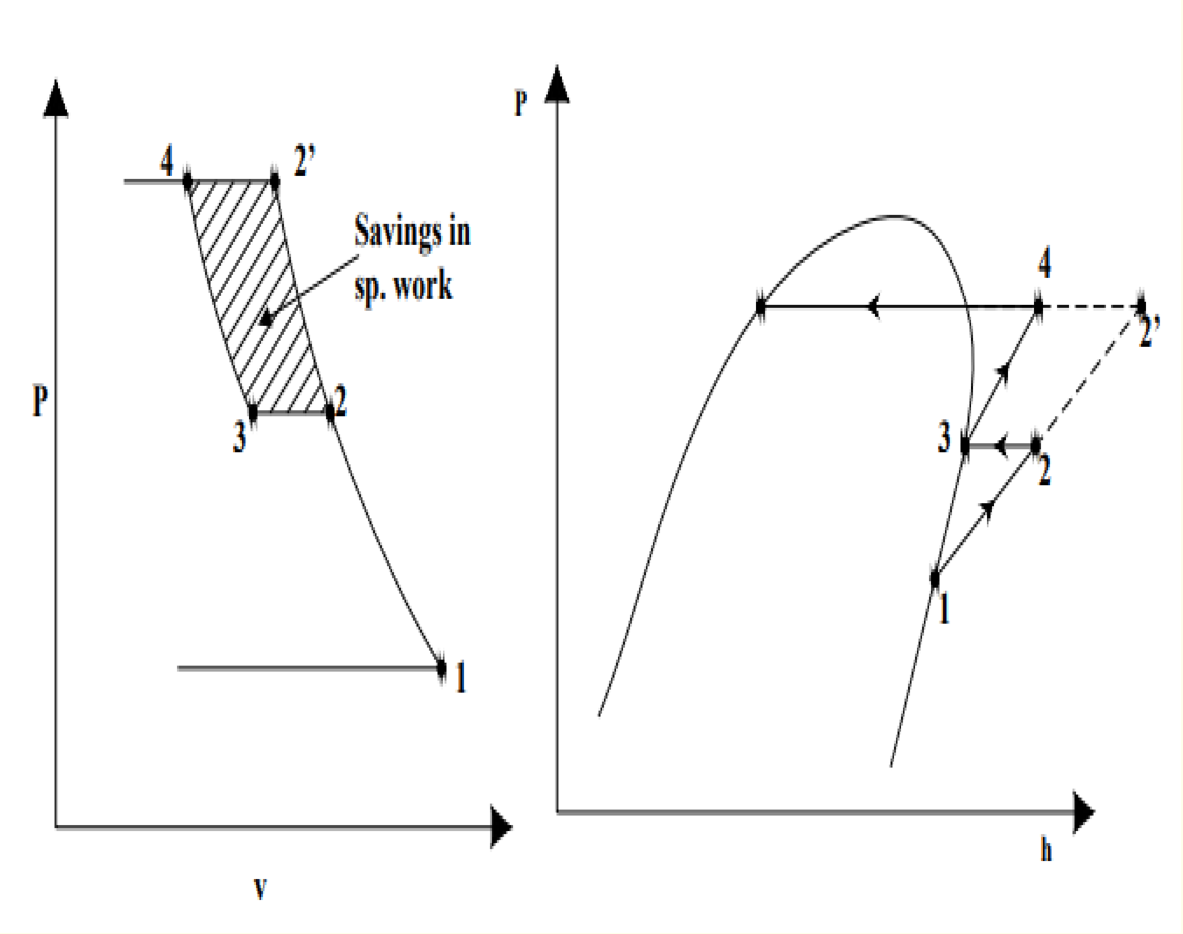
- $w = -\int_1^2 v \cdot dP = \left(\frac{n}{n-1}\right) P_1 v_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{(n-1)/n}\right]$

- Work input reduces if specific volume at compressor inlet, v_1 is reduced by intercooling. This can be verified easily by using P-v and P-h diagrams

Intercooling in multi-stage compression

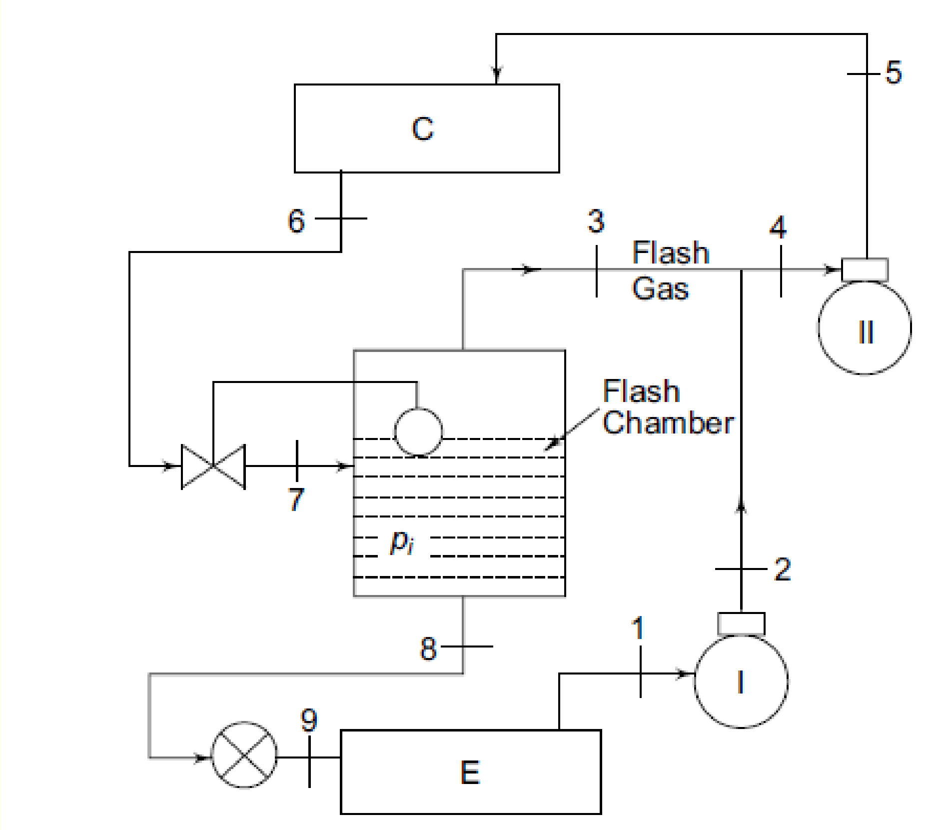
- Intercooling not only reduces the work input but also reduces the compressor discharge temperature

- Intercooling of the vapour may be achieved by using:
    a) A water-cooled heat exchanger
    b) Refrigerant in the flash tank, or
    c) A combination of both



Flash Gas Removal

- In compound compression the throttling expansion of the liquid is carried in stages.
- Liquid from condenser expands first in the flash chamber at *Pi*. Liquid at 8 again expands and enters the Evaporator.

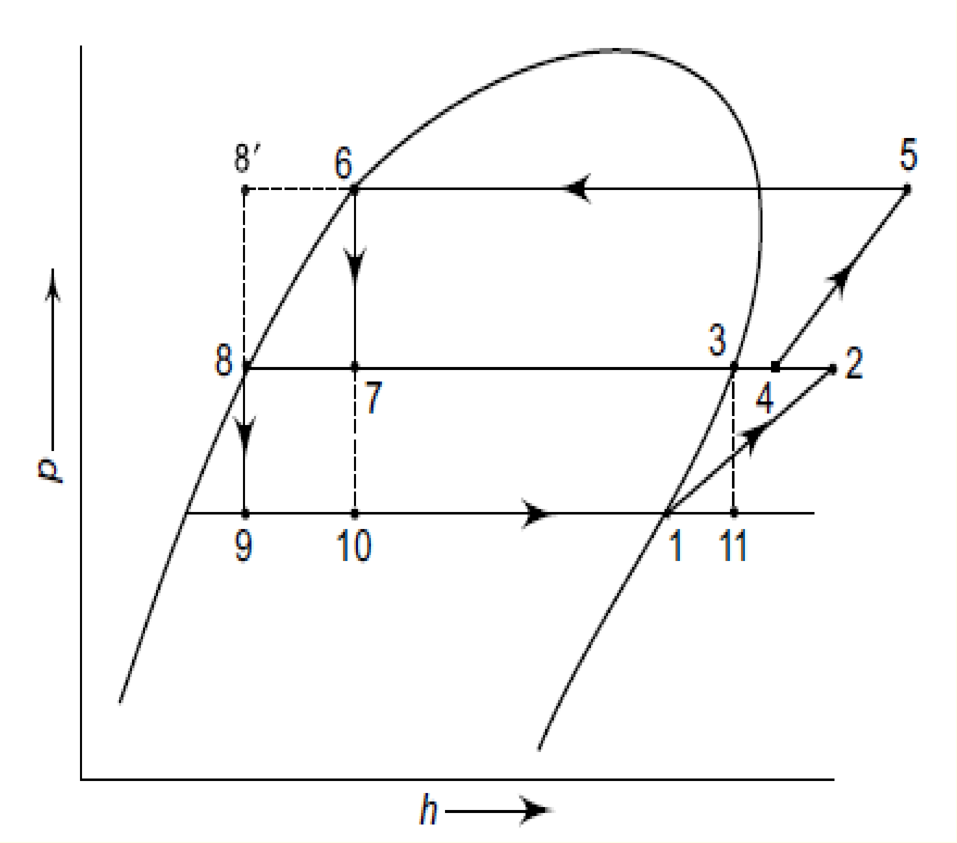


Flash Gas Removal

- In a system without a flash chamber, the liquid from the condenser expands straight to the evaporator pressure (6-10) and vapour flashed at the intermediate pressure also gets throttled to evaporator pressure and needs to be recompressed to *Pi*.

- System with a flash chamber, eliminates this throttling of the vapour generated at the intermediate pressure *p*.

- This system, therefore, results in power economy.

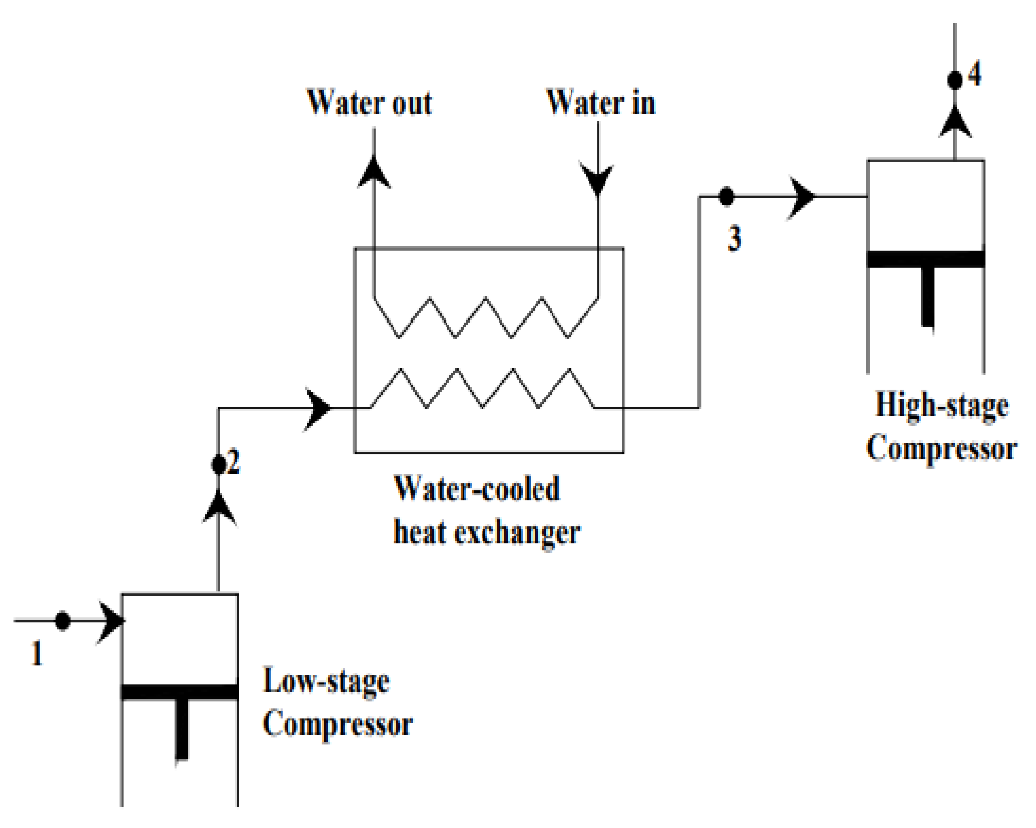


Intercooling using external water cooled heat exchanger

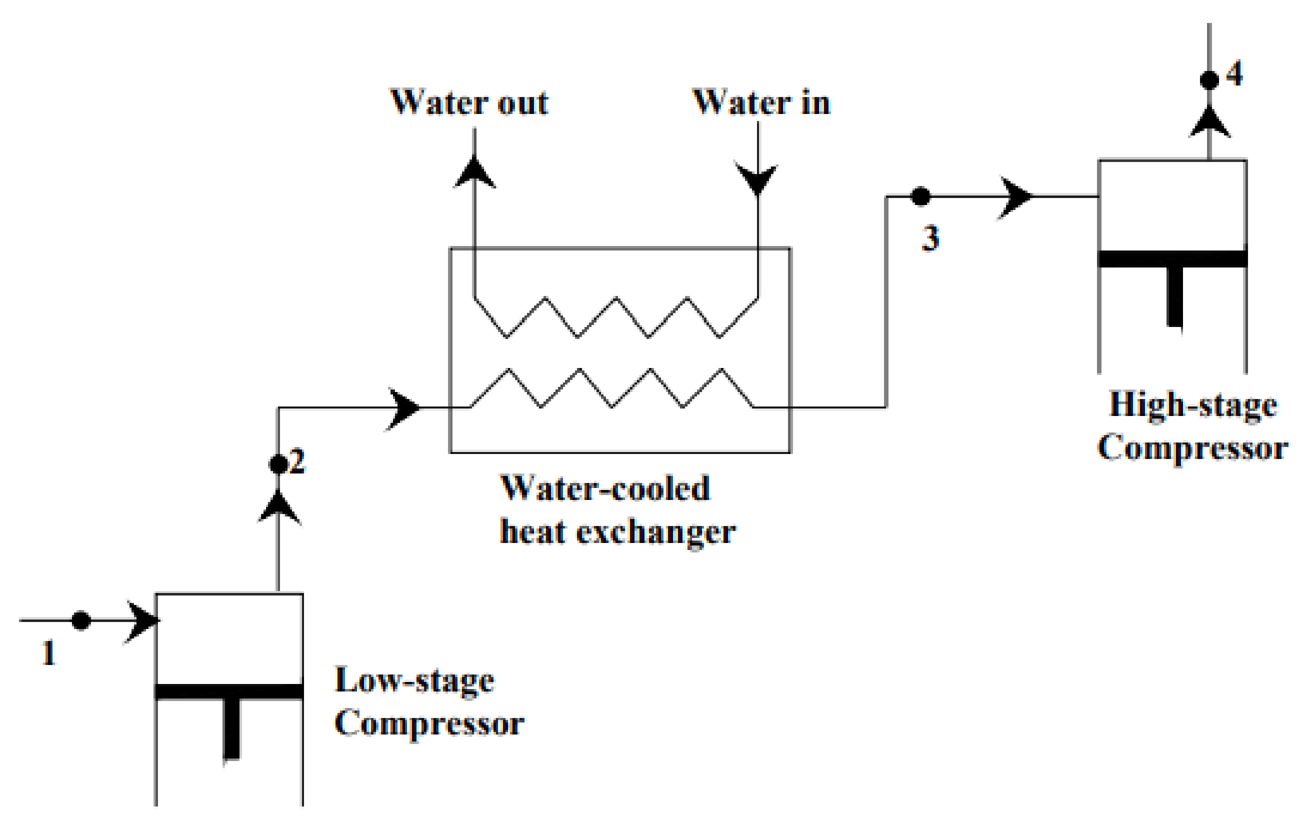
- Intercooling may not always be possible using water-cooled heat exchangers as it depends on the availability of sufficiently cold water to which the refrigerant from low stage compressor can reject heat

- Moreover, with water cooling the refrigerant at the inlet to the high stage compressor may not be saturated

