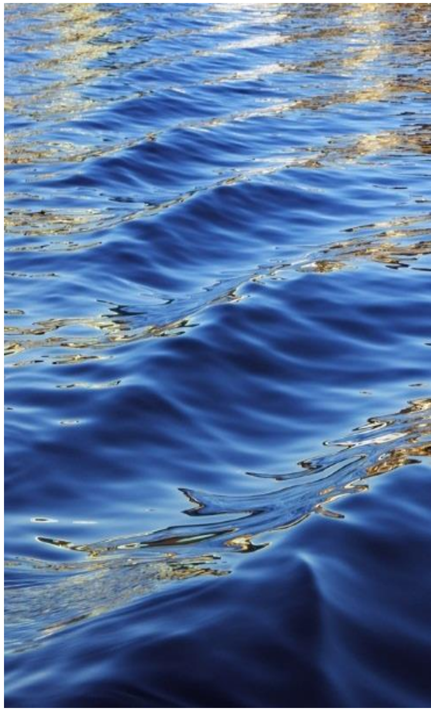
Environmental Thermal Engineering

Lecture Note #5

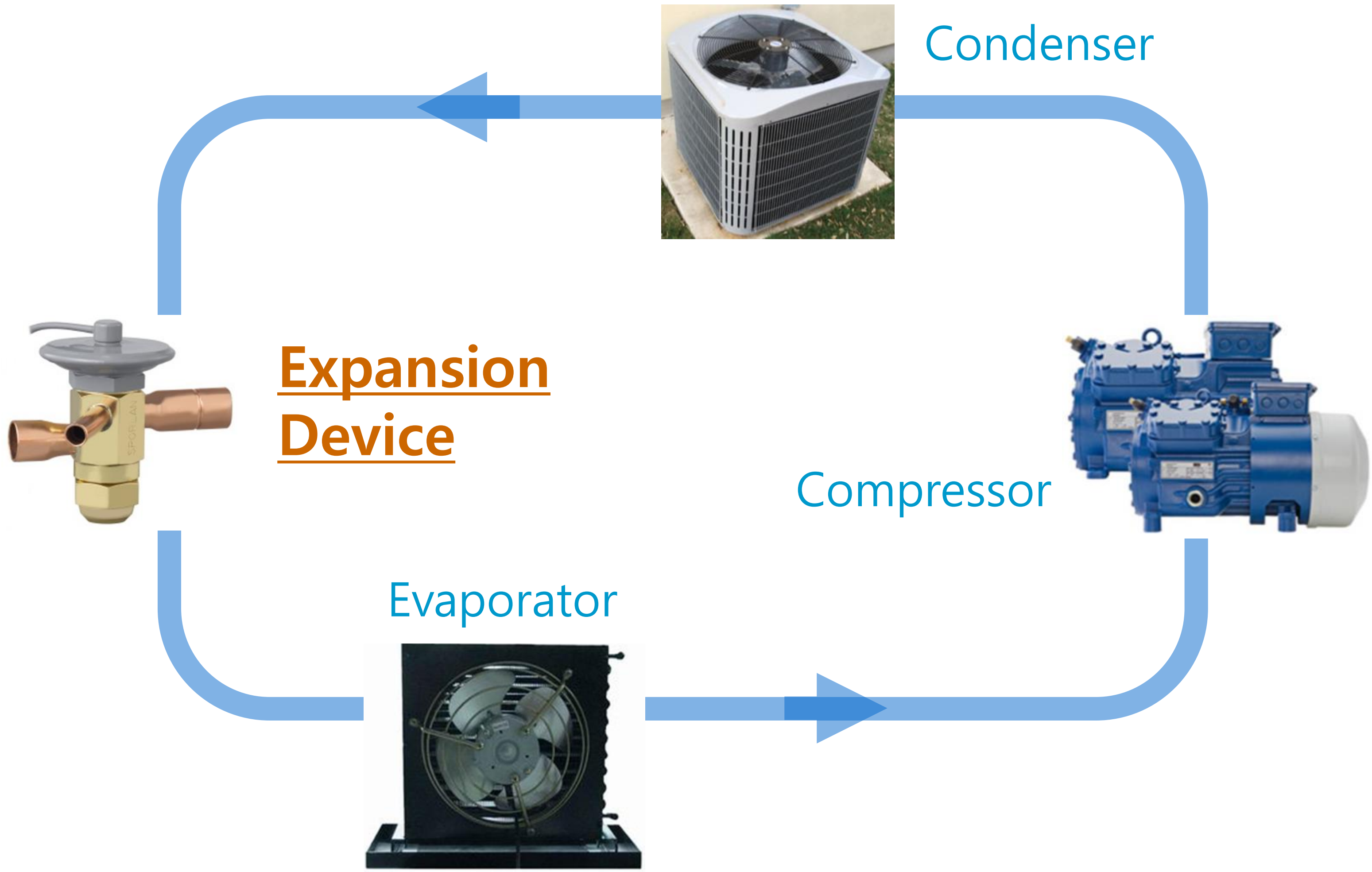
Professor Min Soo KIM



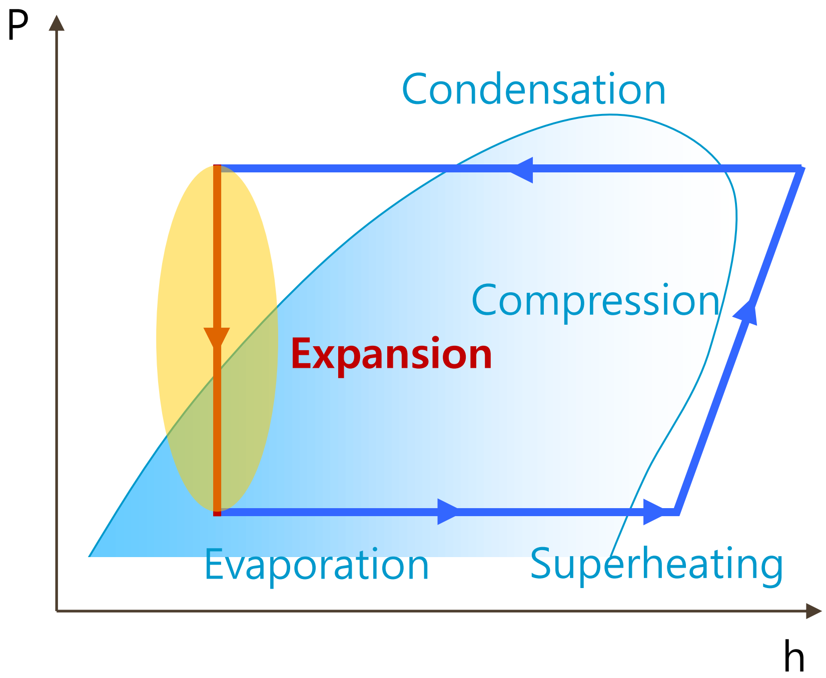
Expansion Device

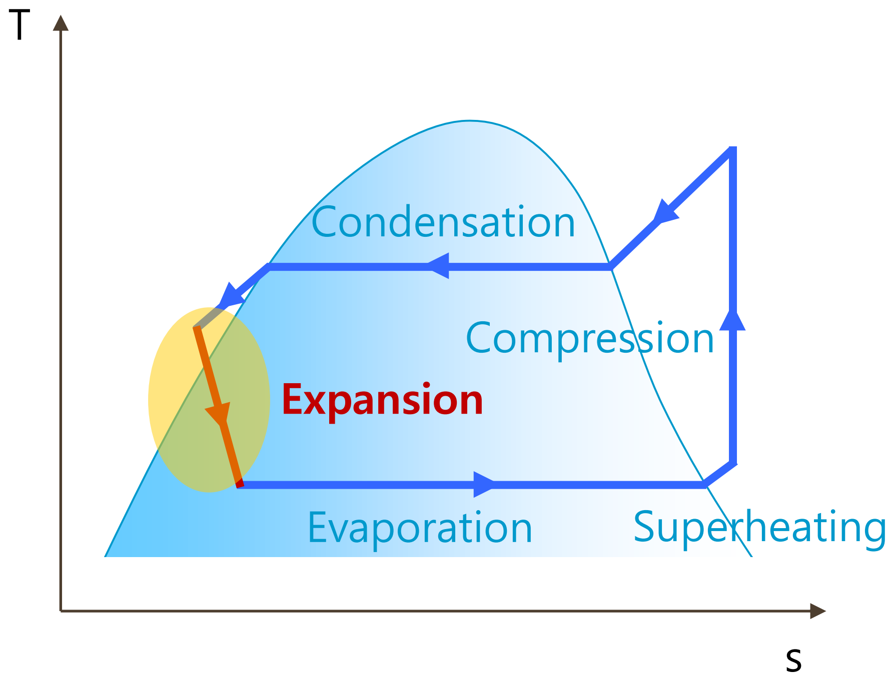
EXPANSION DEVICE

WHERE? – IN REFRIGERATION SYSTEM



Expansion Process





Expansion Process

❑ Purpose

(1) To Reduce the pressure of the liquid refrigerant

(2) To Regulate the flow of refrigerant to the evaporator

❑ Types

(1) Manual expansion valve

(2) Capillary tube

(3) Automatic expansion valve

- Constant pressure expansion valve
- Float type expansion valve
- Thermostatic expansion valve
  (Superheat controlled expansion valve)
- Electric expansion valve

Throttling

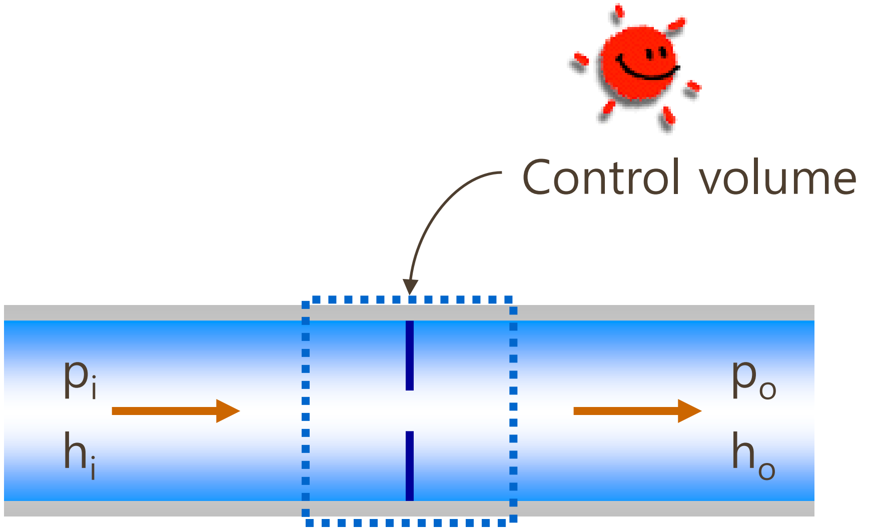
Throttling

- A throttling process occurs when a fluid flowing in a line suddenly encounters a restriction in the flow passage.
- Abrupt pressure drop

  $p_i > p_o$

- Constant enthalpy process

  $h_i = h_o$

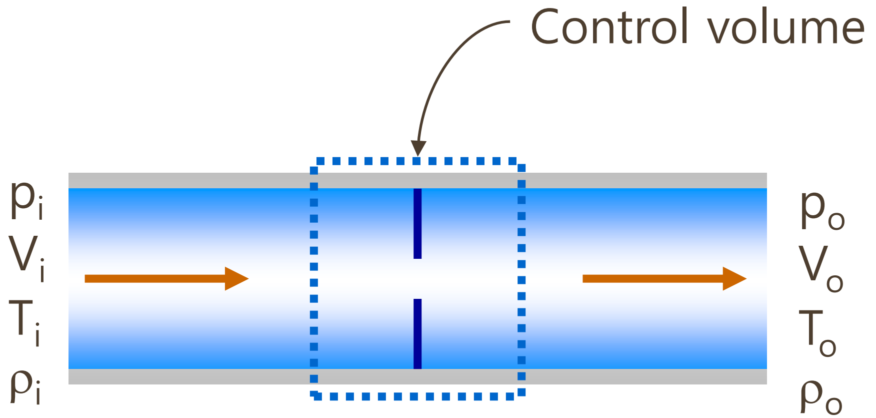


Energy Conservation in Open System

$$\dot{Q} + \int_{A_i} \left(h + \frac{1}{2}V^2 + gz \right) \rho V \, dA = \dot{W}_s + \int_{A_o} \left(h + \frac{1}{2}V^2 + gz \right) \rho V \, dA$$

$$\Rightarrow \quad h_i(p_i, T_i) = h_o(p_o, T_o)$$

- ❑ No heat transfer
- ❑ No shaft work
- ❑ No potential energy change
- ❑ Velocity variation is negligible



Joule-Thomson Effect

❑ Joule-Thomson coefficient

$$\left.\begin{array}{l} h_i = h_o \\ p_i = p_o \end{array}\right]$$

$$\mu_{JT} = \left.\frac{\partial T}{\partial P}\right)_h = \frac{1}{C_p}\left[T\frac{\partial v}{\partial T} - v\right]$$

❑ Joule-Thomson effect

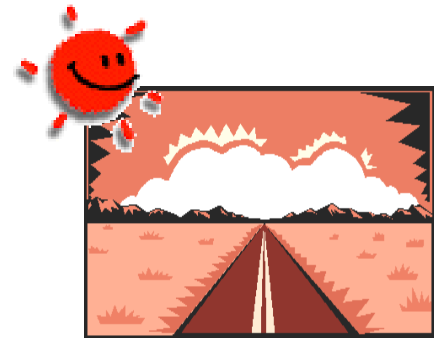
$\mu_{JT} > 0$

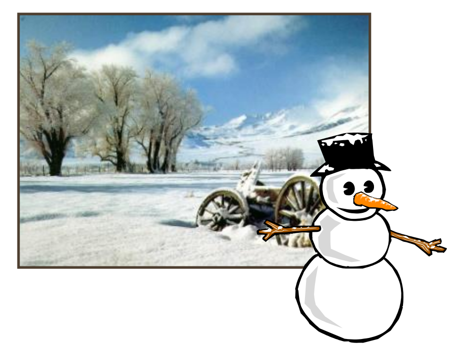
Adiabatic Expansion

→

Refrigeration

Liquefaction





Joule-Thomson Effect (Expansion device)

❑ Joule-Thomson coefficient

$$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h = -\left(\frac{\partial T}{\partial h}\right)_p \left(\frac{\partial h}{\partial p}\right)_T \qquad \left(\frac{\partial T}{\partial p}\right)_h \left(\frac{\partial h}{\partial T}\right)_p \left(\frac{\partial p}{\partial h}\right)_T = -1$$

$$dh = \left.\frac{\partial h}{\partial T}\right)_P dT + \left.\frac{\partial h}{\partial P}\right)_T dP = C_P\, dT + \left[v - T\left.\frac{\partial v}{\partial T}\right)_P\right] dP$$

$$\rightarrow \left.\frac{\partial h}{\partial T}\right)_P = C_P, \qquad \left.\frac{\partial h}{\partial P}\right)_T = v - T\left.\frac{\partial V}{\partial T}\right)_P$$

$$\mu_{JT} = \left.\frac{\partial T}{\partial P}\right)_h = -\left.\frac{\partial T}{\partial h}\right)_P \left.\frac{\partial h}{\partial P}\right)_T$$

$$= \frac{1}{C_P}\left[T\left.\frac{\partial v}{\partial T}\right)_P - v\right]$$

Joule-Thomson Effect (Expansion device)

Maxwell's Relation

$$-\left(\frac{\partial S}{\partial P}\right)_T = \left(\frac{\partial V}{\partial T}\right)_P$$

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial p}{\partial S}\right)_V$$

$$\left(\frac{\partial T}{\partial p}\right)_s = +\left(\frac{\partial V}{\partial S}\right)_p$$

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial p}{\partial T}\right)_V$$

$$Tds = dh - vdP$$

$$T\left(\frac{ds}{dP}\right)_T = \left(\frac{dh}{dP}\right)_T - v$$

$$-T\left(\frac{\partial V}{\partial T}\right)_P = \left(\frac{dh}{dP}\right)_T - v$$

Inversion Curve

❑ Inversion Temperature

- The temperature at which

$$\mu_{JT} = \left.\frac{\partial T}{\partial P}\right)_h = \frac{1}{C_p}\left[T\frac{\partial v}{\partial T} - v\right] = 0$$

❑ Joule-Thomson cooling effect

- Left area of the inversion curve

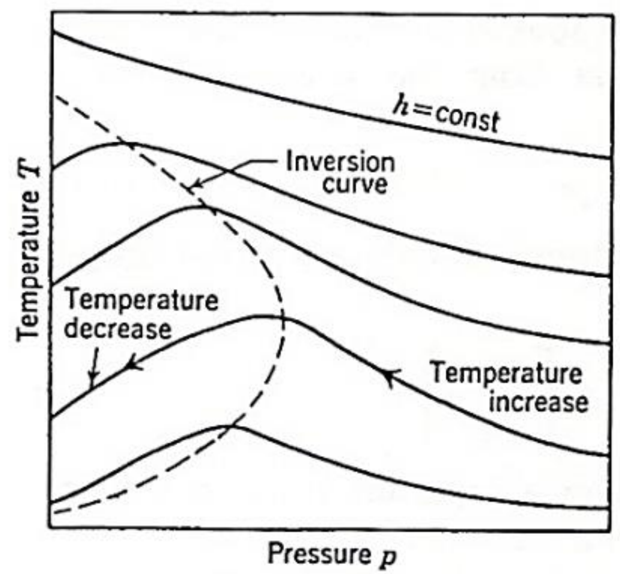


FIGURE Isenthalpic, inversion curve for a real gas

Manual Expansion Valve

Manual Expansion Valve

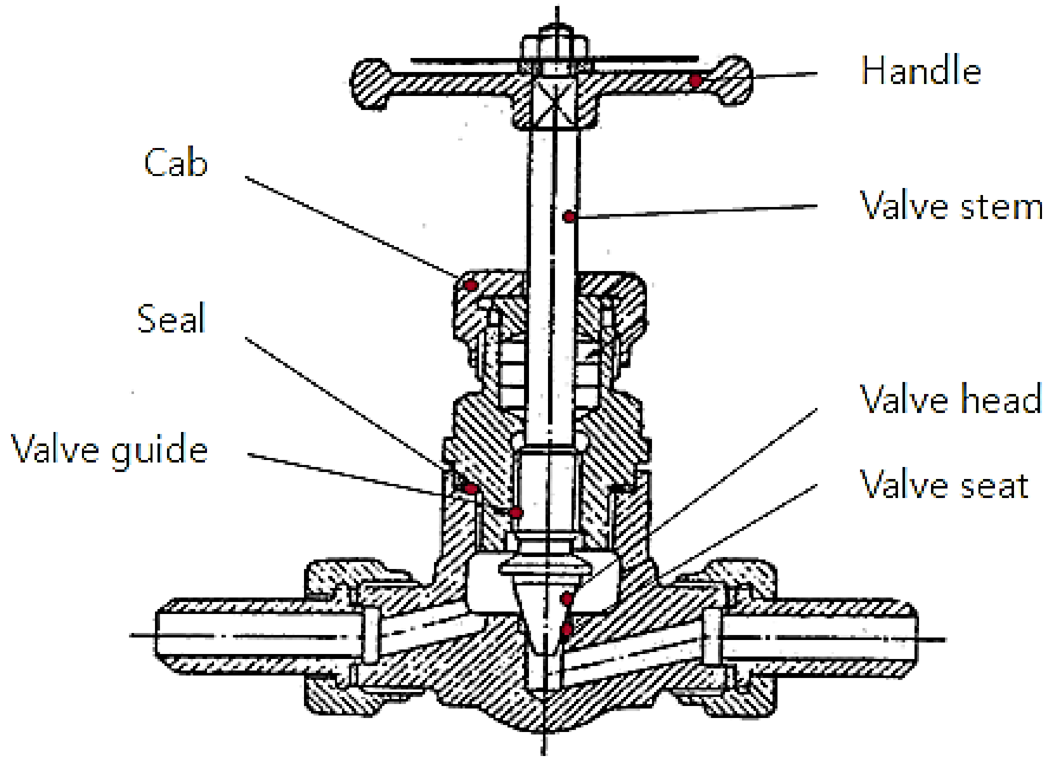


FIGURE Manual type expansion valve (cone type)

Manual Expansion Valve

- Used in ammonia refrigerator
- Mass flow rate is adjusted manually by controlling handle
- Scale plate on the handle
- Filter is installed in entrance to prevent scale or sand to be mixed and circulated

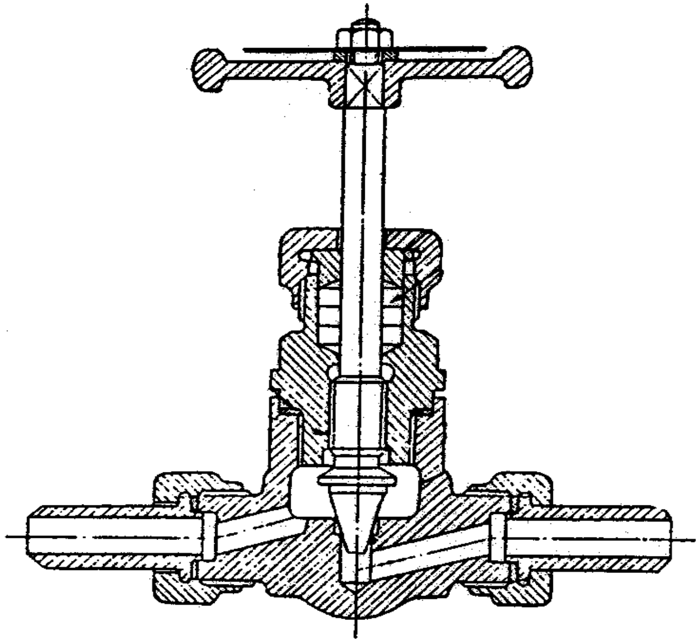


FIGURE Manual type expansion valve

Capillary Tube

Capillary Tube

- Small refrigeration system
  - ~ 10kW
- Pressure drop due to friction and acceleration of the refrigerant.
- Liquid flashing into vapor
- The tube cannot adjust to variations in discharge pressure, suction pressure, or load

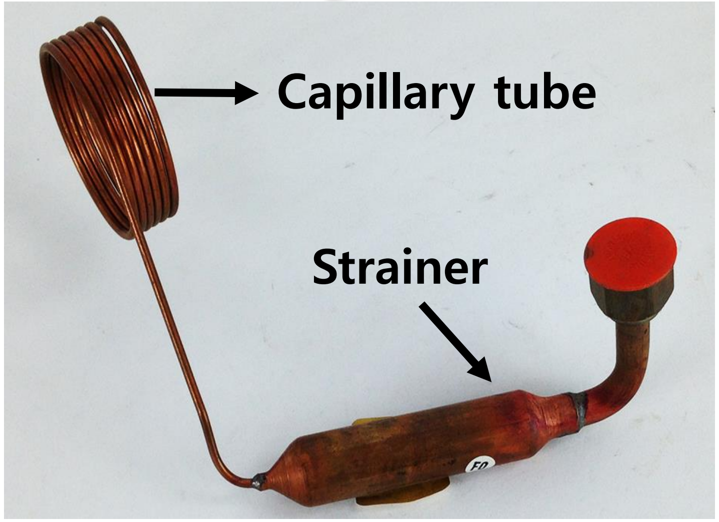


FIGURE Capillary tube and strainer

Balance Point

- **Balance Point**
  - Expansion valve feeds as much as the compressor pumps from the evaporator.
- **The heat transfer coefficient of the evaporator must also satisfied.**

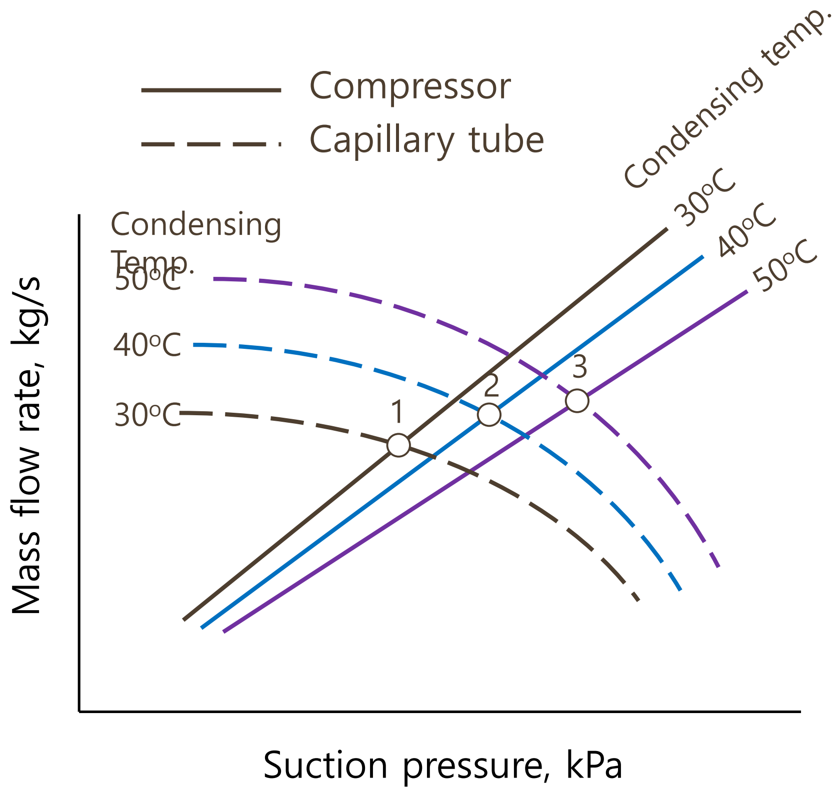


FIGURE Balance points with a reciprocating compressor and capillary tube.