- Water cooling is commonly used in air compressors



Intercooling using external water cooled heat exchanger



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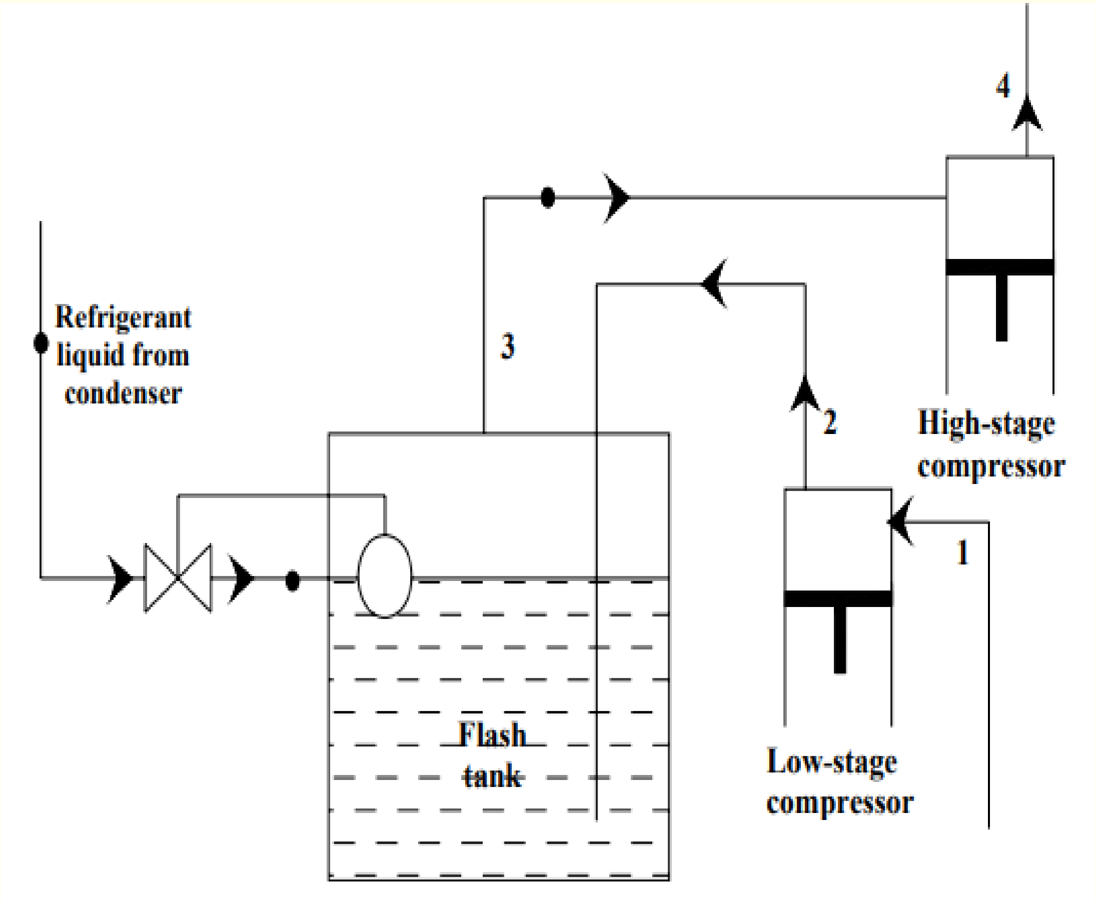
Intercooling using liquid refrigerant in flash tank

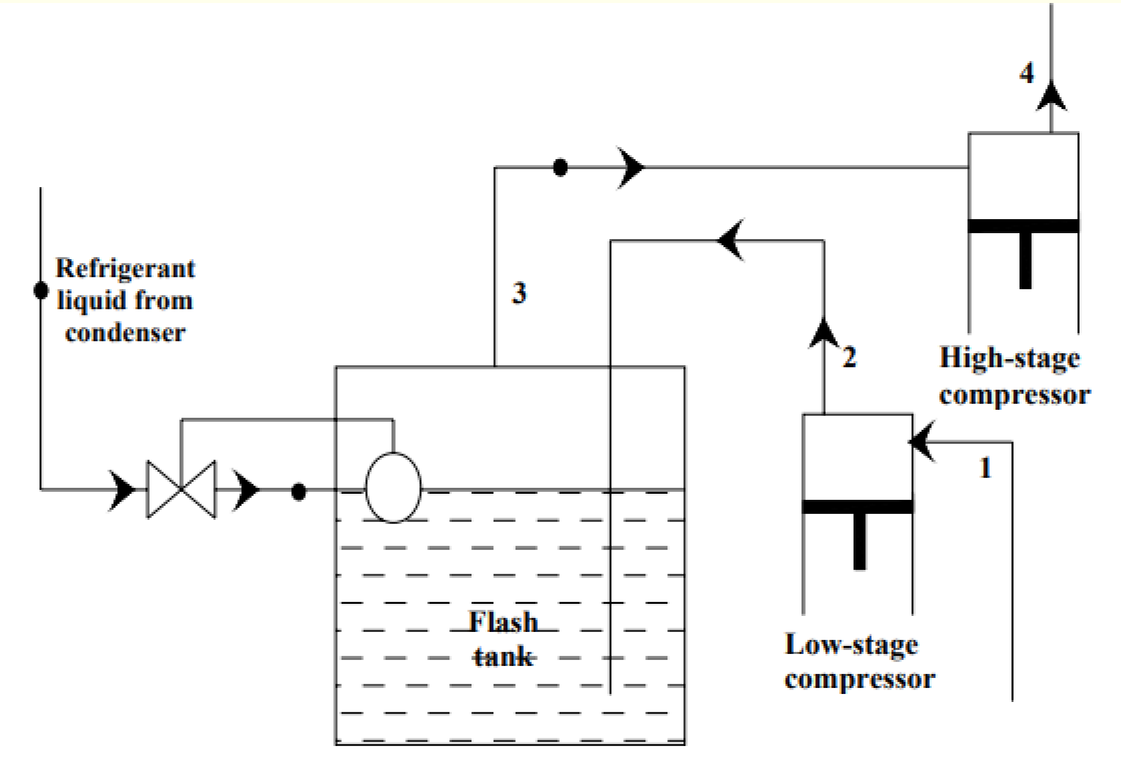
- Intercooling using liquid refrigerant in the flash tank may or may not reduce the power input to the system

- Because heat rejected by the refrigerant during intercooling generates additional vapour in the flash tank, which has to be compressed by the high stage compressor

- Thus mass flow rate through high-stage compressor will be more than flow rate through low-stage compressor



Intercooling using liquid refrigerant in flash tank



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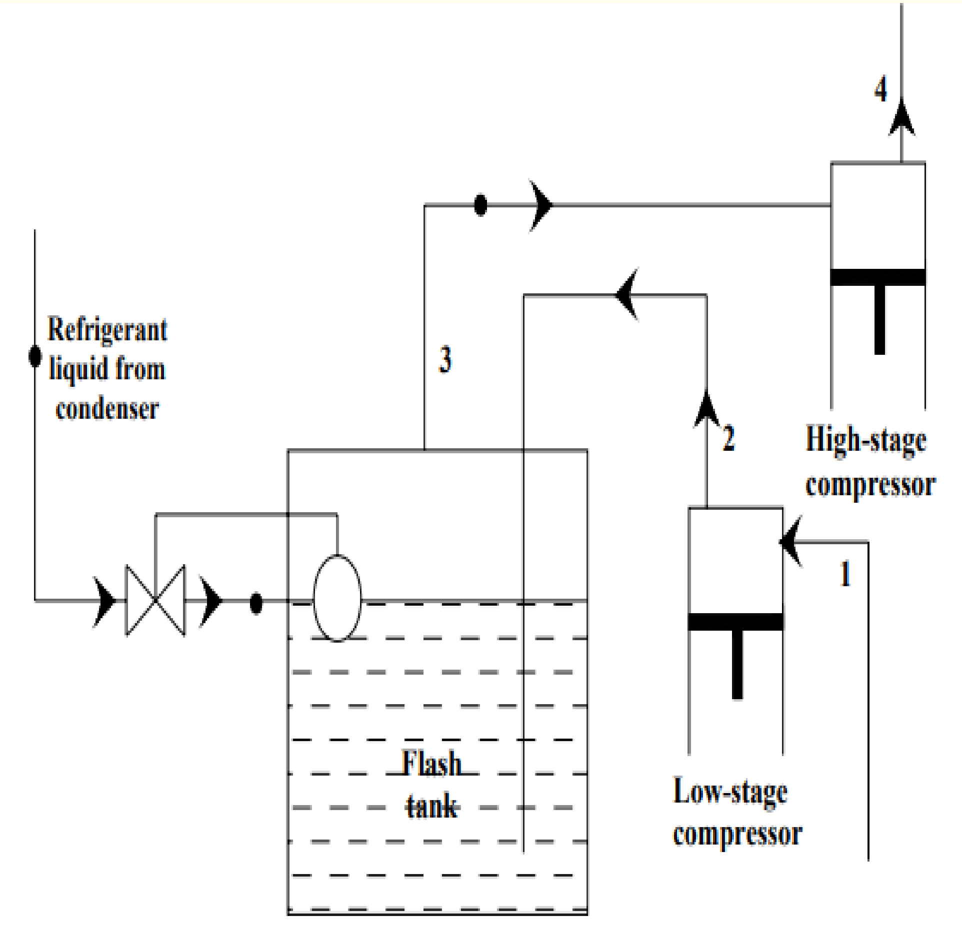
Intercooling in multi-stage compression

- Total power input to the system decreases or not depends on whether the increased power consumption due to higher mass flow rate is compensated by reduction in specific work of compression or not.

- For ammonia, the power input usually decreases with intercooling by liquid refrigerant.

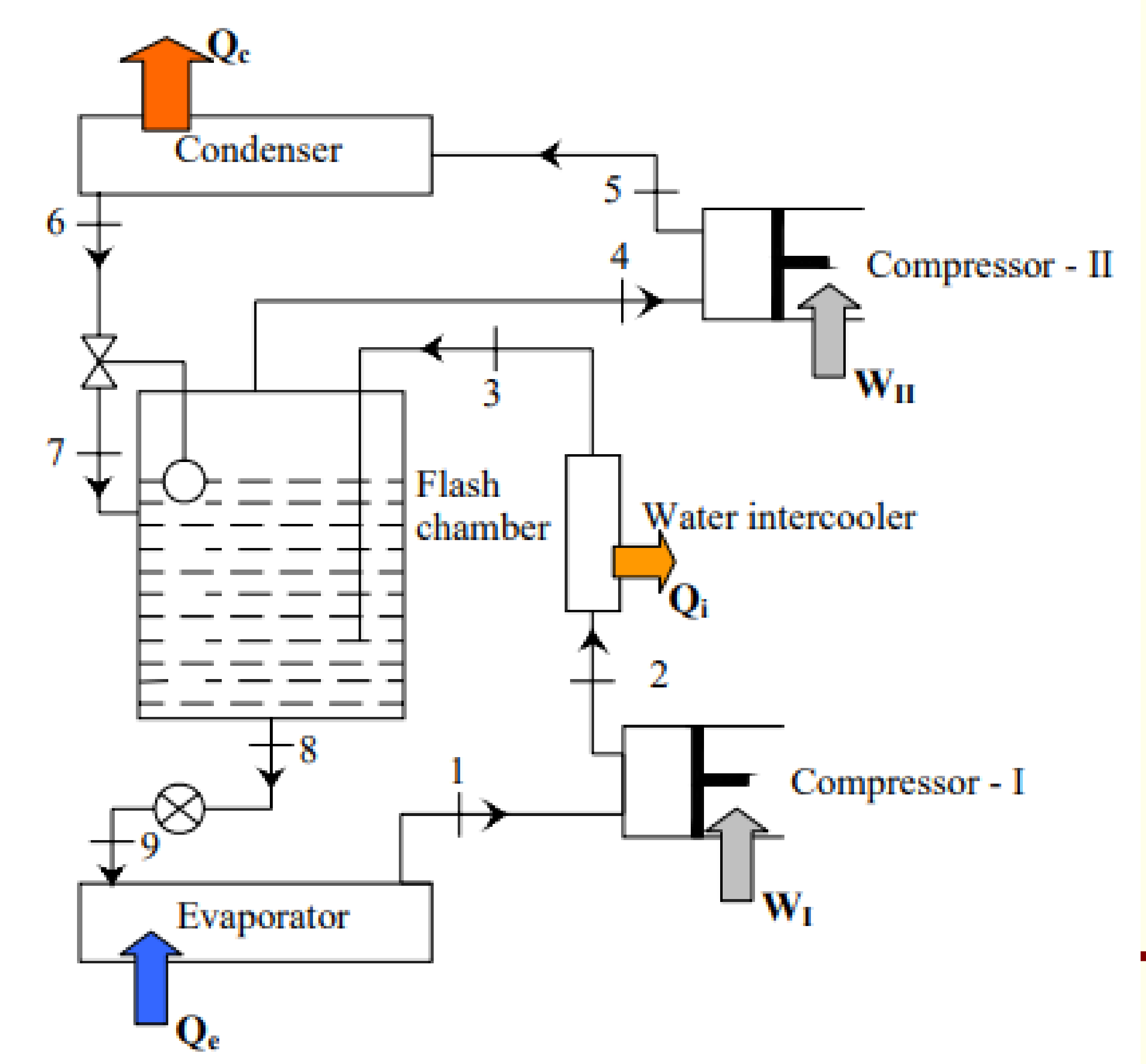
- For refrigerants such as R12, R22, the power input marginally increases with refrigerant liquid intercooling

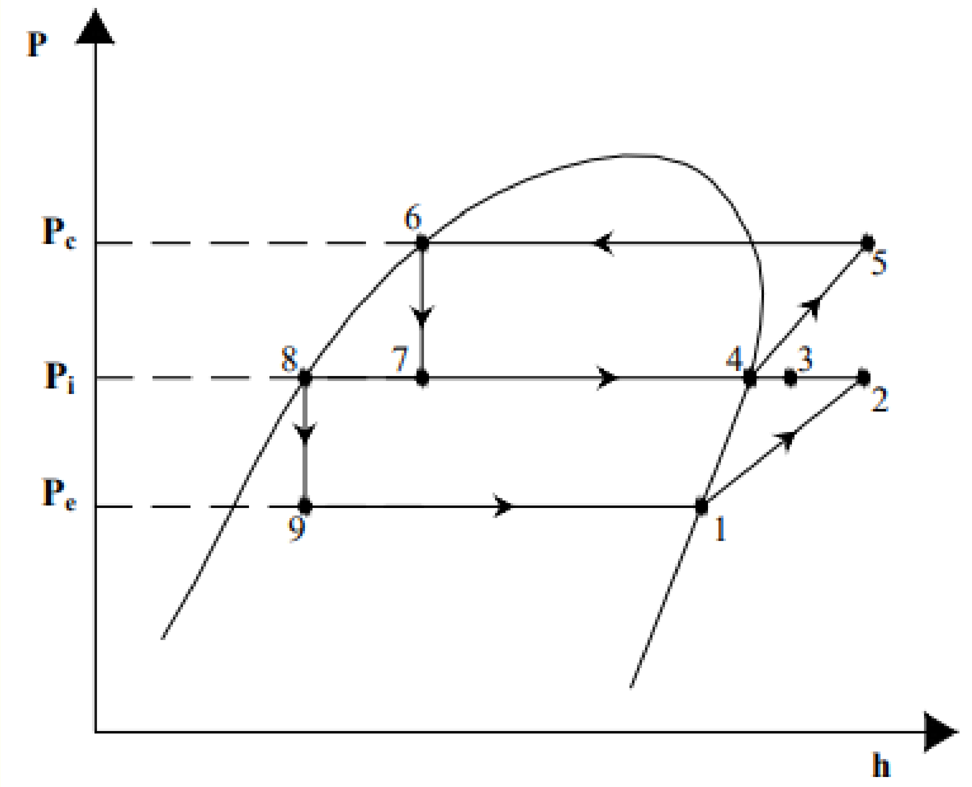


Multi-stage system with flash gas removal & intercooling

- The system uses a combination of water cooling and flash intercooling
- The superheated vapour from the water cooled heat exchanger bubbles through the refrigerant liquid in the flash tank
- It is assumed that the vapour at the exit of flash tank is saturated
- Steady state performance is obtained by applying mass and energy balance across each component

Multi-stage system with flash gas removal & intercooling





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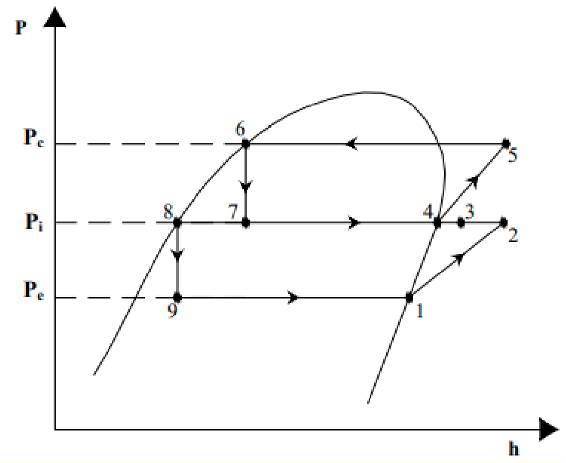
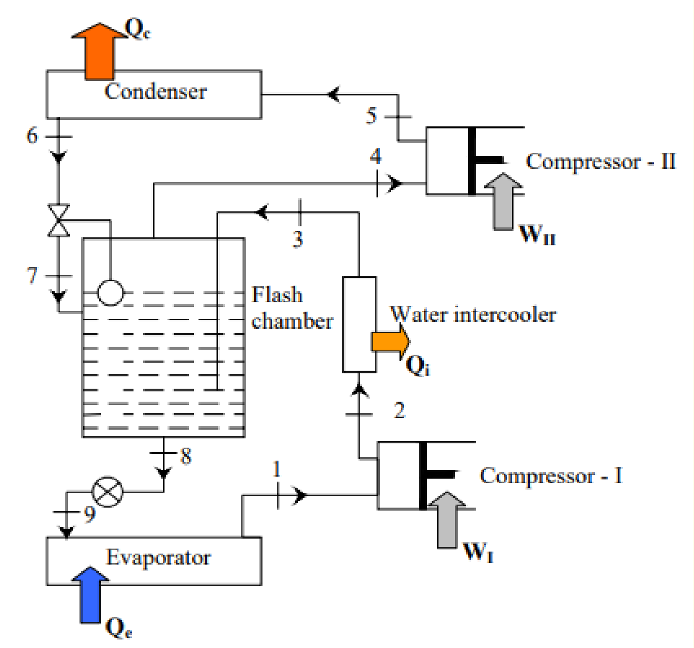
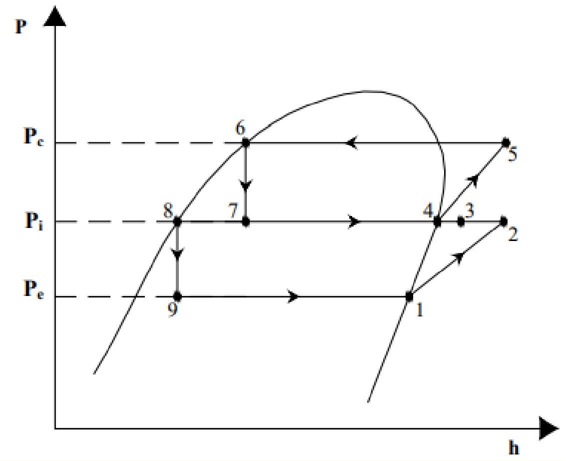
Multi-stage system with flash gas removal & intercooling

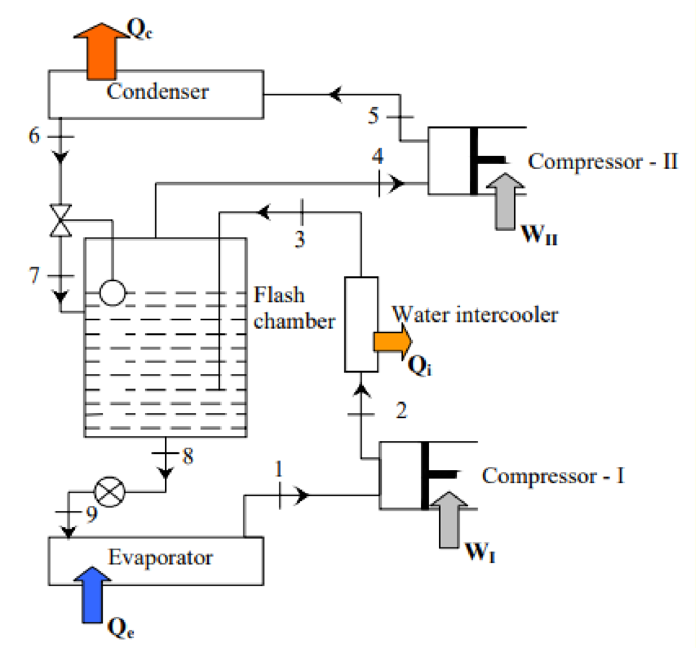




- Flash tank: Mass and Energy Balance
- $m_7 + m_3 = m_8 + m_4$
- $m_7 h_7 + m_3 h_3 = m_8 h_8 + m_4 h_4$
- $m_8 = m_9 \quad ; \quad h_8 = h_9$
- Evaporator: $m_9 = m_1$
- $Q_e = m_1(h_1 - h_9)$

Multi-stage system with flash gas removal & intercooling



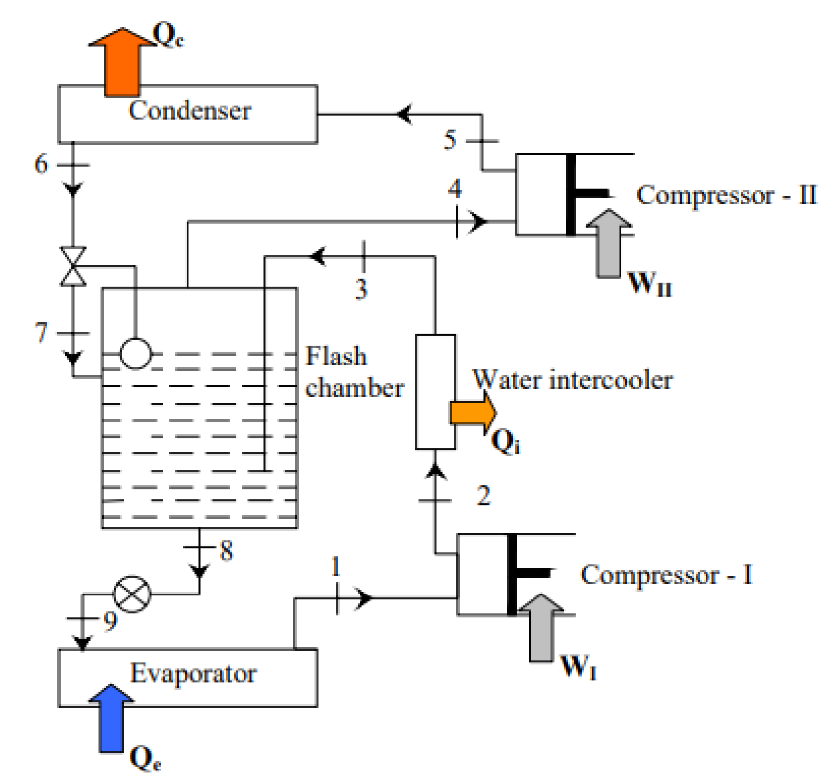


- Float valve : $m_6 = m_7 = m_{II}$
- $h_6 = h_7$

- From above equations

- $m_7 = m_4 = m_{II}$
- $m_3 = m_8 = m_I$

Multi-stage system with flash gas removal & intercooling



$m_{II}h_7 + m_I h_3 = m_I h_8 + m_{II} h_4$

- $m_{II} = m_I \left[\frac{h_3 - h_8}{h_4 - h_7}\right]$

- Amount of additional vapor generated in flash tank due to de-superheating of refrigerant vapour

- $m_{gen} = m_I \left[\frac{h_3 - h_4}{h_4 - h_8}\right]$

- $COP = \frac{Q_e}{W_I + W_{II}} = \frac{m_I(h_1 - h_9)}{m_I(h_2 - h_1) + m_{II}(h_5 - h_4)}$

Advantages

- Quality of refrigerant at evaporator inlet reduces leading to lower pressure drop and better heat transfer in the evaporator
- Throttling losses are reduced as vapour generated is separated in the flash tank and recompressed by Compressor-II
- High compressor volumetric efficiency due to reduced pressure ratios
- Considerably reduced compressor discharge temperatures

Disadvantages

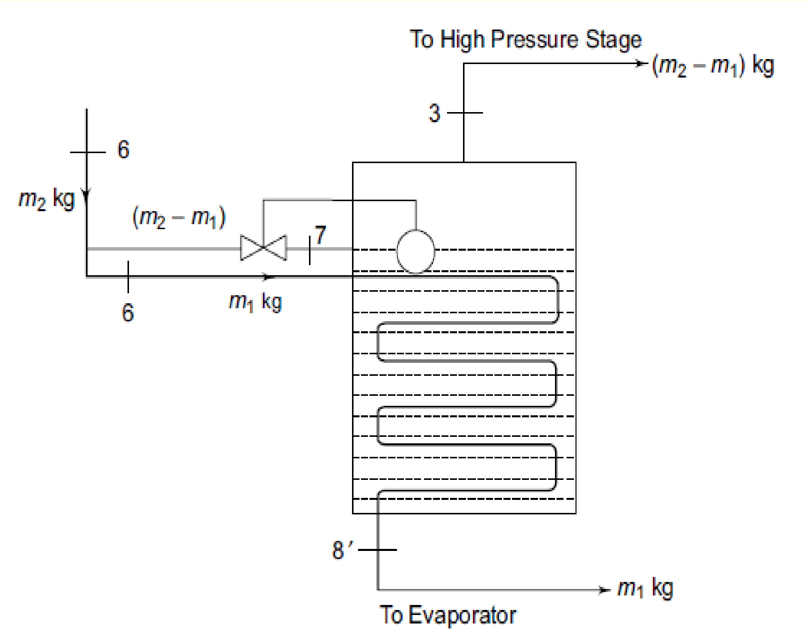
- However, since refrigerant liquid in the flash tank is saturated, there is a possibility of liquid flashing ahead of the expansion valve due to pressure drop or heat transfer in the pipelines

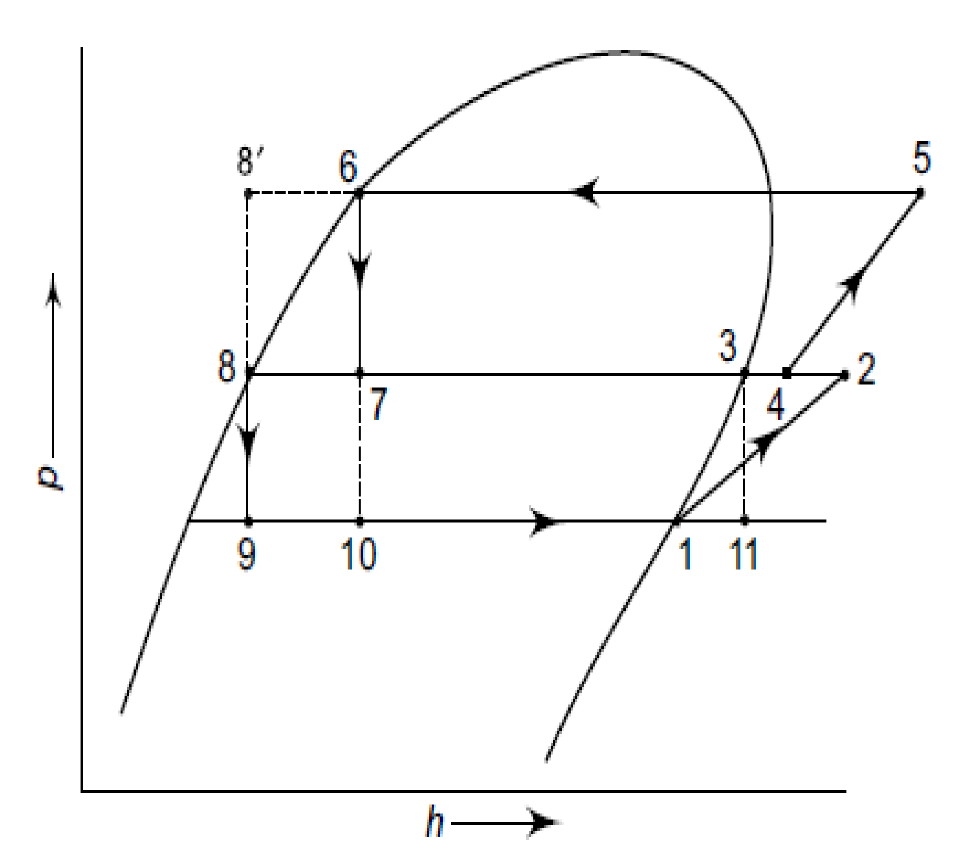
- Sometimes a liquid subcooler is used as an alternative to prevent vapour entry into expansion device

- Due to subcooling in flash tank, a small amount of vapour is generated in flash tank, which has to be recompressed

Flash Chamber as a Liquid Subcooler

- The liquid subcooler subcools the liquid by the evaporation of the liquid refrigerant in the flash chamber.

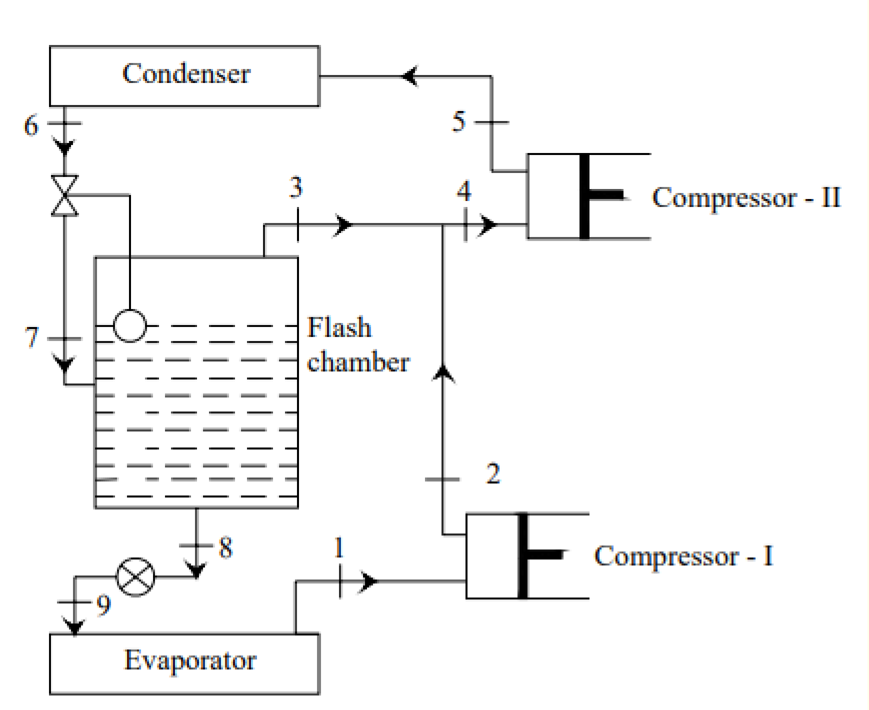


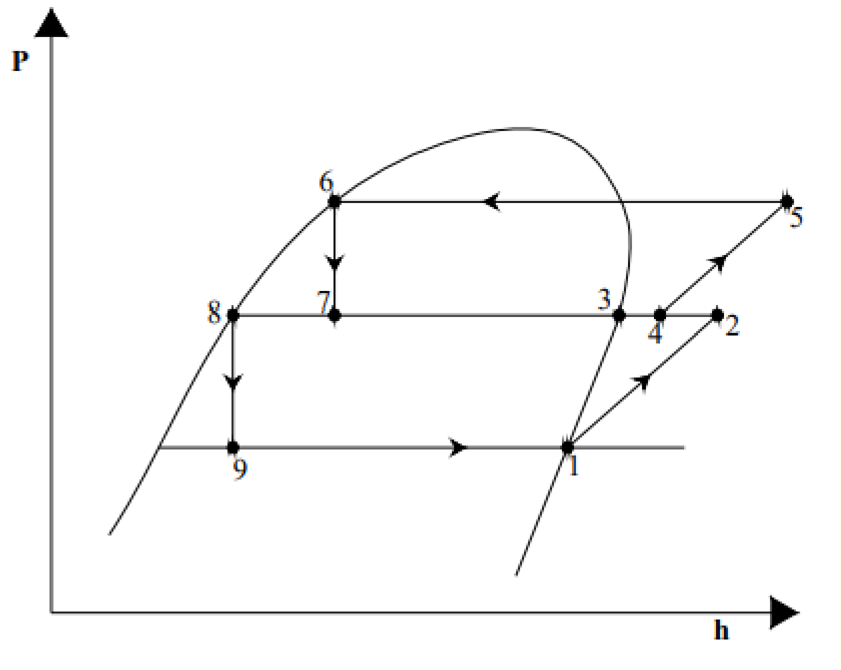


Advantages & disadvantages

- Intercooling using water-cooled heat exchangers is possible in ammonia systems due to high discharge temperature of ammonia
- However, this is generally not possible in R 12 systems due to low discharge temperatures
- In R12 systems, vapour from flash tank is mixed with vapour coming from low-stage compressor (flash tank intercooling is not generally used as it increases power input)
- The inlet condition to the high stage compressor will be slightly superheated.