Capillary Tube

Starving

- ❑ **Heavy heat load condition**
  - (1) Suction pressure rise
  - (2) Capillary tube does not feed sufficient refrigerant

➢ **Starving the evaporator**

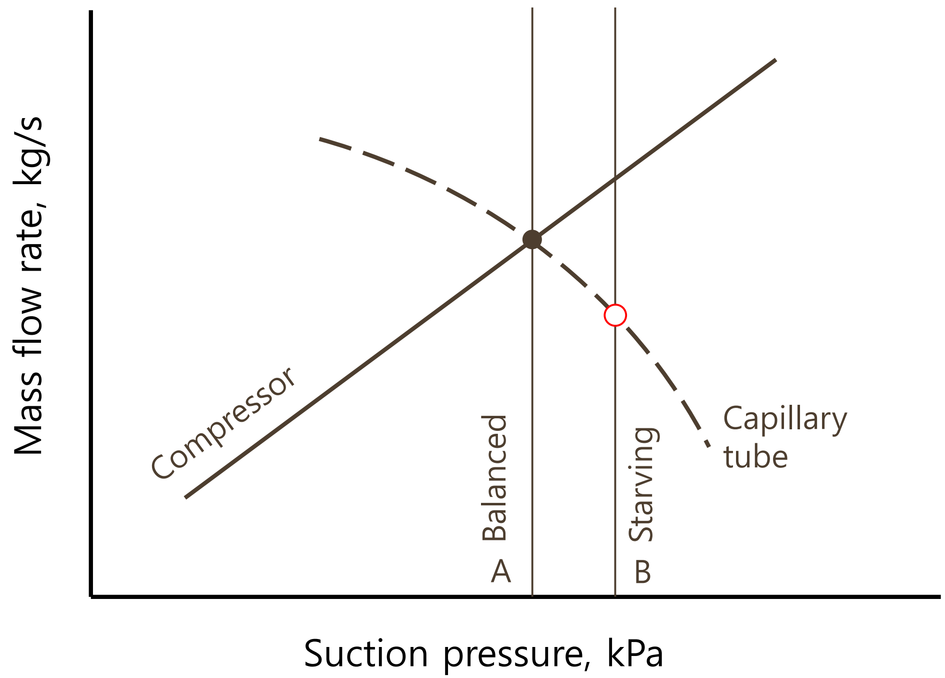


FIGURE Unbalanced conditions causing starving or flooding of the evaporator.
The condensing pressure is constant.

Capillary Tube

Starving

- **At point B (Starving condition)**
  - (1) The compressor draws more refrigerant out of the evaporator that the capillary tube supply.
  - (2) The evaporator becomes short of refrigerant

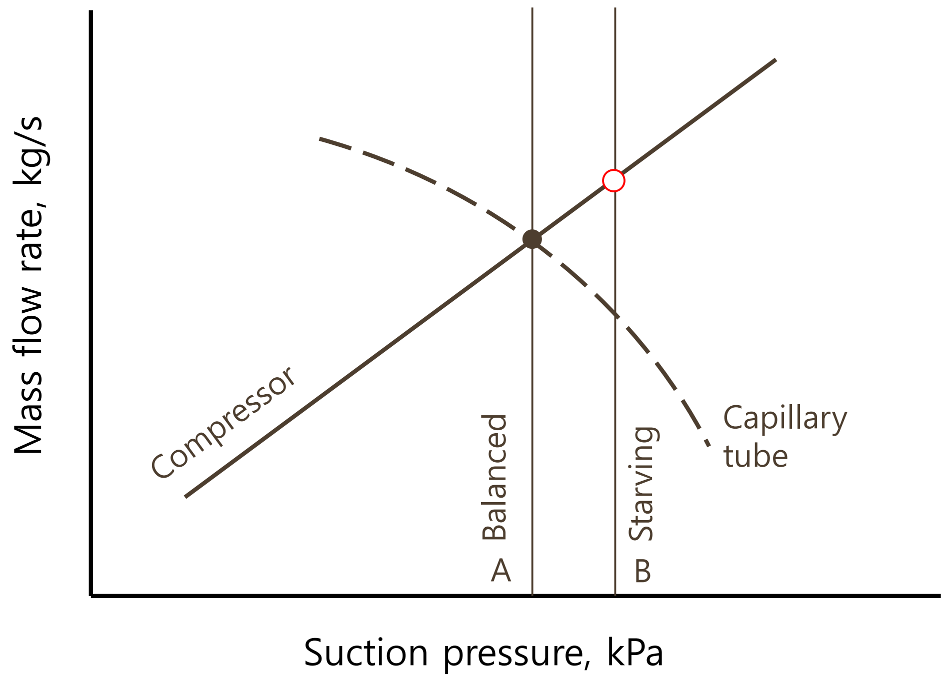


FIGURE Unbalanced conditions causing starving or flooding of the evaporator. The condensing pressure is constant.

Starving

1. **Liquid back up into the condenser**
   - Reducing condensing area
   - Raising condenser pressure
   - Reducing compressor capacity
   - Increasing the feed rate of capillary tube

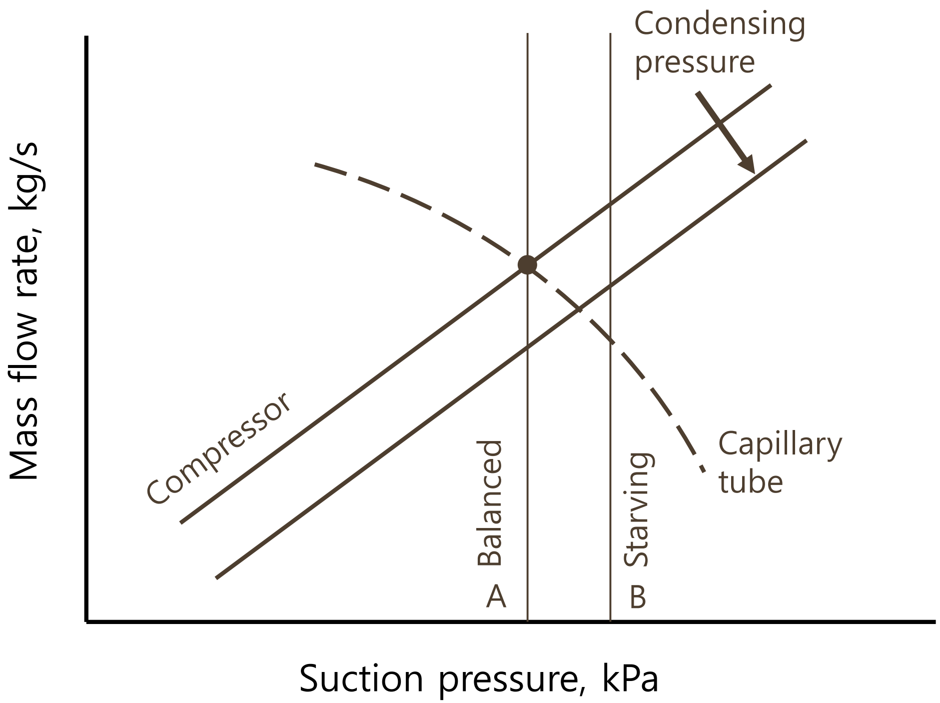


FIGURE Unbalanced conditions causing starving or flooding of the evaporator. The condensing pressure is constant.

Starving

2. **Decrease of the heat transfer coefficient of the evaporator**

   ➢ Suction pressure drops back to the pressure A.

Restoring balanced flow

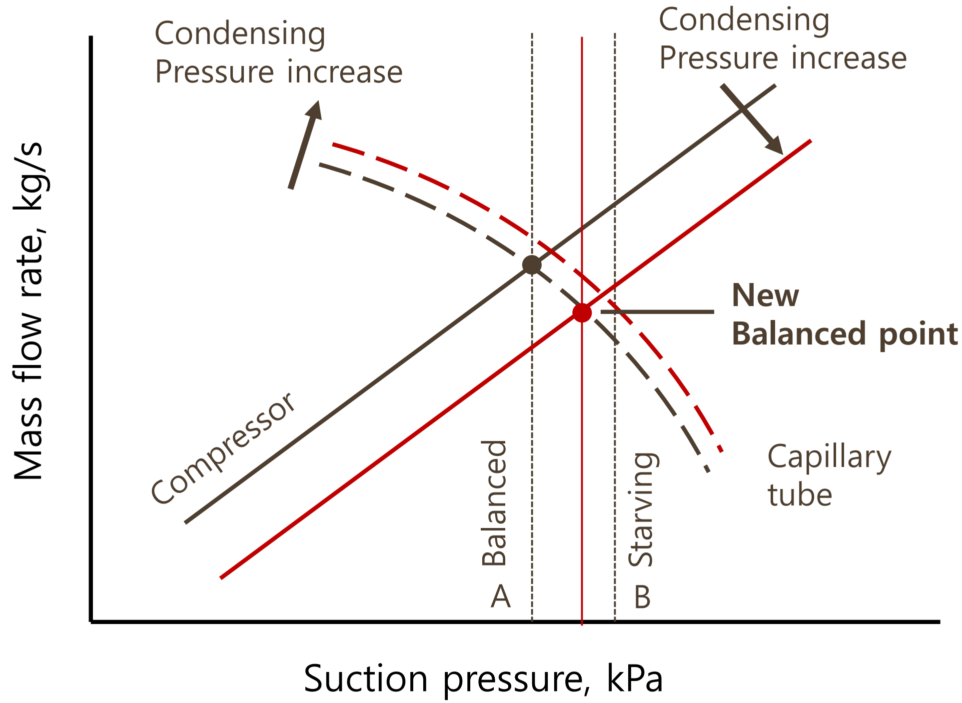


FIGURE Unbalanced conditions causing starving or flooding of the evaporator.
The condensing pressure is constant.

Flooding

- **Low heat load condition**
  - Suction temperature and pressure drops to point C

Flooding the evaporator

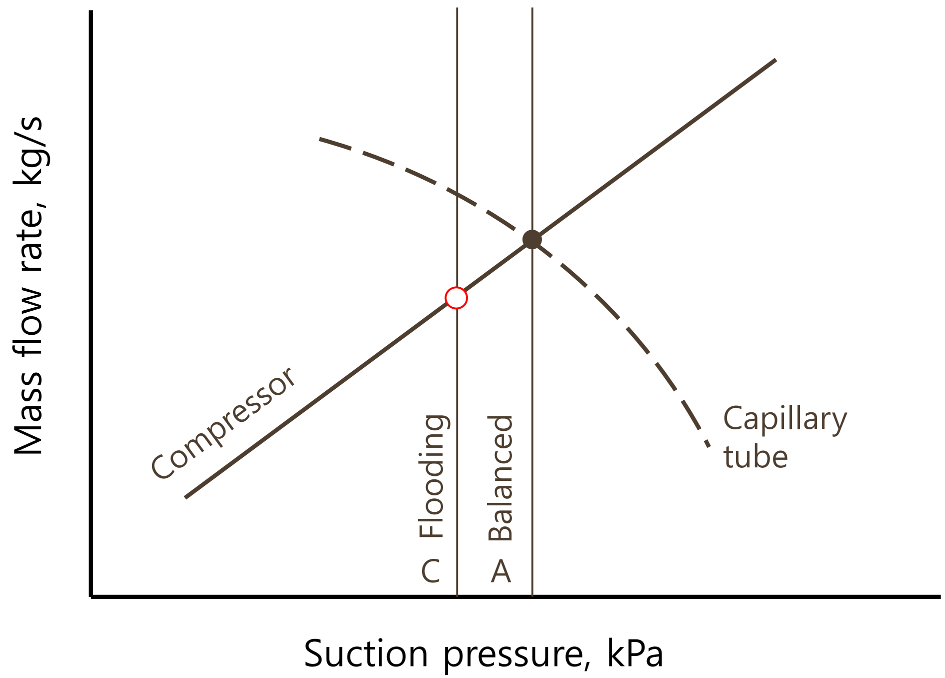


FIGURE Unbalanced conditions causing starving or flooding of the evaporator. The condensing pressure is constant.

Capillary Tube

Flooding

- **At point C (Flooding condition)**
  - (1) The capillary tube feed more refrigerant to the evaporator than the compressor draw out
  - (2) The evaporator fills with liquid and would **spill over into the compressor**

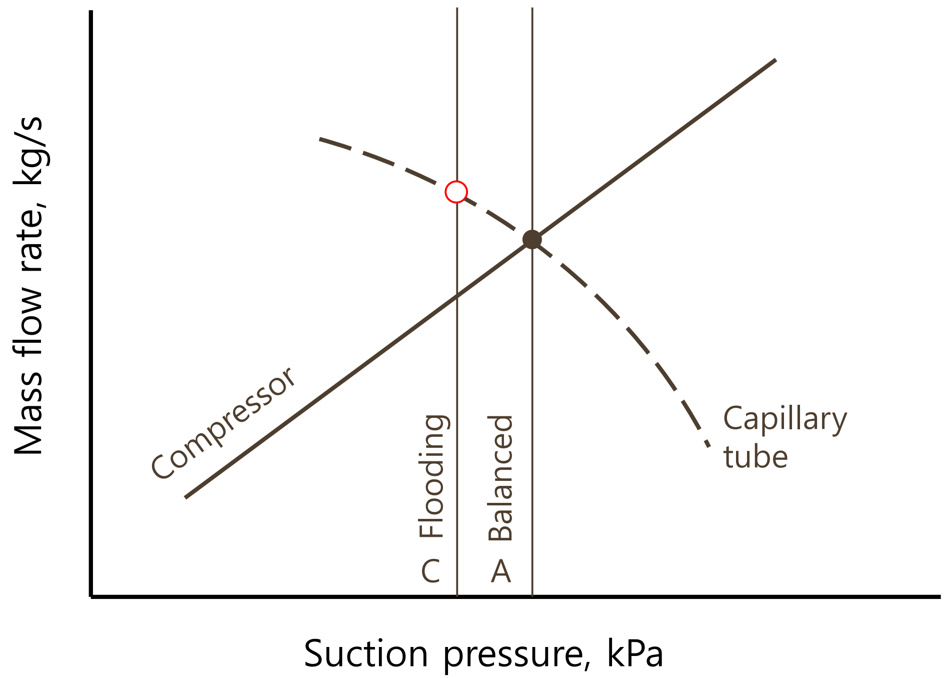


FIGURE Unbalanced conditions causing starving or flooding of the evaporator. The condensing pressure is constant.

Flooding

- **Gas enters the capillary tube**
  - High specific volume of the vapor
  - Reducing the feed rate of capillary tube

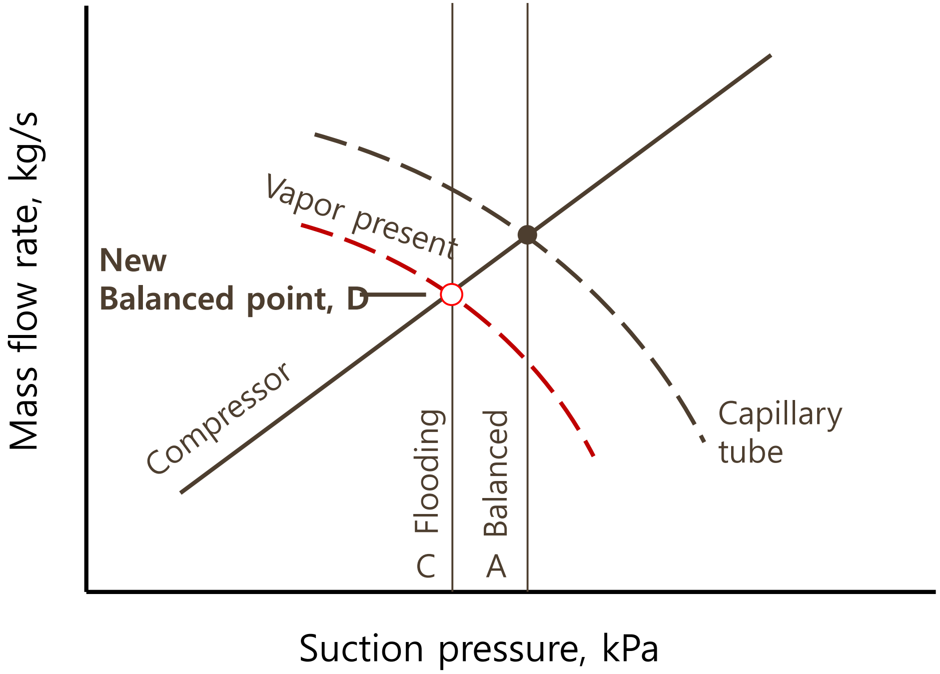


FIGURE Unbalanced conditions causing starving or flooding of the evaporator.
The condensing pressure is constant.

Flooding

- **At point D**
  - (1) Balanced condition, not a satisfactory condition
  - (2) Reducing refrigerating effect compared with that when saturated or sub-cooled liquid enters the capillary tube

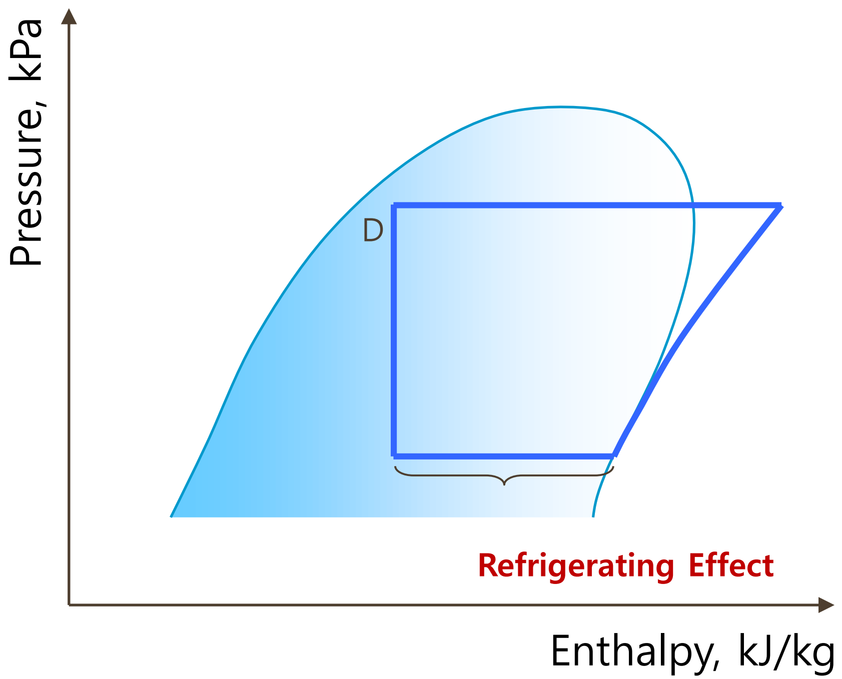


FIGURE Reduction in refrigerating effect when some vapor enters the capillary tube

Liquid-Line Suction-Line Heat Exchanger

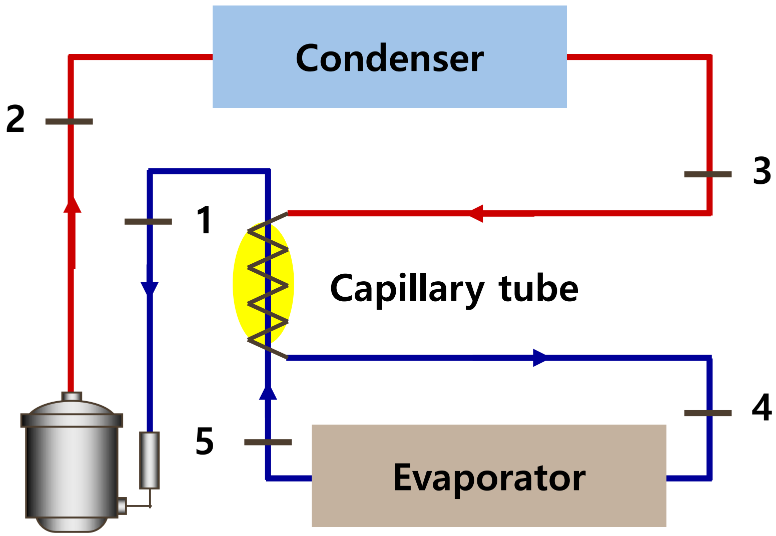


FIGURE Schematic diagram of the refrigeration system with LLSL heat exchanger

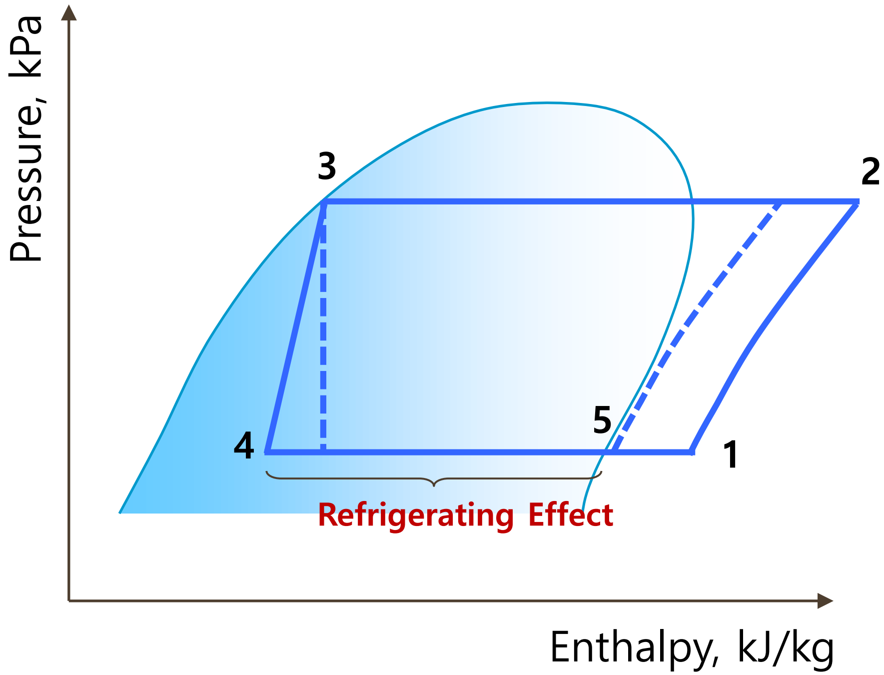
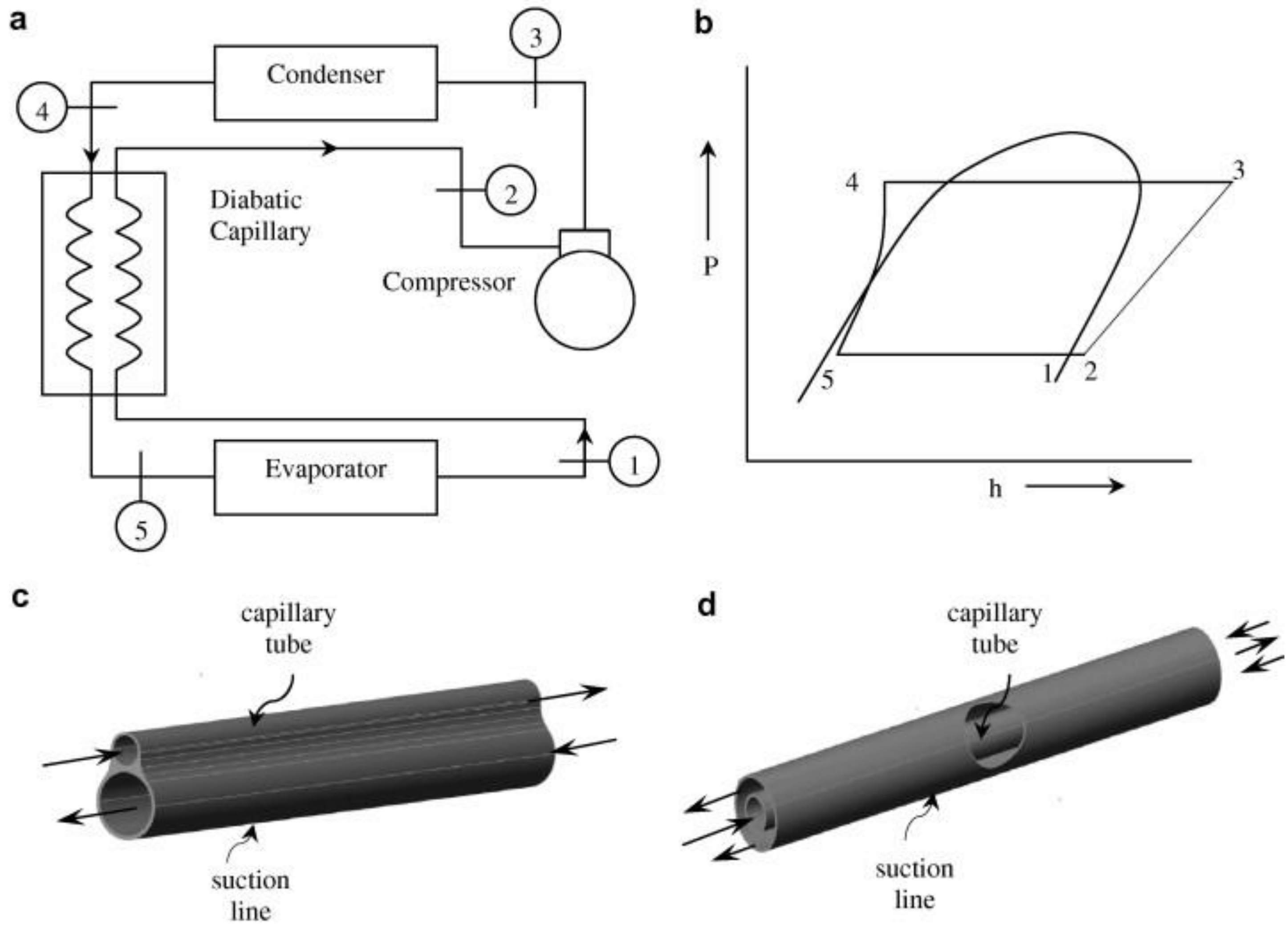