Intercooling in R12 systems





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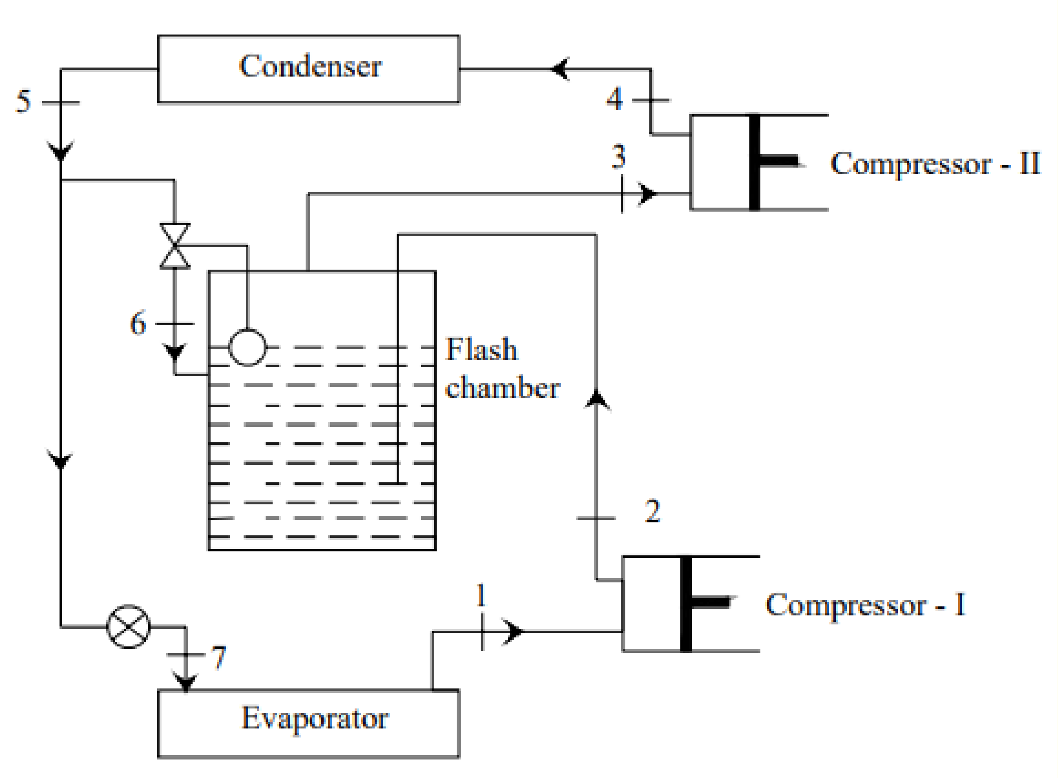
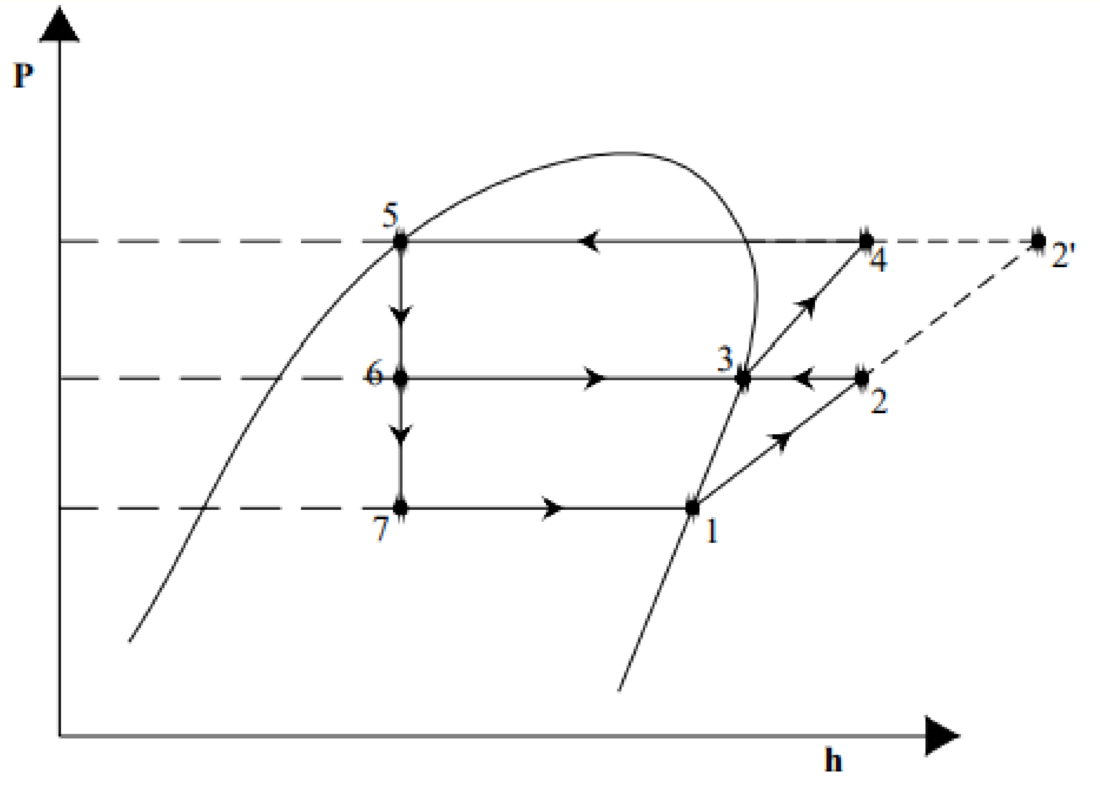
Use of flash tank for intercooling alone

- Sometimes the flash tank is used for intercooling of the refrigerant only, it is not used for flash gas removal
- Flash tank for intercooling alone can be used in ammonia systems as it reduces the power input
- It is not used in R 12 systems
- Flash gas removal is desirable for all systems, whereas flash intercooling is good for certain refrigerants only

Use of flash tank for intercooling alone





An ammonia refrigerating plant is working at an evaporating temperature of -30°C and a condensing temperature of 37°C. There is no subcooling of the liquid refrigerant, and the vapour is in dry saturated condition at the inlets to the compressors. The capacity is 150kW refrigeration. Estimate the power consumption

1. When one stage is used
2. When two stage compression with flash intercooling is used, and
3. When two stage compression with flash chamber as liquid subcooler use. Assume suitable intermediate pressure.

1. When one stage is used

From property table

$$h_1 = 1422 \cdot 8kJ/kg \qquad s_1 = 6.0636kJ/kg \cdot k$$

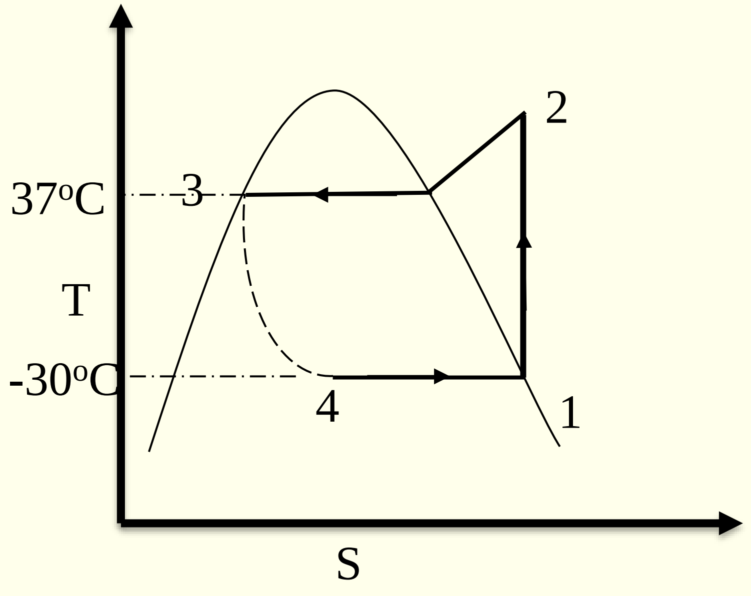
$$h_3 = h_4 = 375.9kJ/kg$$

By extrapolation from superheat table of ammonia

$$h_2 = 1803.9kJ/kg$$

$$\dot{m}=\frac{150}{(h_1-h_4)} = 0.1432\frac{kg}{s}$$

W= $\dot{m}(h_2 - h_1)$=54.6 kW



2. When two stage compression with flash intercooling

Intermediate pressure

$$P_{int} = \sqrt{P_1 P_4} = \sqrt{1.1990 * 14.314} = 4.1427\ bar$$

$$h_2 = 1589.4 kJ/kg$$

$$h_3 = 1460.6 kJ/kg$$

$$h_4 = 1637.48 kJ/kg$$

$$h_5 = h_6 = h_7 = 375.9 kJ/kg$$

Compressor work = $m_1(h_2-h_1)+m_2(h_4-h_3)$

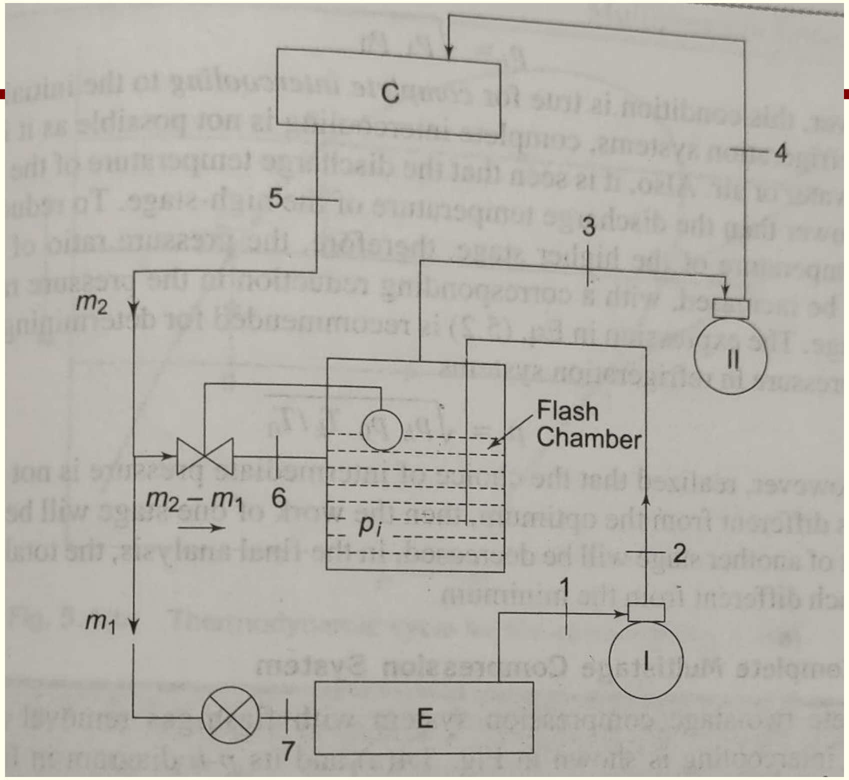
Energy balance at flash intercooler

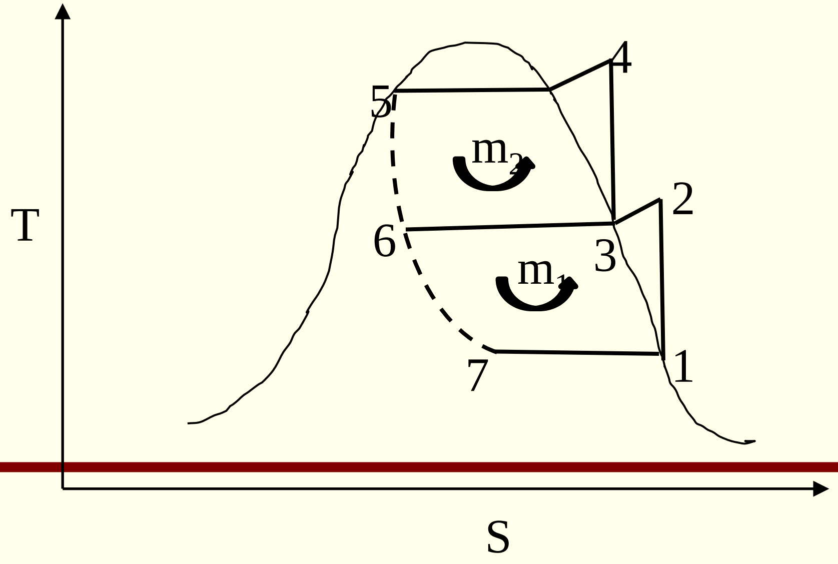
$$m_1 h_2 + (m_2 - m_1) h_6 = m_2 h_3$$

$$m_1 (h_1 - h_7) = 150$$

Which gives $\dot{m}_1 = 0.14328 kg/s$ $\quad$ $\dot{m}_2 = 0.16403 kg/s$

Putting these values $w = 52.22 kw$





3. When two stage compression with flash chamber as subcooler

$$h_5 = h_6 = h_7 = 375.9kJ/kg$$

$$T_{in} = -1^0C \ corresponding \ to \ P_{int} = 4.1427 \ bar$$

$$h_6 = h_5 = h_7 = 195.4kJ/kg$$

$$h_2 = 1589.4kJ/kg \qquad h_3 = 1460.6kJ/kg$$

$$h_4 = 1637.48kJ/kg \qquad h_a = h_b = 375.9kJ/kg$$

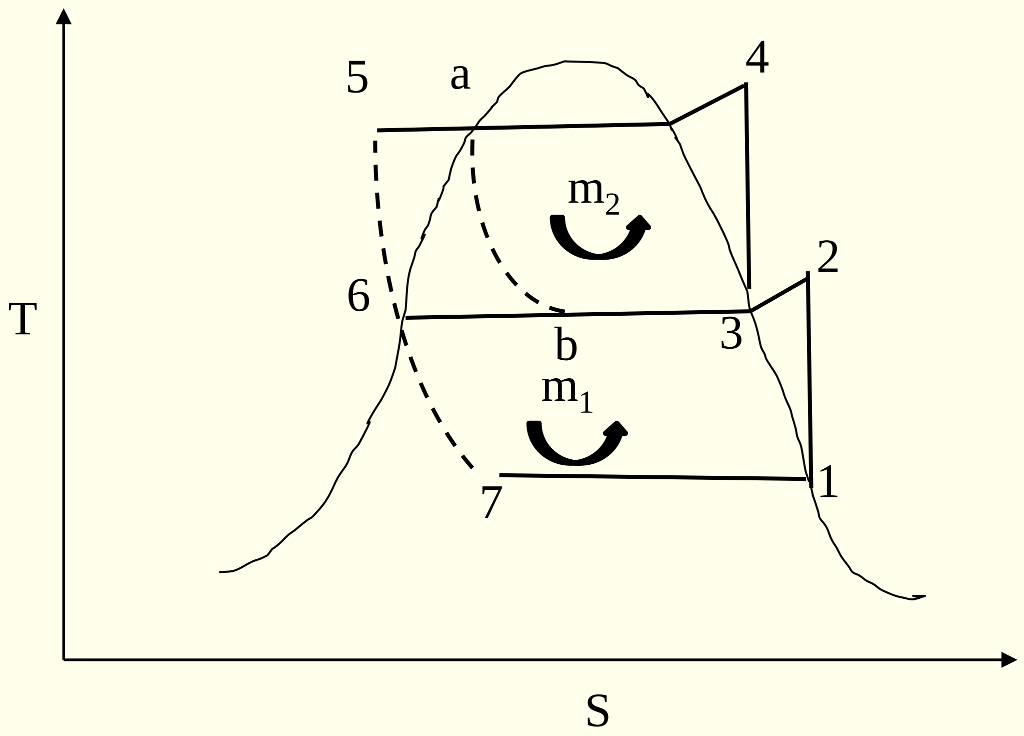
Energy balance at flash chamber as subcooler

$$m_1(h_a - h_5) + m_1(h_2 - h_3) = (m_2 - m_1)(h_3 - h_b)$$

$$m_1(h_1 - h_7) = 150$$

Which gives $m_1 = 0.122\text{kg/s}$ $\quad m_2 = 0.157\text{kg/s}$

Compressor work = $m_1(h_2-h_1)+m_2(h_4-h_3)$=48.11kW



Multi Evaporator systems

- There are many applications where refrigeration is required at different temperatures.
- For example, in a typical food processing plant,
- cold air may be required at -30°C for freezing, and
- at +7°C for cooling of food products or space cooling