FIGURE P-h diagram of the refrigeration system with LLSL heat exchanger

Capillary Tube



Ref. Mohd. Kaleem Khan et al, Flow characteristics of refrigerants flowing through capillary tubes – A review, Applied Thermal Engineering, Volume 29, Issues 8–9, 2009, pp. 1426-1439

Capillary Tube

Advantages & Disadvantages

Advantages	Disadvantages
1. Simple 2. No moving parts 3. Inexpensive 4. Equalizes the pressures in the system during the off cycle ➢ **Low starting torque**	1. Not adjustable to changing load condition 2. Susceptible to clogging by foreign matter 3. The mass of refrigerant charge should be held in close limits

Capillary Tube “Selection“

Flooding

- ❑ **Bore and the length of the capillary tube**
  - The compressor and the tube fix a balance point at the desired evaporating temperature
- ➢ **Analytical method**
- ➢ **Graphical method**

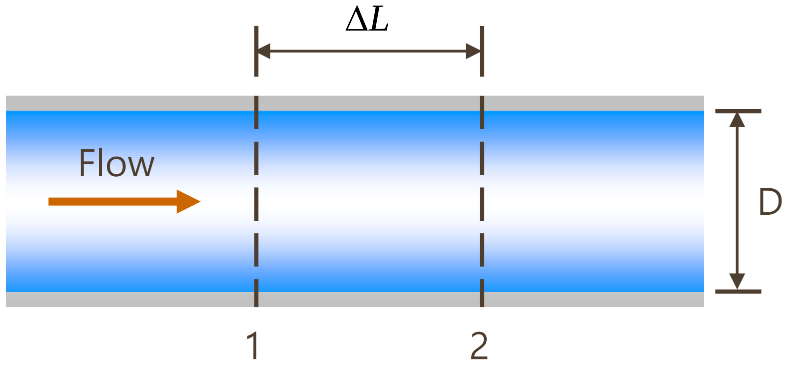


FIGURE Incremental length of capillary tube

Analytical Method

❑ Notations

A = cross-sectional area of inside of tube, m^2
D = inner diameter of tube, m
f = friction factor
ΔL = length of increment, m
p = pressure, Pa
T = temperature, °C
Re = Reynolds number
V = velocity, m/s
m = mass flow rate, kg/s
G = mass flux, kg/m^2s
x = quality
h = enthalpy, J/kg
v = specific volume, m^3/kg
μ = viscosity, Pa·s
τ_w = wall shear stress, Pa

❑ Subscript

f = saturated liquid
g = saturated vapor

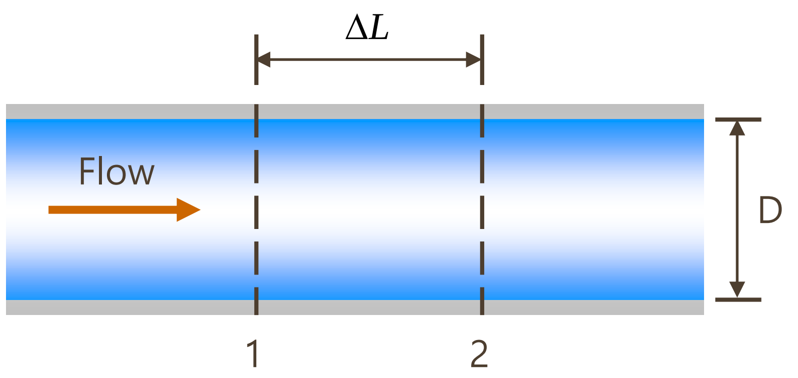


FIGURE Incremental length of capillary tube

Analytical Method

- **Refrigerant property calculation**
  - The mass flow rate and all the conditions at point 1 are known.
  - Select T_2
  - Compute the followings

    $p_2, h_{f_2}, h_{g_2}, v_{f_2}, v_{g_2}, \mu_{f_2}, \mu_{g_2}$

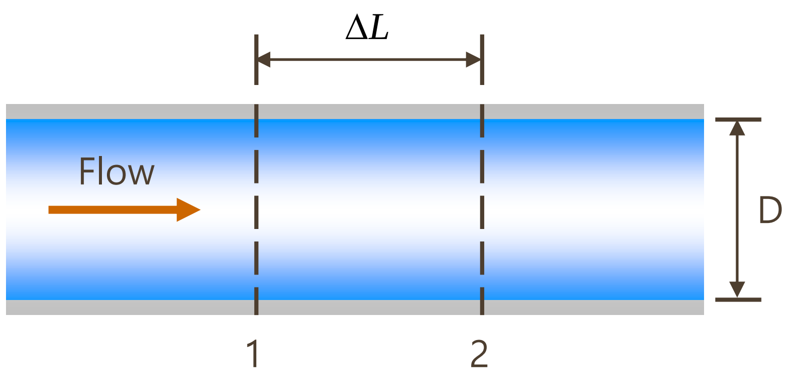
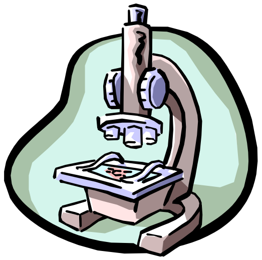


FIGURE Incremental length of capillary tube

Capillary Tube - Selection

Analytical Method

❑ **Equations for properties of saturated refrigerant 22**



$$\ln\left(\frac{p}{1000}\right) = 15.06 - \frac{2418.4}{T + 273.15}$$

$$v_f = \frac{0.777 + 0.002063T + 0.00001608T^2}{1000}, \quad v_g = \frac{-4.26 + 94050(T + 273.15)/p}{1000}$$

$$\frac{h_f}{1000} = 200.0 + 1.172T + 0.001854T^2, \quad \frac{h_g}{1000} = 405.5 + 0.3636T - 0.002273T^2$$

$$\mu_f = 0.0002367 - 1.715\times10^{-6}T + 8.869\times10^{-9}T^2$$

$$\mu_g = 11.945\times10^{-6} + 50.06\times10^{-9}T + 0.2560\times10^{-9}T^2$$

Analytical Method

❑ Conservation of mass

$$\dot{m} = \frac{AV_1}{v_1} = \frac{AV_2}{v_2}$$

$$G = \frac{\dot{m}}{A} = \frac{V_1}{v_1} = \frac{V_2}{v_2}$$

❑ Conservation of energy

- Heat transfer is negligible
- No work, no potential energy change

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

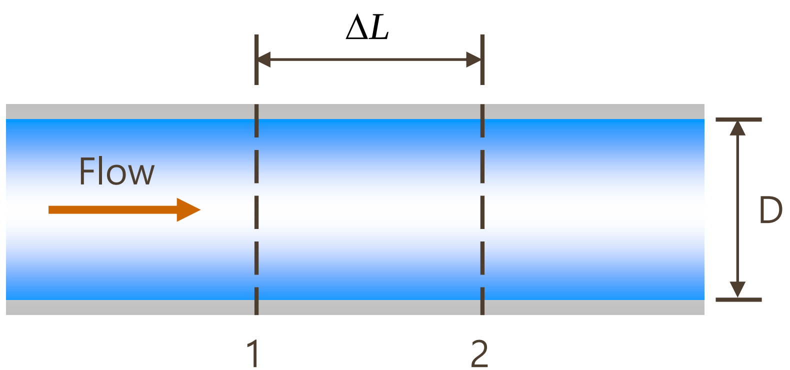


FIGURE Incremental length of capillary tube

Analytical Method

❑ Combination of mass & energy conservation

$$h_1 + \frac{(Gv_1)^2}{2} = h_2 + \frac{(Gv_2)^2}{2}$$

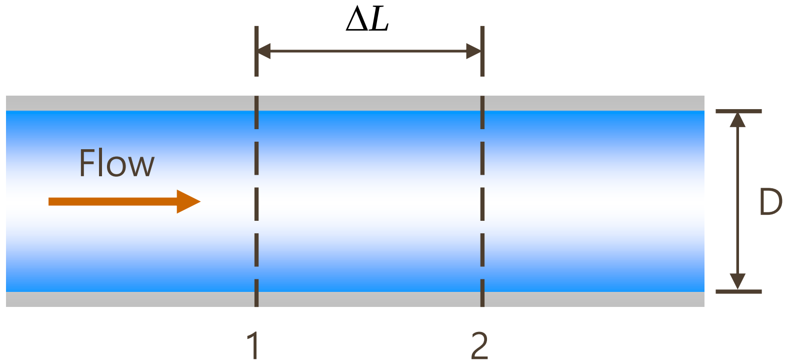


FIGURE Incremental length of capillary tube

❑ Equations of h_2 & v_2

$$h_2 = h_{f2}(1-x) + h_{g2}x$$

$$v_2 = v_{f2}(1-x) + v_{g2}x$$

$$\{h_{f2} + (1-x)h_{g2}\} + \frac{\left[G\{v_{f2} + (1-x)v_{g2}\}\right]^2}{2} = h_1 + \frac{(Gv_1)^2}{2} \Rightarrow X$$