Multi Evaporator systems

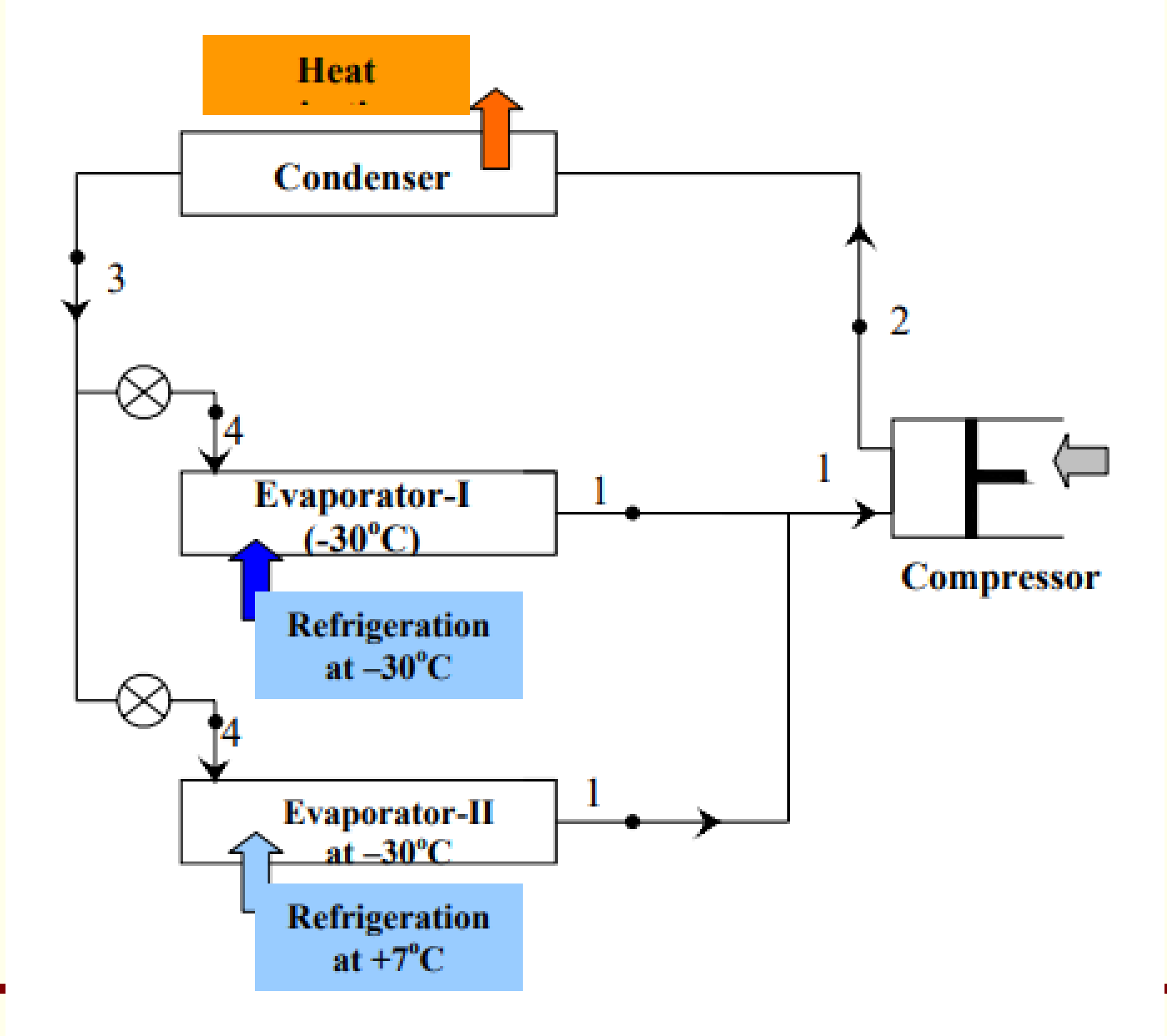
- Options available are:

  a) Use of individual refrigeration systems to cater to different refrigeration loads

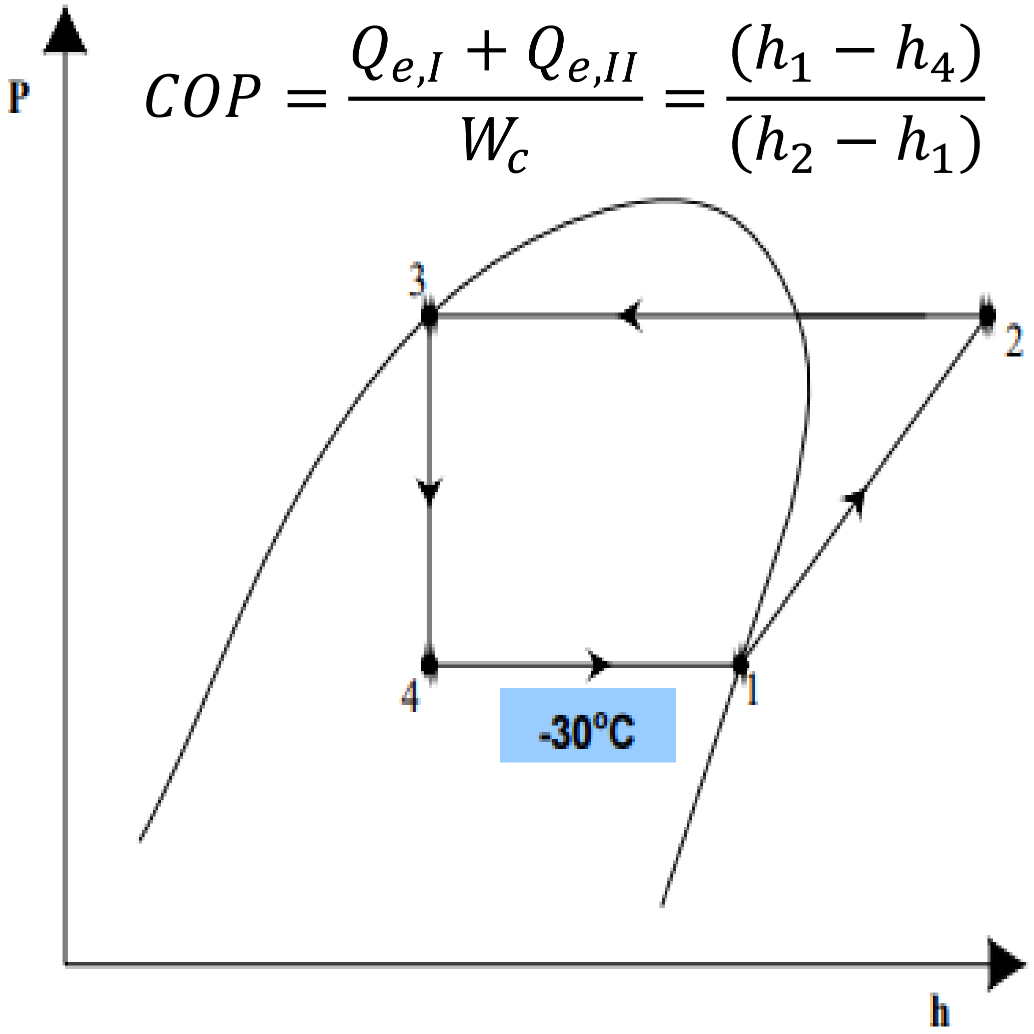
  b) Use of a single stage system with two evaporators, both of which operate at same temperature (-30°C)

  c) Use of multi-stage system with multiple evaporators operating at different temperatures

Single stage system with multiple evaporator



$$COP = \frac{Q_{e,I} + Q_{e,II}}{W_c} = \frac{(h_1 - h_4)}{(h_2 - h_1)}$$



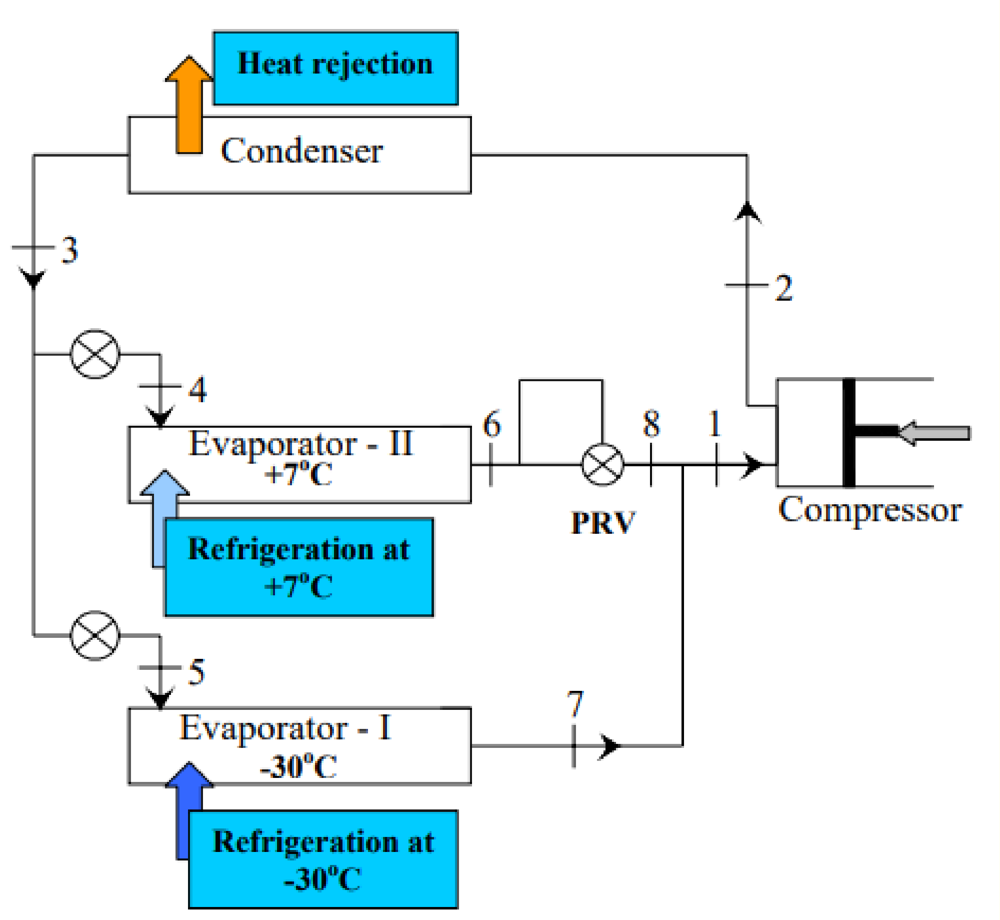
Multi Evaporator systems

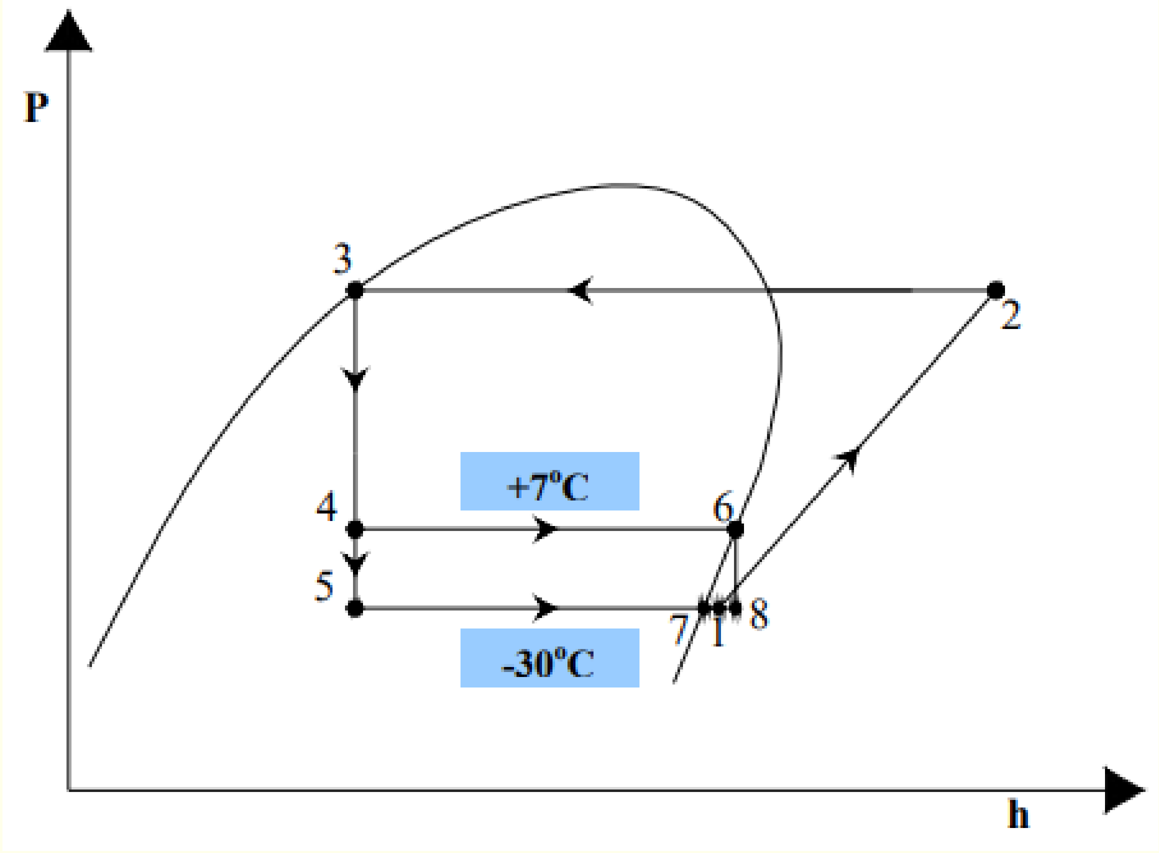
- Use of individual refrigeration systems may not be economically viable
- Use of single stage system with two evaporators operating at the lowest required temperature is : Thermodynamically not efficient
- May create practical problems such as frost formation or freezing of secondary fluids at high temperature loads.
- Excessive water losses in refrigerated products stored at high temperature due to very dry supply air.

Individual evaporators and one compressor with PRV

- Individual expansion valves
- Higher refrigeration effect at high temperature evaporator
- Higher specific work input due to operation of compressor in superheated region
- Better than single stage system due to proper operation of high temperature evaporator

Single compressor Individual expansion valve



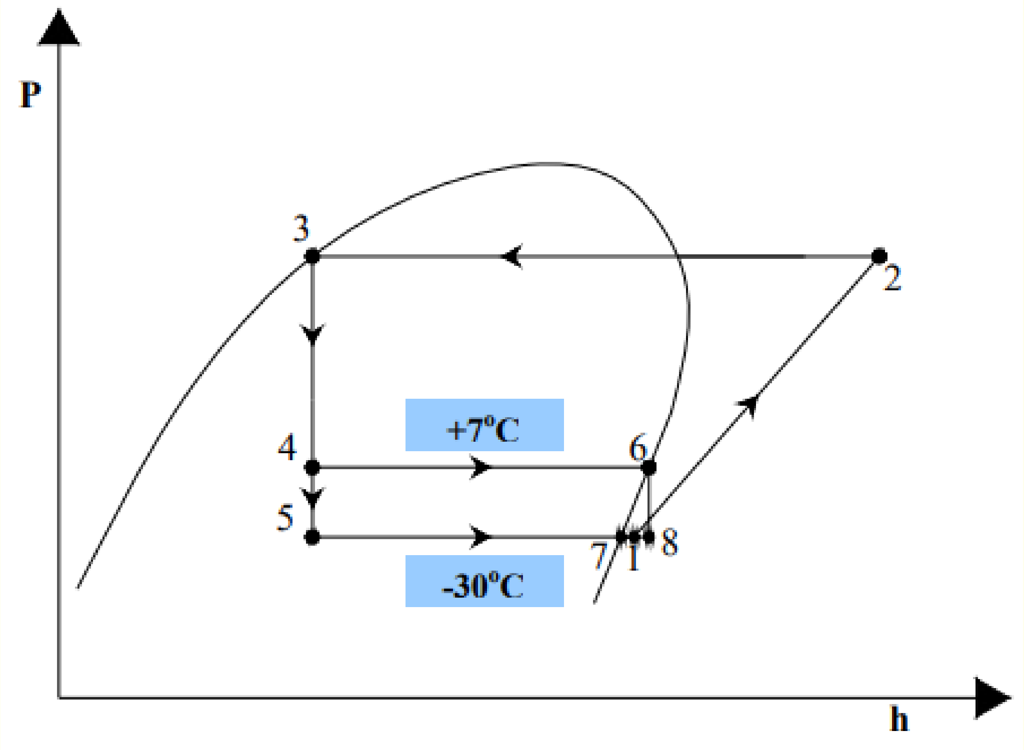


Single compressor Individual expansion valve

- $COP = \frac{Q_{e,I}+Q_{e,II}}{W_c} = \frac{m_I(h_7-h_5)+m_{II}(h_6-h_4)}{(m_I+m_{II})(h_2-h_1)}$

- $m_I = \frac{Q_{e,I}}{(h_7-h_5\ )}$, $m_{II} = \frac{Q_{e,II}}{(h_6-h_4)}$

- $h_1 = \frac{m_I h_7+m_{II} h_8}{m_I+m_{II}}$

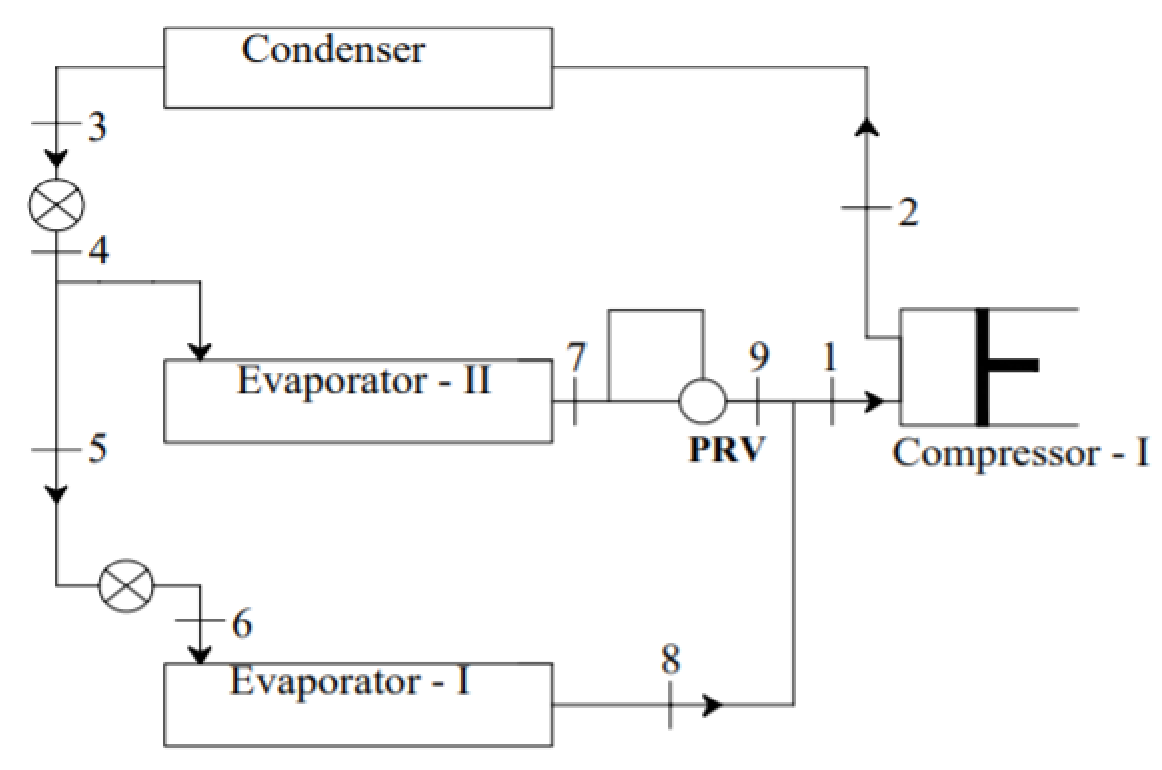


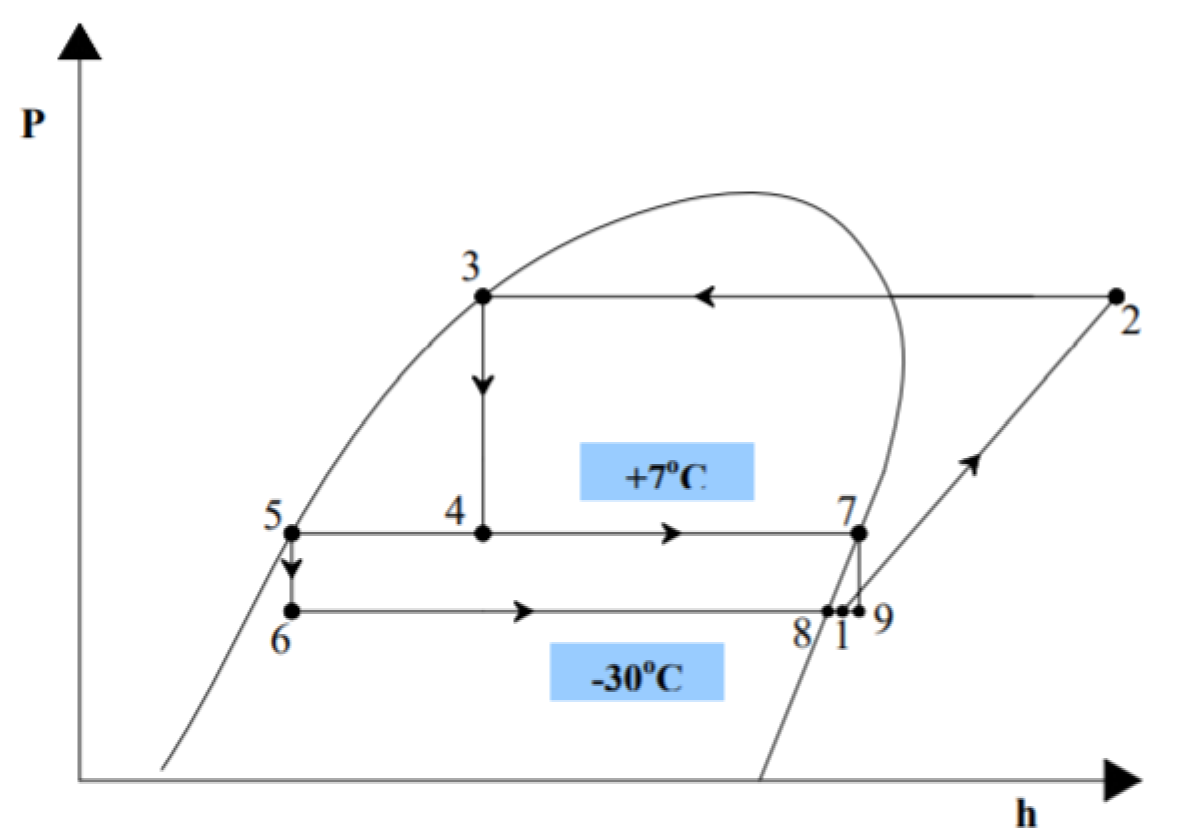
Individual Evaporators, Single compressor, multiple expansion valve and PRV

- Refrigeration effect of the low temperature evaporator increases as saturated liquid enters the low stage expansion valve
- Since the flash gas is removed, the low temperature evaporator operates more efficiently
- Improvement in COP with single compressor is marginal as refrigerant vapour is throttled then compressed again

Individual evaporators and one compressor with PRV

- **Multiple expansion valves**



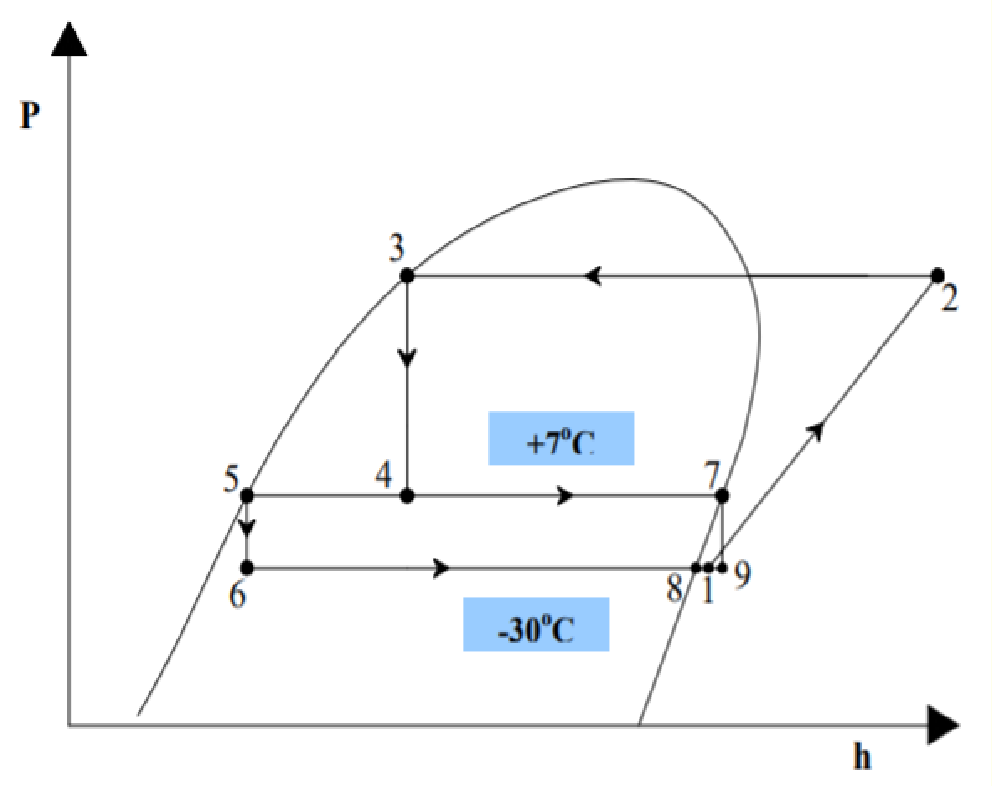


Individual evaporators and one compressor with PRV

- $COP = \frac{Q_{e,I}+Q_{e,II}}{W_c} = \frac{m_I(h_8-h_6)+m_{II}(h_7-h_4)}{(m_{I+m_{II}})(h_2-h_1)}$

- $m_I = \frac{Q_{e,I}}{(h_8-h_6\ )}$

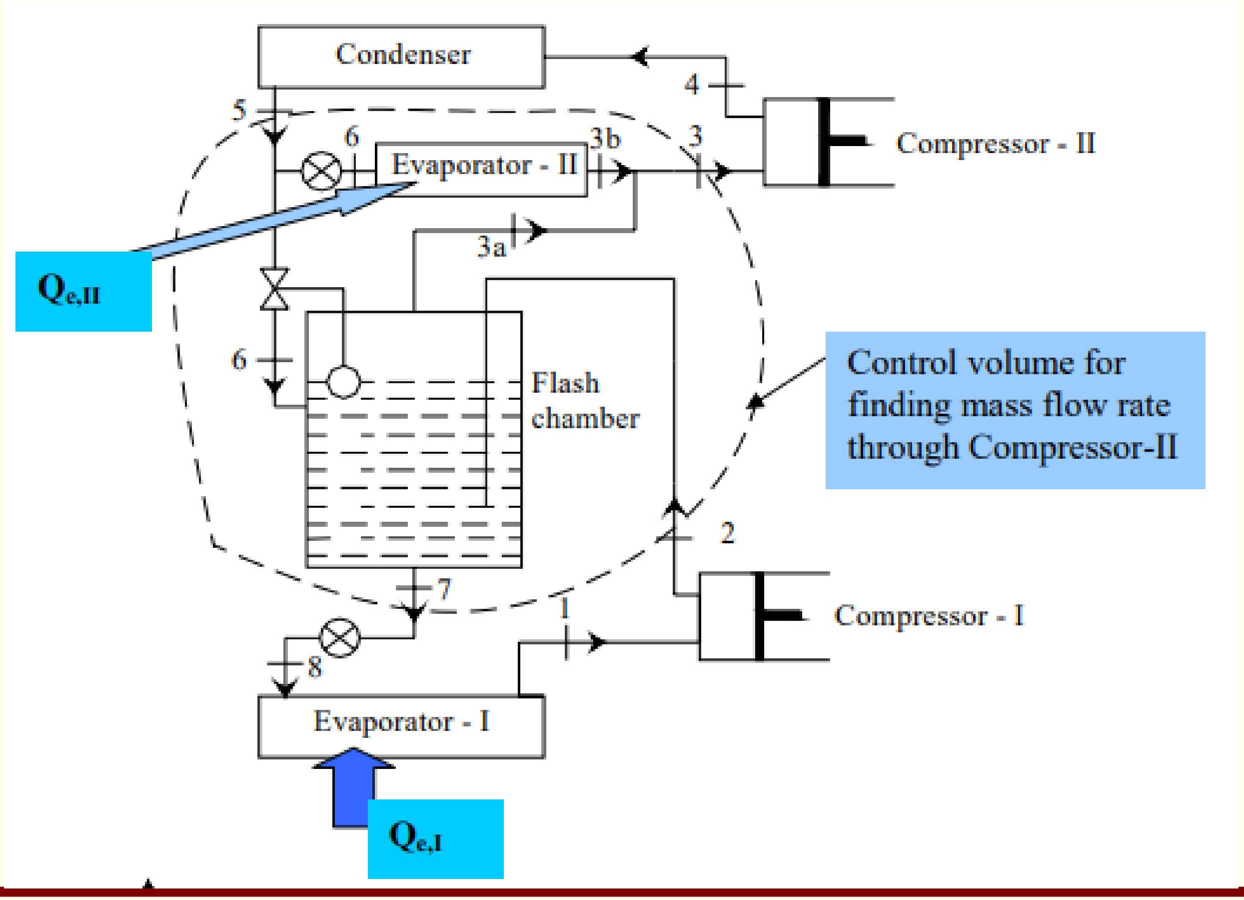
- $m_{e,II} = \frac{Q_{e,II}}{(h_7-h_4)}$