Analytical Method

- **Friction factor *f***
  - Lower range of turbulent region

$$f = \frac{0.33}{\text{Re}^{0.25}} = \frac{0.33}{(VD/\mu v)^{0.25}}$$

$$\mu = \mu_f (1-x) + \mu_g x$$

- **Shear stress τ_w**

$$\tau_w = f_m \frac{V_m^{\,2}}{8 v_m} = f_m \frac{v_m G^2}{8}$$

$$f_m = \frac{f_1 + f_2}{2}, \quad v_m = \frac{v_1 + v_2}{2}$$

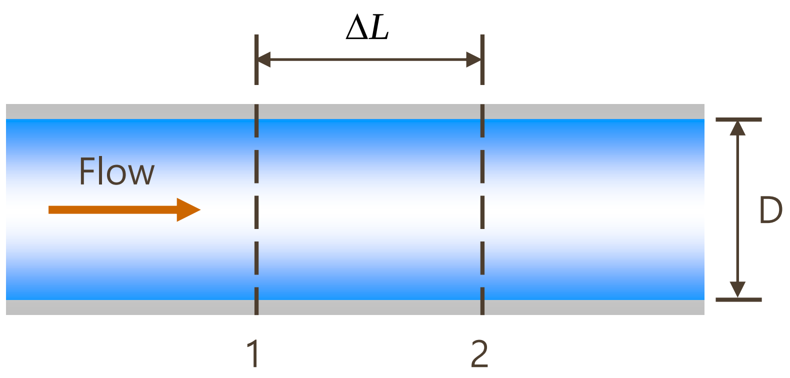


FIGURE Incremental length of capillary tube

Analytical Method

- **Conservation of momentum**
  - The difference in forces applied to the element

$$p_1A - p_2A - \tau_w P\Delta L = \frac{AV_1}{v_1}(V_2 - V_1)$$

$$P = \pi D, \quad A = \frac{\pi D^2}{4}$$

$$\Rightarrow \quad p_1 - p_2 = f\frac{G^2\Delta L}{2\rho D} + G(V_2 - V_1)$$

$$\Rightarrow \quad \Delta L$$

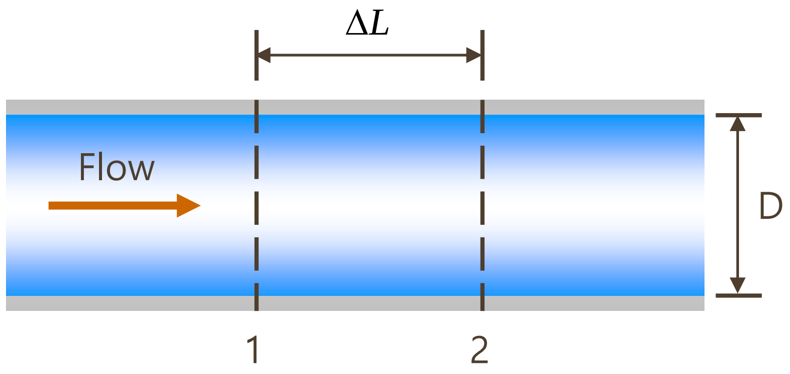


FIGURE Incremental length of capillary tube

Constant Pressure Expansion Valve

Constant Pressure Expansion Valve

Schematic View

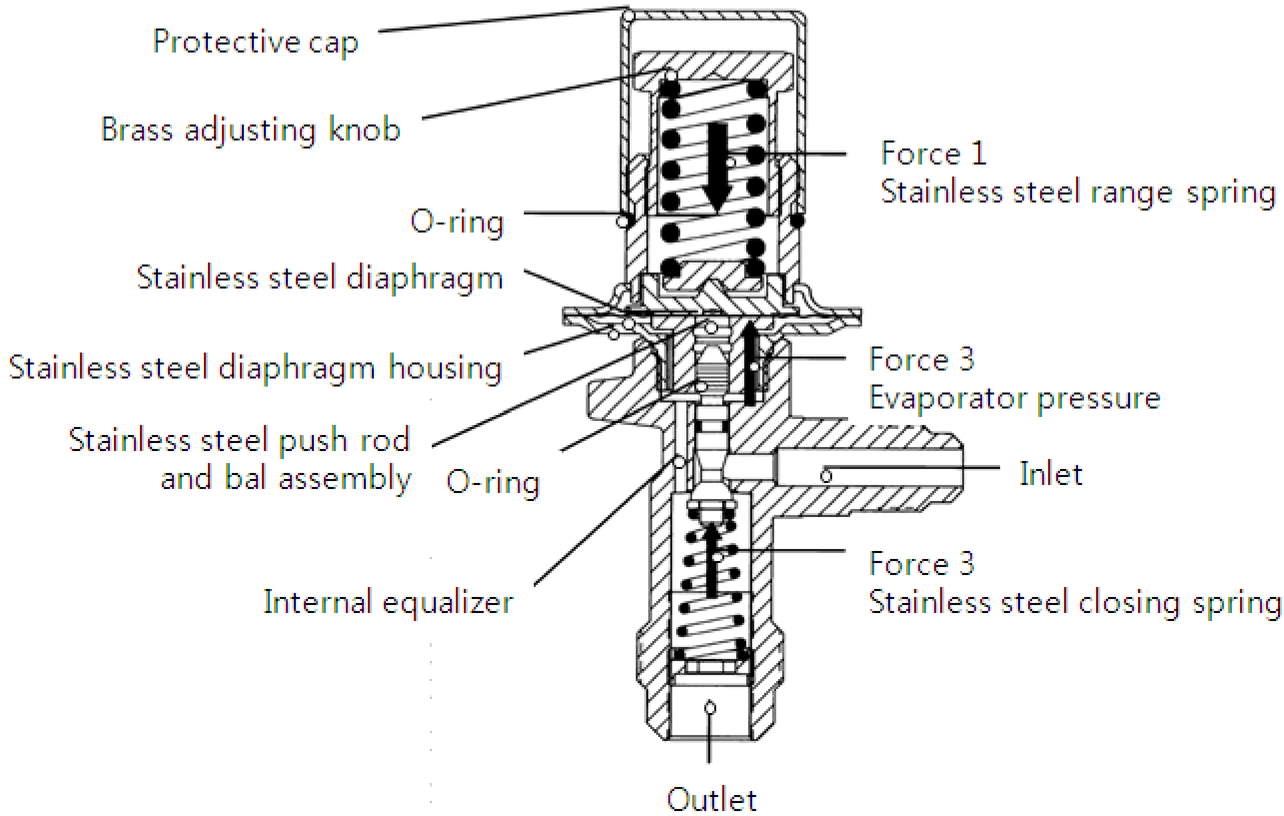


FIGURE Schematic view of a constant pressure expansion valve

Constant Pressure Expansion Valve

- **Maintains a constant pressure at its outlet**
- **Sensing the evaporator pressure**
  - **Below the control point**
    - → Opens wider
  - **Above the control point**
    - → Partially closes
- **Less than about 30 kW**
- **Critical charge – feasible to prevent liquid from flooding**
- **Pressure limiting characteristic**
  - **Constant evaporating temperature**
  - **Control the humidity**
  - **Prevent freezing in water coolers**
  - **Protection against overload of the compressor**

Balance Point

- **Balance Point, A**
  - Expansion valve feeds as much as the compressor pumps from the evaporator

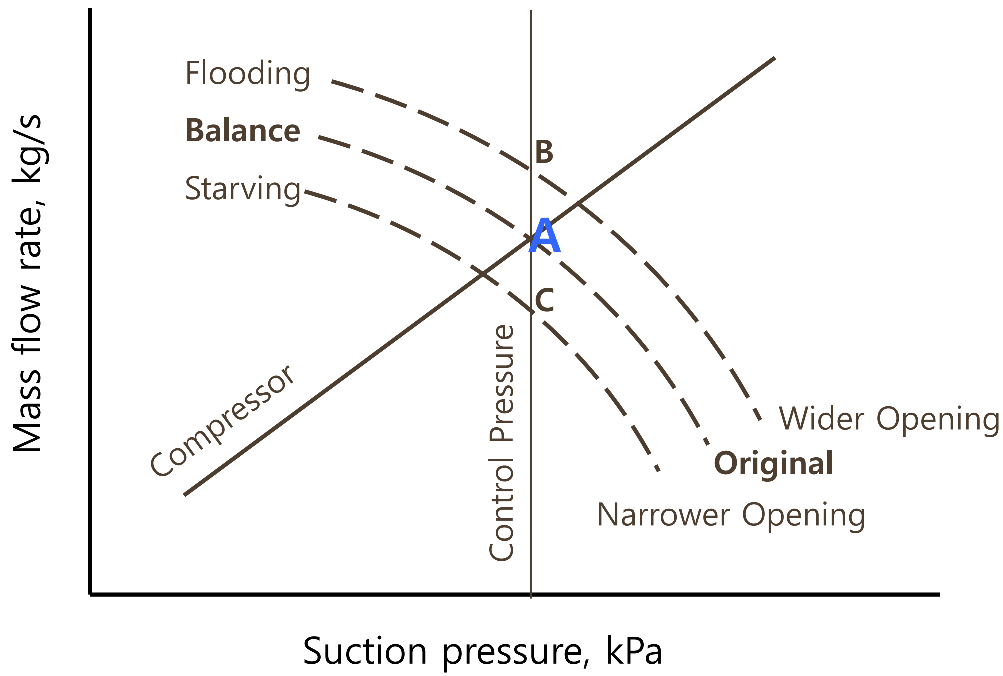


FIGURE Balanced and unbalanced conditions using a constant-pressure expansion valve. The condensing pressure is constant.

Starving Condition

- **Heavy heat load condition**
  - Temperature and pressure attempt to rise
  - The valve partially closes
  - Prevent the rise in pressure
  - Decrease in the feed rate of the valve

Point C : Starving of the evaporator

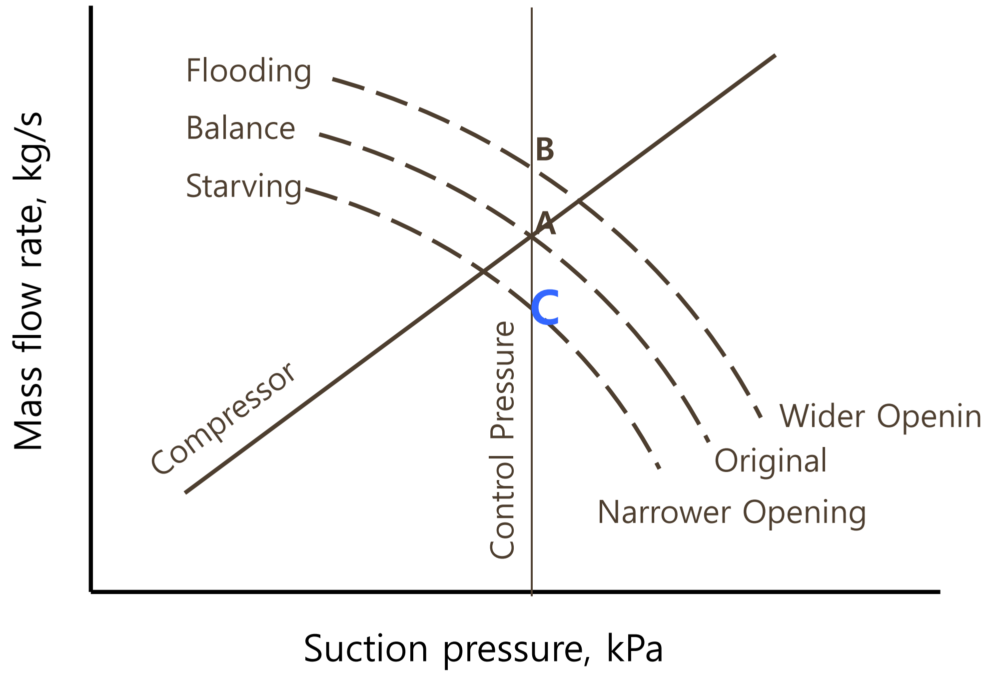


FIGURE Balanced and unbalanced conditions using a constant-pressure expansion valve. The condensing pressure is constant.

Constant Pressure Expansion Valve

Flooding Condition

- **Low heat load condition**
  - Temperature and pressure attempt to drop off
  - The valve opens wider
  - Prevent the drop in pressure
  - Increase the feed rate of the valve

Point B : Flooding of the evaporator

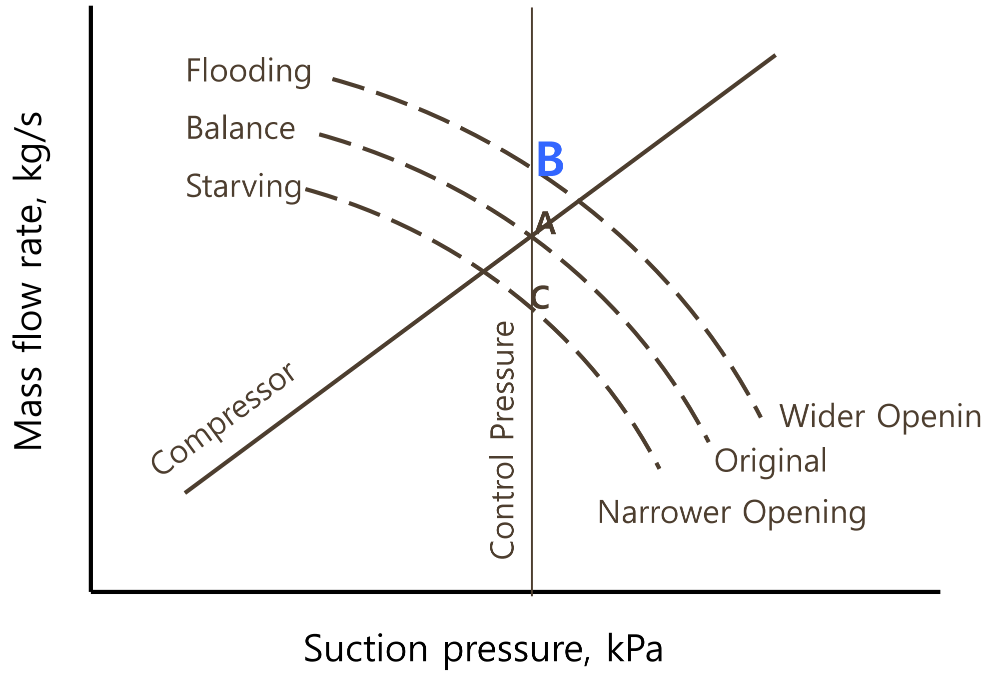


FIGURE Balanced and unbalanced conditions using a constant-pressure expansion valve. The condensing pressure is constant.