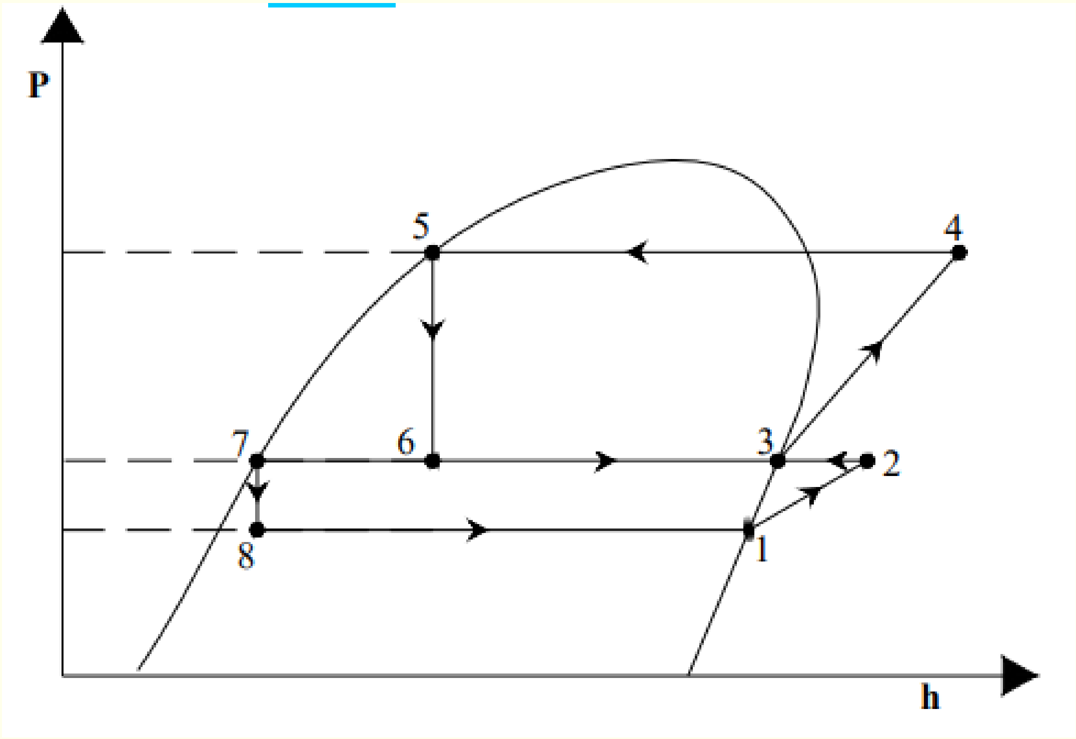


Multi evaporator, multi compression, intercooling and flash gas removal

- Good for low temperature applications with different refrigeration loads,
- e.g., -40°C for quick freezing and -25°C for storage of frozen food
- The low temperature evaporator operates efficiently as flash gas is removed in the flash tank
- High-stage compressor operates efficiently as the suction vapour is saturated

Multi evaporator, multi compressor, intercooling and flash gas removal



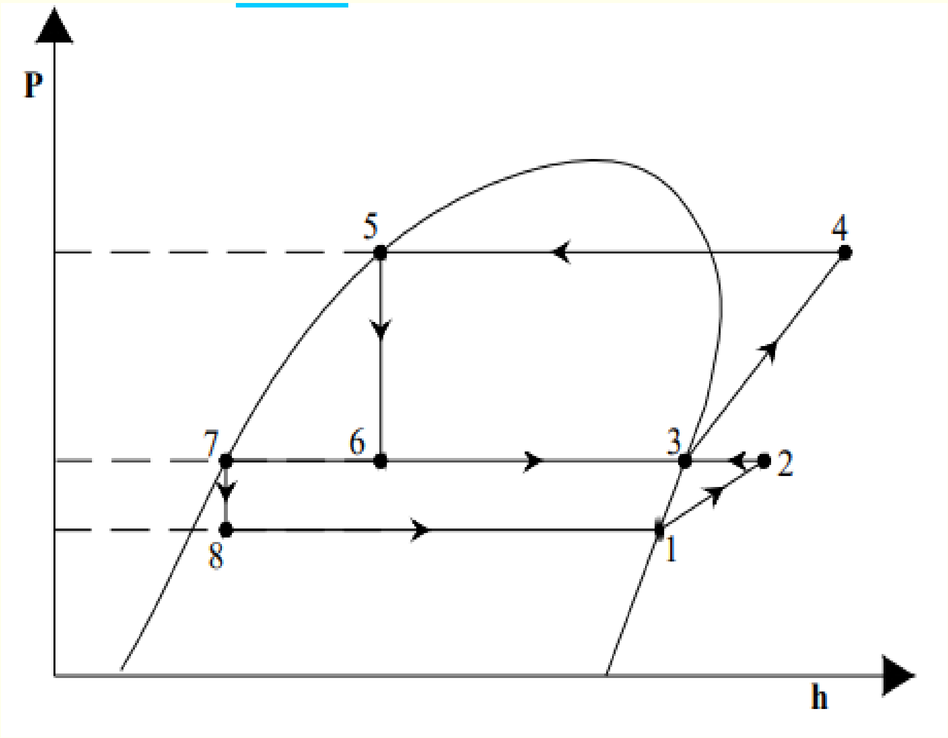


Multi evaporator, multi compression, intercooling and flash gas removal

- $COP = \frac{Q_{e,I}+Q_{e,II}}{W_{c,I}+W_{c,II}} = \frac{m_I(h_1-h_8)+m_{e,II}(h_3-h_6)}{m_I(h_2-h_1)+m_{II}(h_4-h_3)}$

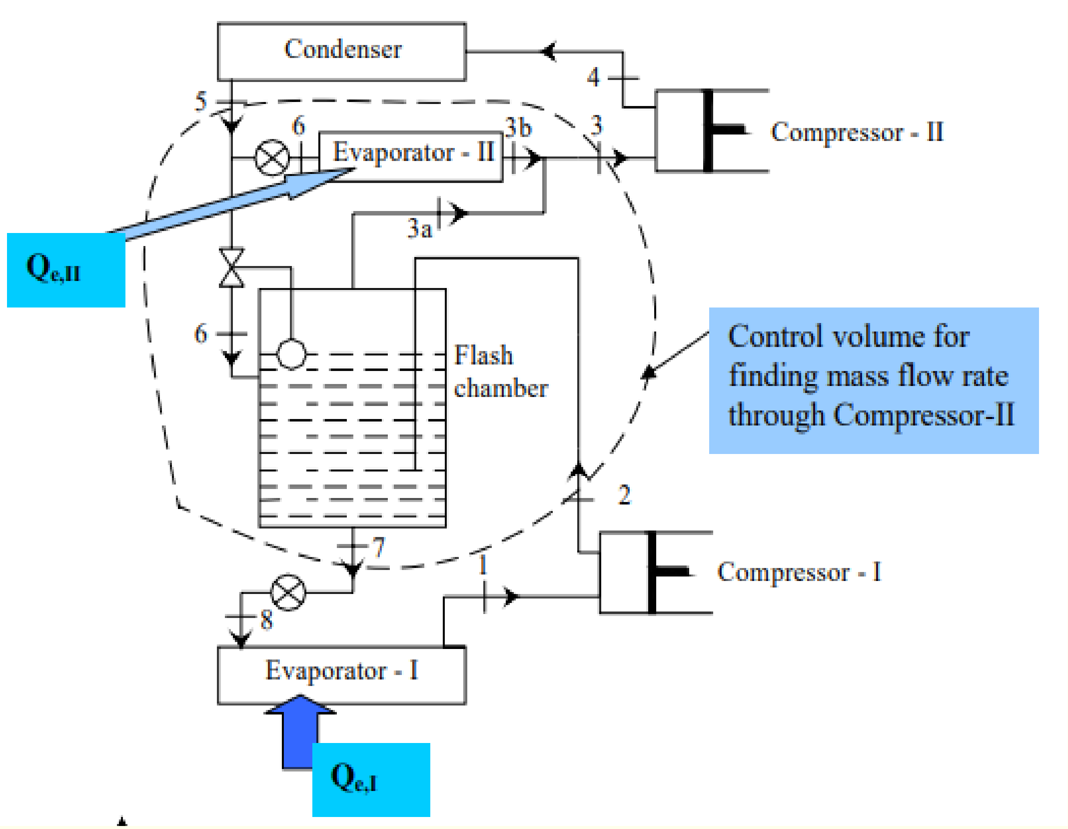
- $m_I = \frac{Q_{e,I}}{(h_1-h_8\ )}$

- $m_{e,II} = \frac{Q_{e,II}}{(h_3-h_6)}$

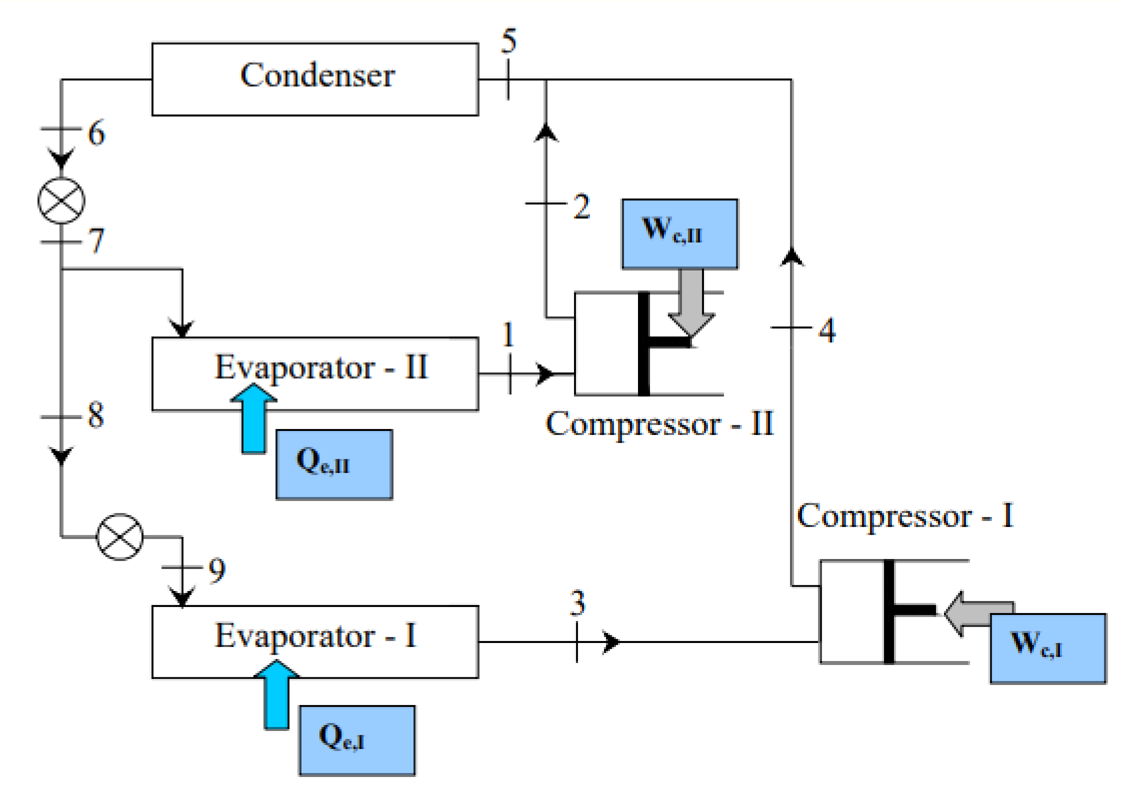


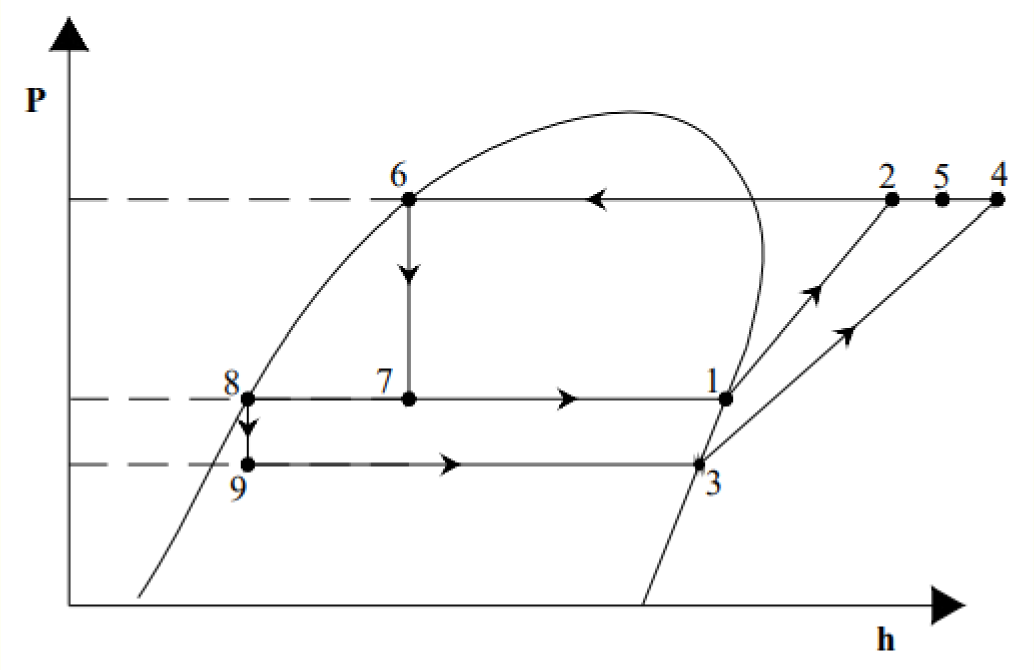
Mass and Energy balance

- Applying balance across the control volume
- Mass balance: $m_5 + m_2 = m_7 + m_3;$
- $m_5 = m_{II} = m_3$ & $m_2 = m_I = m_7$
- Energy balance:
- $m_5 h_5 + m_2 h_2 + Q_{e,II} = m_7 h_7 + m_3 h_3$



Multi-evaporator system with individual compressors and multiple expansion valves



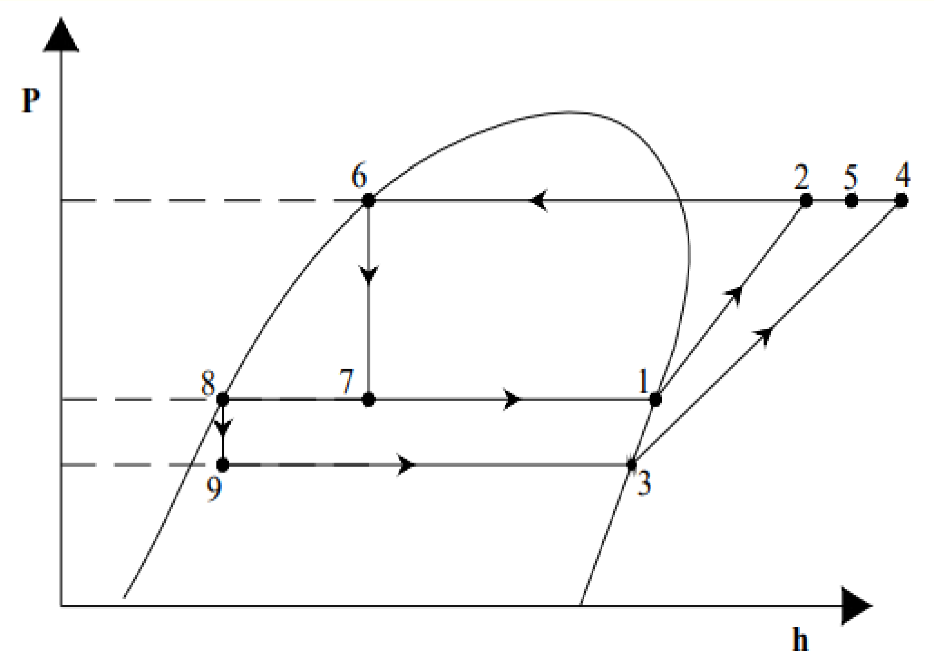


Multi-evaporator system with individual compressors and multiple expansion valves

- $COP = \frac{Q_{e,I}+Q_{e,II}}{W_{c,I}+W_{c,II}} = \frac{m_I(h_3-h_9)+m_{II}(h_1-h_7)}{m_I(h_4-h_3)+m_{II}(h_2-h_1)}$

- $m_I = \frac{Q_{e,I}}{(h_3-h_9\,)}$

- $m_{II} = \frac{Q_{e,II}}{(h_1-h_7)}$



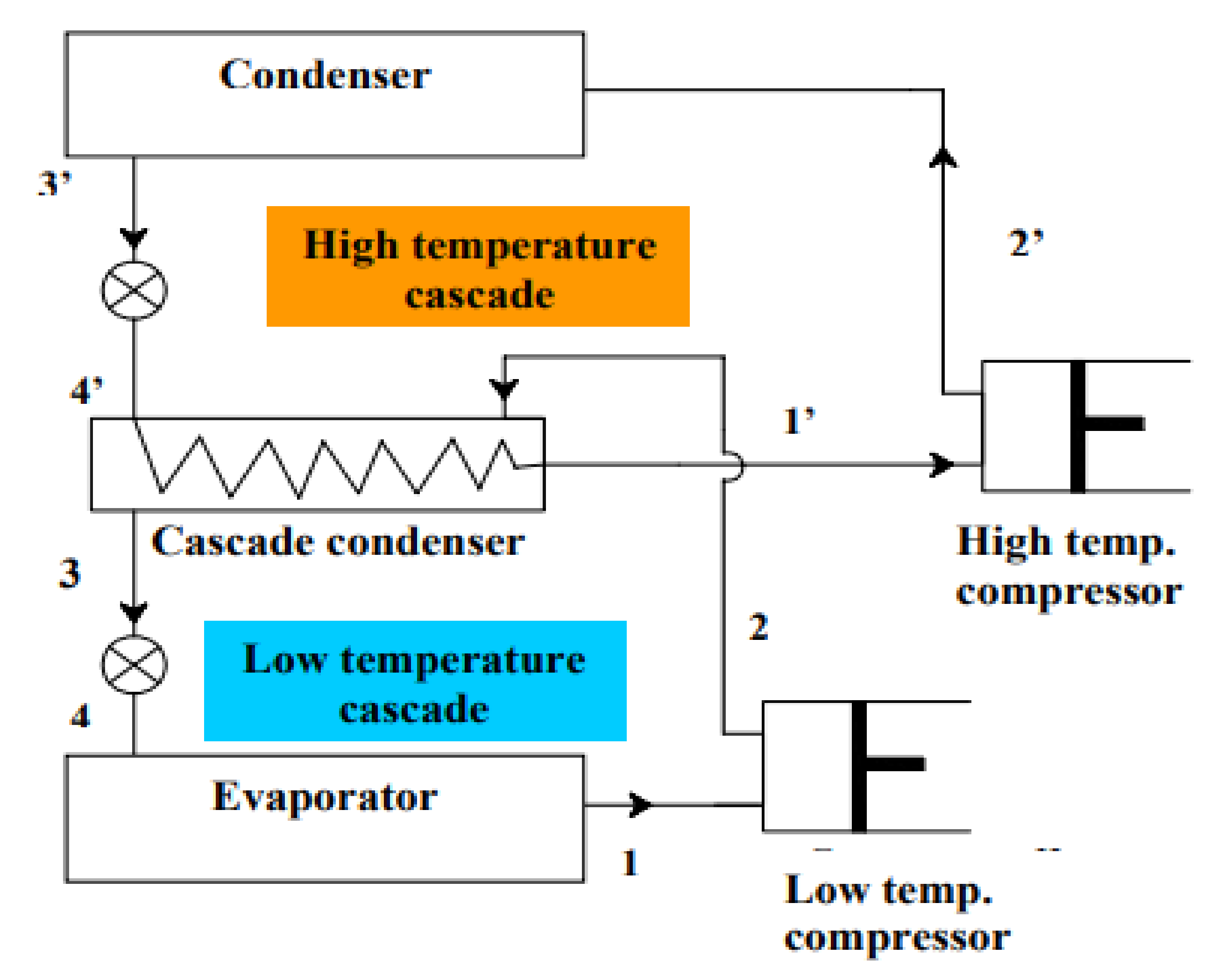
Limitations of multi-stage systems

- Since only one refrigerant is used throughout the system, the refrigerant used should have high critical temperature and low freezing point.
- The operating pressures may become too high or too low.
- Possibility of migration of lubricating oil from one compressor to other leading to compressor break-down.

Cascade Systems

- In a cascade system a series of refrigerants with progressively lower boiling points are used in a series of single stage units
- The condenser of lower stage system is coupled to the evaporator of the next higher stage system and so on
- The component where heat of condensation of lower stage refrigerant is supplied for vaporization of next level refrigerant is called cascade condenser

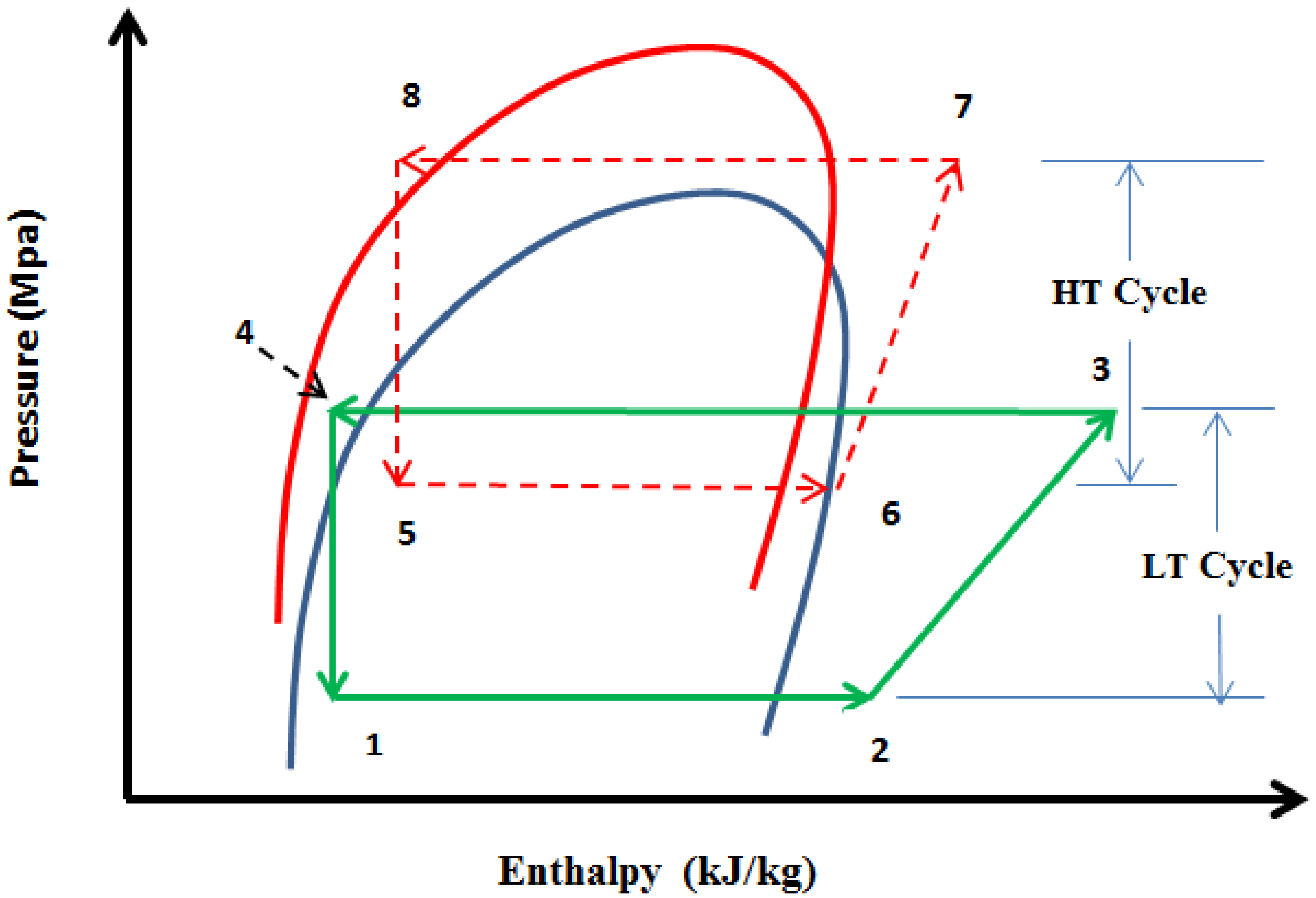
Two-stage cascade refrigeration system



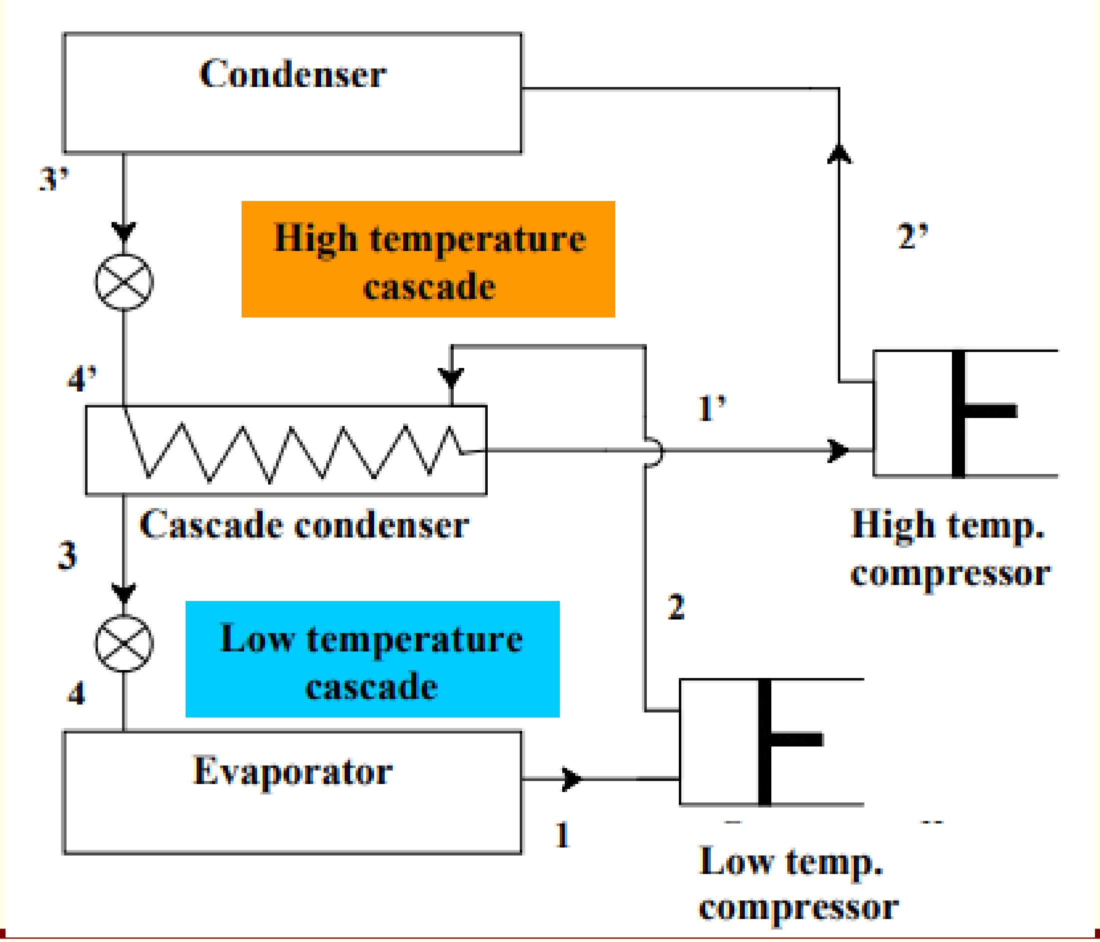
Cascade Systems

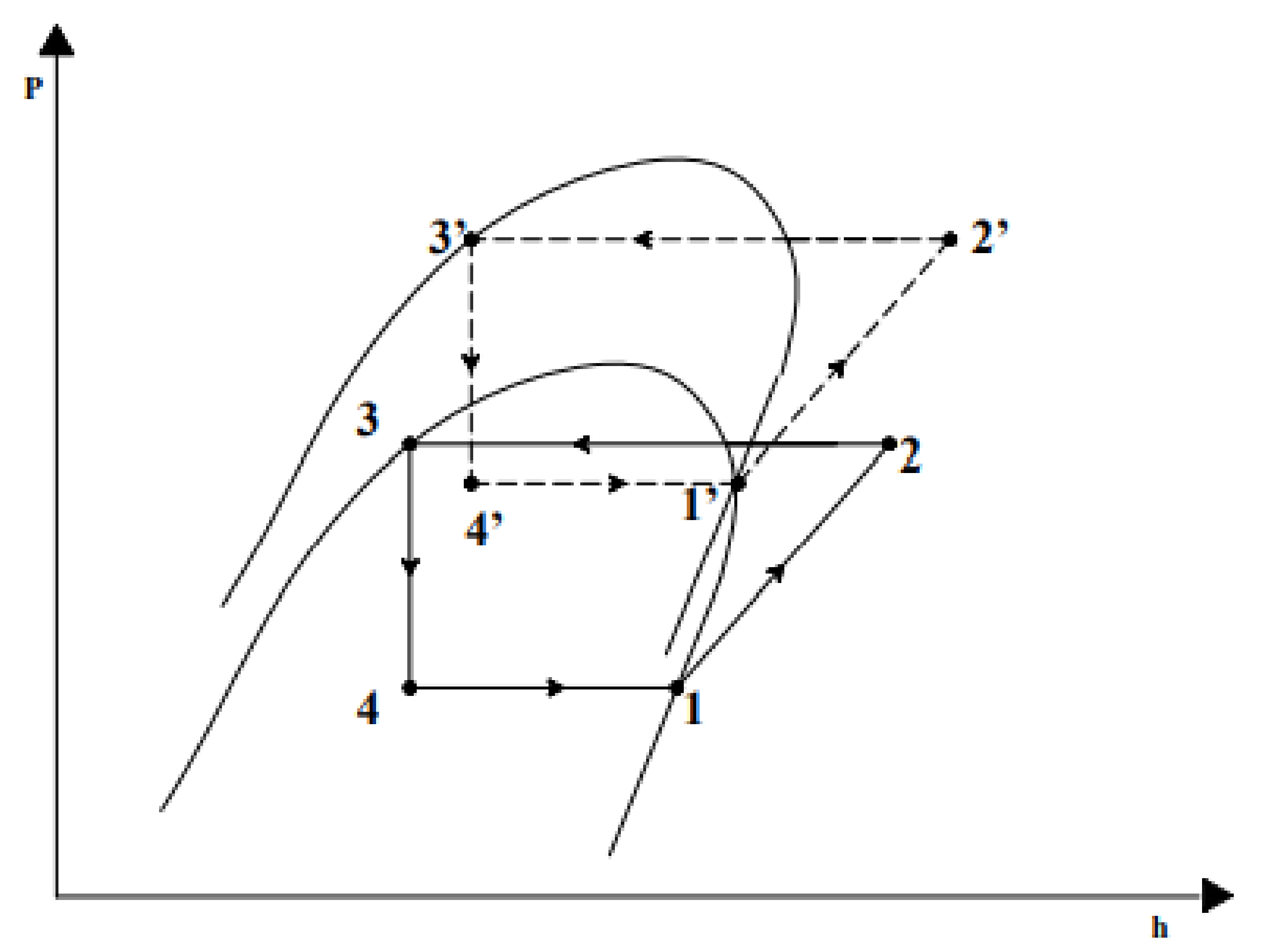
- Number of cascade stages can be two or more.
- It is also possible to combine multi staging with cascading.
- The refrigerants selected should have suitable temperature pressure characteristics.
- An example of refrigerant combination is:

Carbon dioxide (NBP = -78.40°C, T_{cr} =31.06 °C) in low temperature cascade and Ammonia (NBP = -33.33 °C, T_{cr} = 132.25 °C) in high temperature cascade


Pressure (Mpa)
Enthalpy (kJ/kg)
8
7
4
3
5
6
1
2
HT Cycle
LT Cycle

Two-stage cascade refrigeration system





Two-stage cascade refrigeration system

Optimum cascade condenser temperature for maximum COP of a 2 stage cascade with Carnot cycle

$$T_{cc,opt} = \sqrt{T_e, T_c}$$

Optimum cascade condenser temperature for maximum COP of a 2 stage cascade with actual cycles

$$T_{cc,opt} = \left[\frac{b_1 + b_2}{\frac{b_2}{T_c} + \frac{b_1}{T_e}}\right]$$

- b1 and b2 = Clausius-Clayperon equation constants

Advantages of cascade systems

- Since each cascade uses a different refrigerant, it is possible to select a refrigerant that is best suited for that particular range. Very high or very low pressures can be avoided
- Individual compressors with different refrigerants. Therefore no migration of lubricating oil.
- In practice, matching of loads in the cascade condenser is difficult. especially during the system pull-down. Hence the cascade condensers are normally oversized

Applications of Cascade Refrigeration Systems

- Liquefaction of petroleum vapours
- Liquefaction of industrial gases
- Manufacturing of dry ice
- Deep freezing in cold storages etc.