Float Type Expansion Valve

Float Type expansion Valve

- Maintains the liquid at a constant level in a vessel or an evaporator.
- Always establishes balanced conditions of flow between the compressor and itself.
- Float valves and float-switch-solenoid combinations are used primarily in large installations.
- Regulate the flow to flooded evaporators in response to the level of the evaporator.

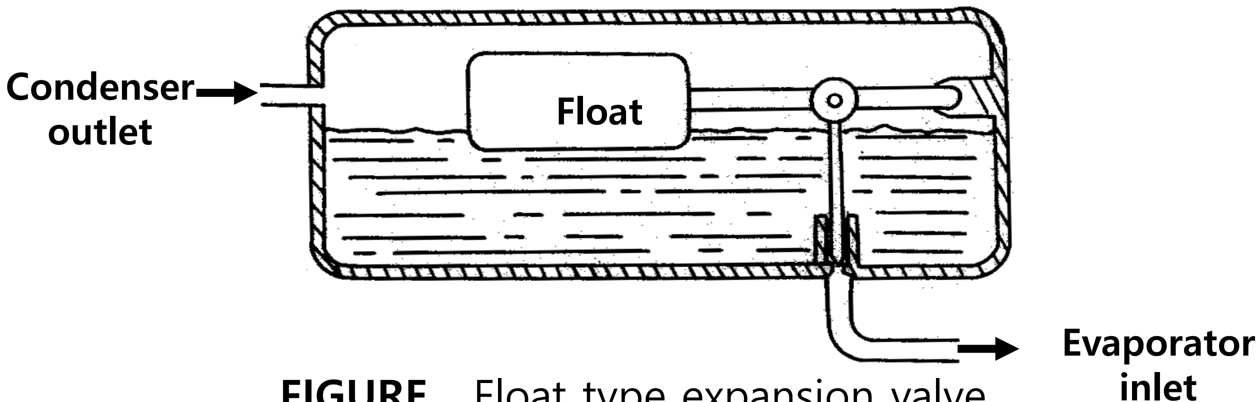


FIGURE Float type expansion valve

Starving Condition

- **Heavy heat load condition**
  - Evaporating temperature and pressure rise
  - The compressor pumps a greater rate of flow than the valve feeding
  - The valve opens wider

A new balance point, B

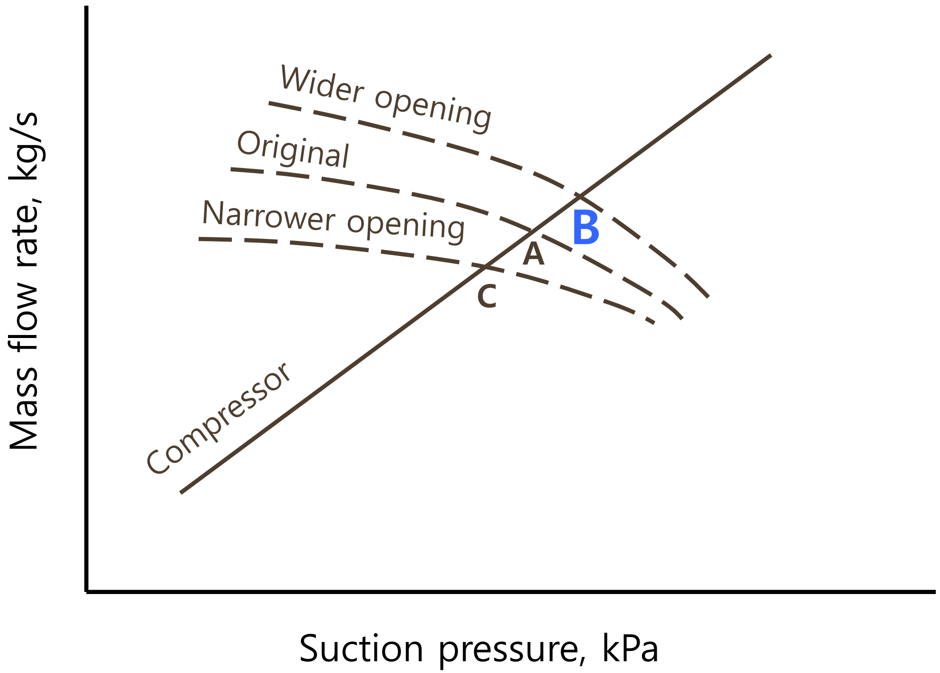


FIGURE Balance points with various load conditions using a float valve. The condensing pressure is constant.

Float Type Expansion Valve

Flooding Condition

- **Low heat load condition**
  - Evaporating temperature and pressure drop
  - The compressor pumps a lesser flow than the valve feeding
  - The valve partially closes

A new balance point, C

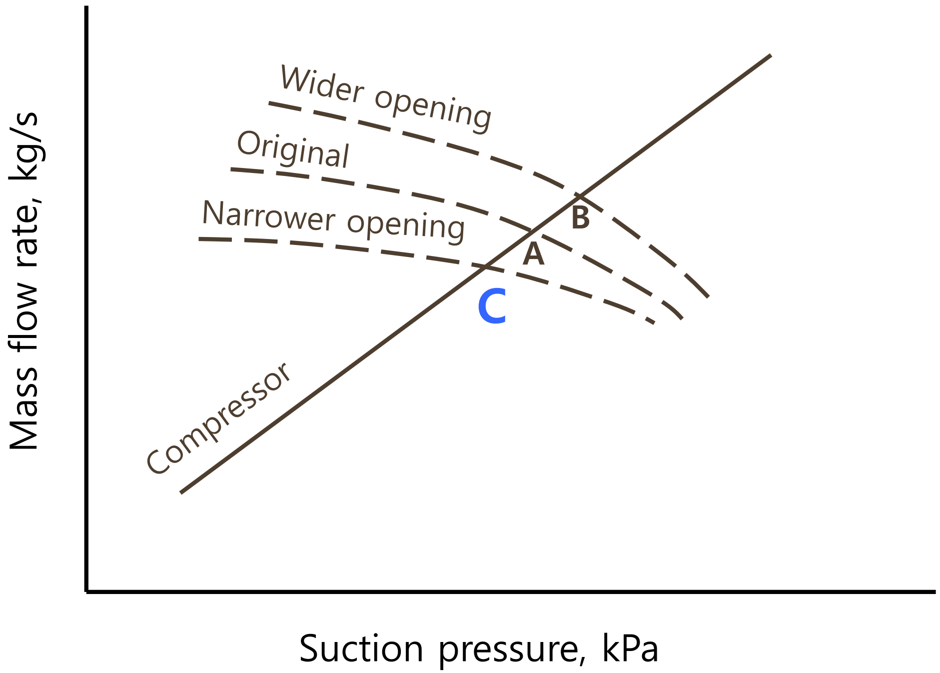


FIGURE Balance points with various load conditions using a float valve. The condensing pressure is constant.

Thermostatic Expansion Valve

Schematic View

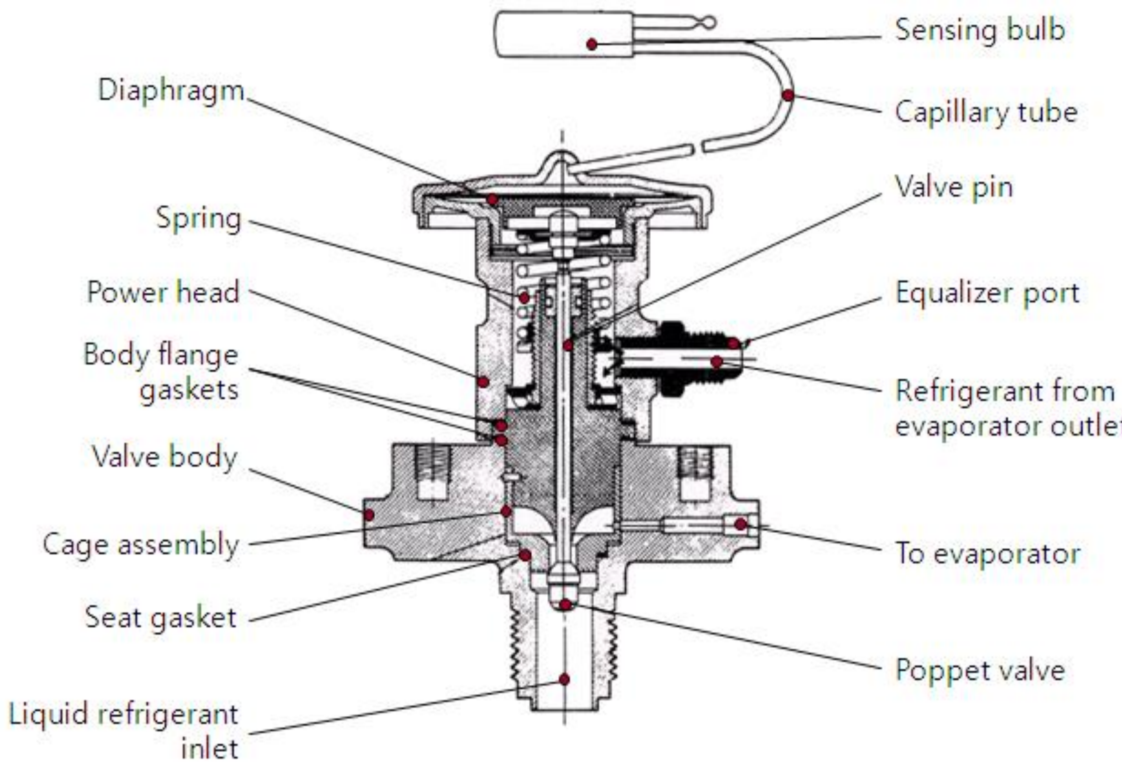


FIGURE Schematic view of a thermostatic expansion valve

Thermostatic Expansion Valve

- Moderate-sized refrigeration system
- Regulating the rate of flow of liquid refrigerant in proportion to the rate of evaporation
- The balance of the flow rate is identical to those of the thermostatic expansion valve.

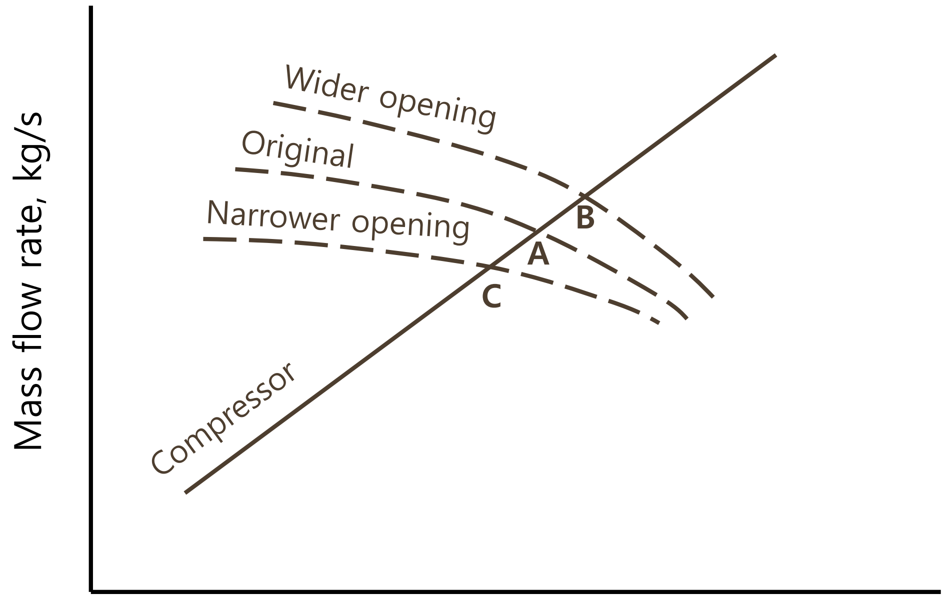
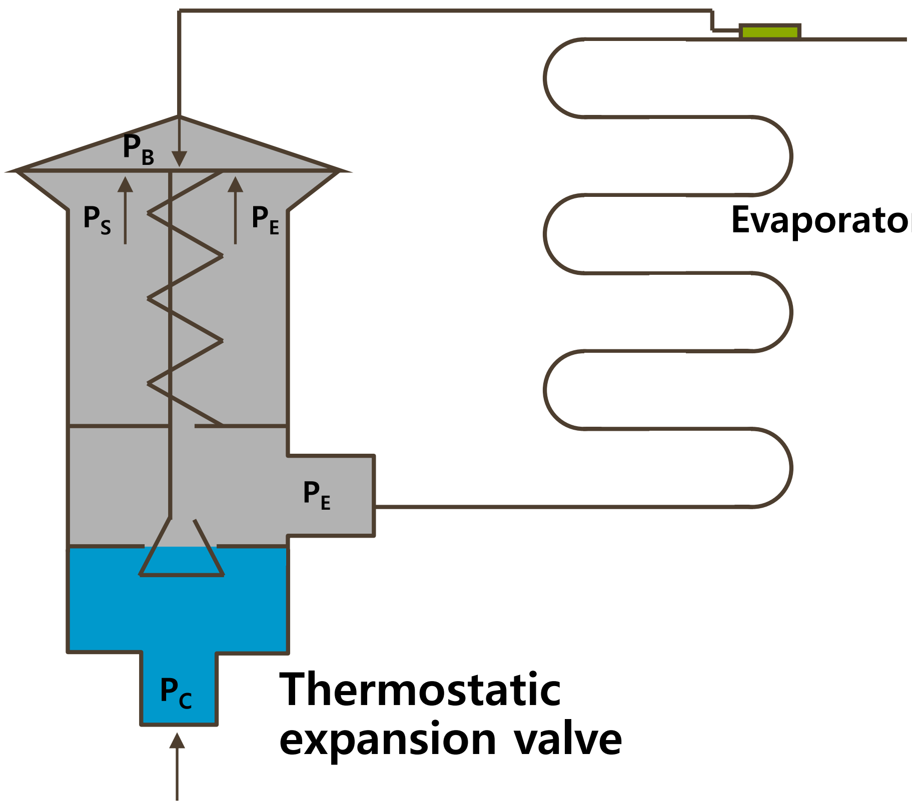
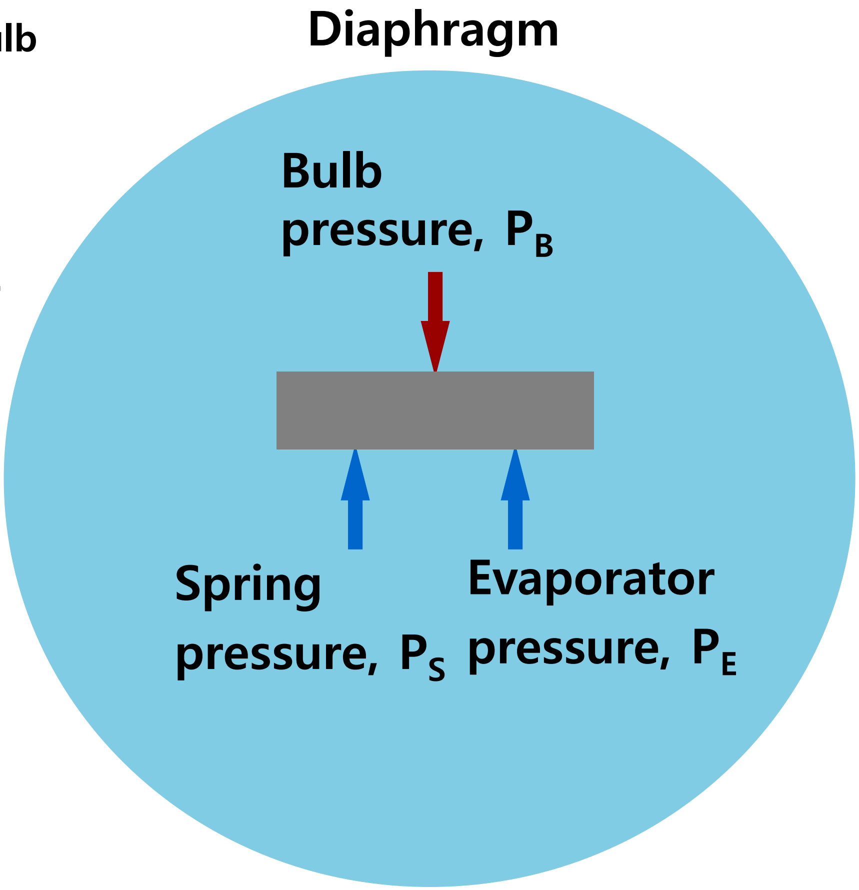


FIGURE Balance points with various load conditions using a float valve. The condensing pressure is constant.

Thermostatic Expansion Valve





Thermostatic Expansion Valve

- **Power fluid**
  – the fluid in the bulb
- **A certain amount of superheat is required (4K)**
- **7K of superheat is needed to open valve completely.**
- **The operation of the valve maintains an approximately constant quantity of liquid**

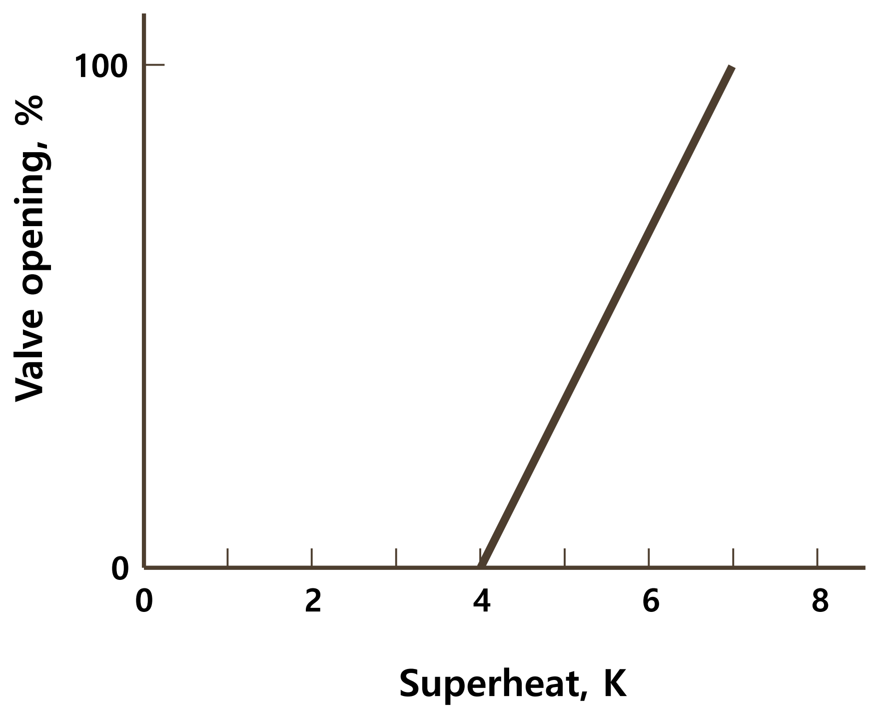


FIGURE Throttling range of thermostatic valve

Thermostatic Expansion Valve

Cross Change

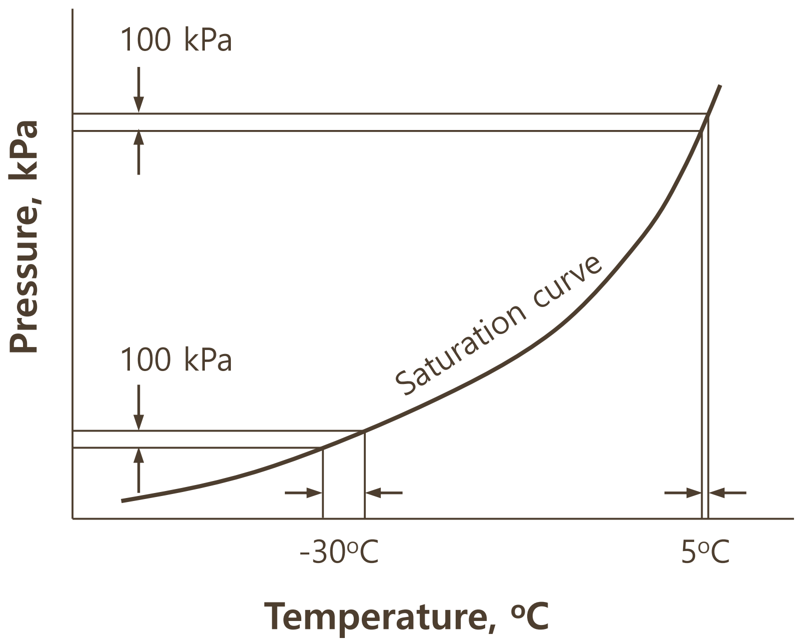


FIGURE Pressure-temperature characteristic of a refrigerant R22 power fluid.

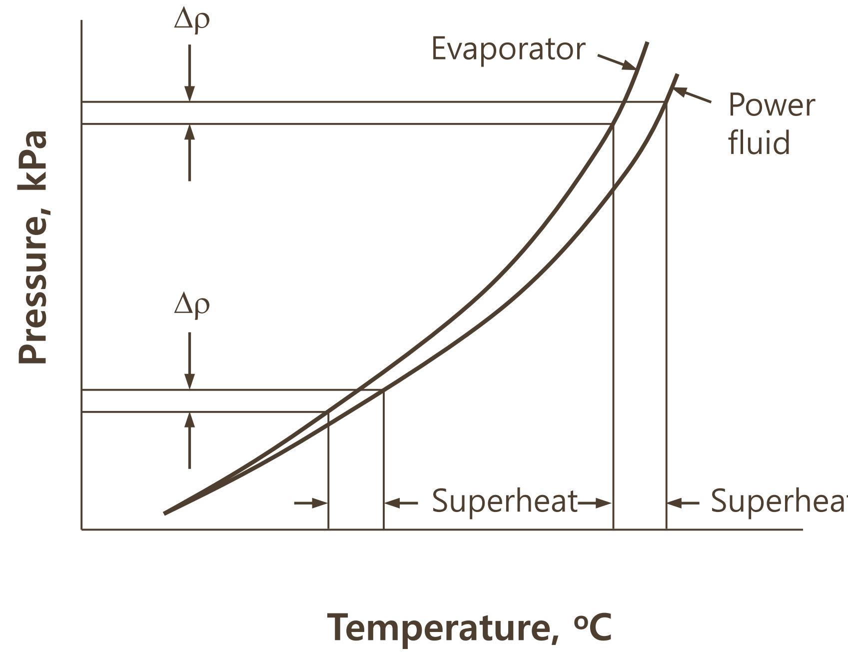
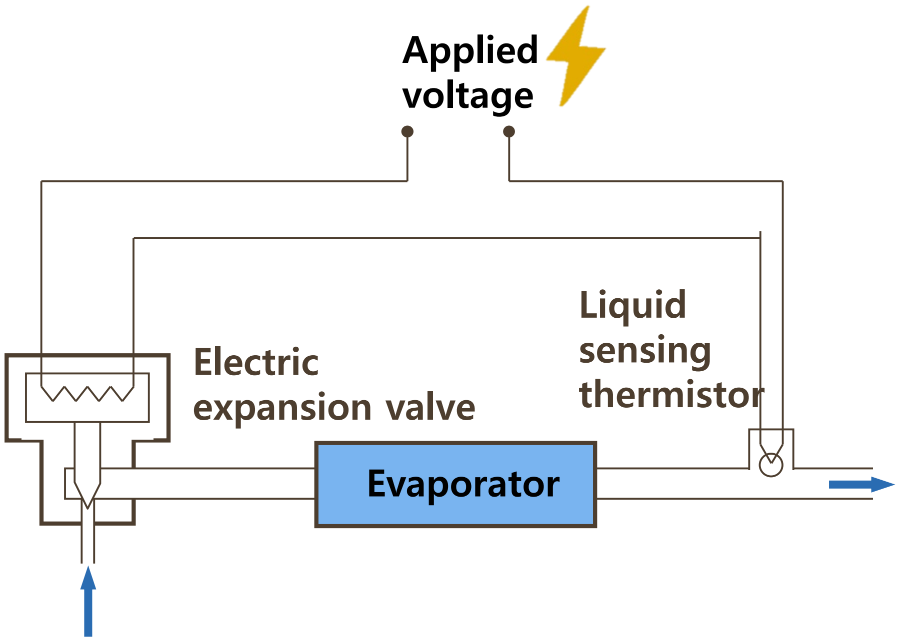


FIGURE Evaporator and power fluid temperature in a thermostatic expansion valve with a cross charge.

Electric Expansion Valve

Electric Expansion Valve



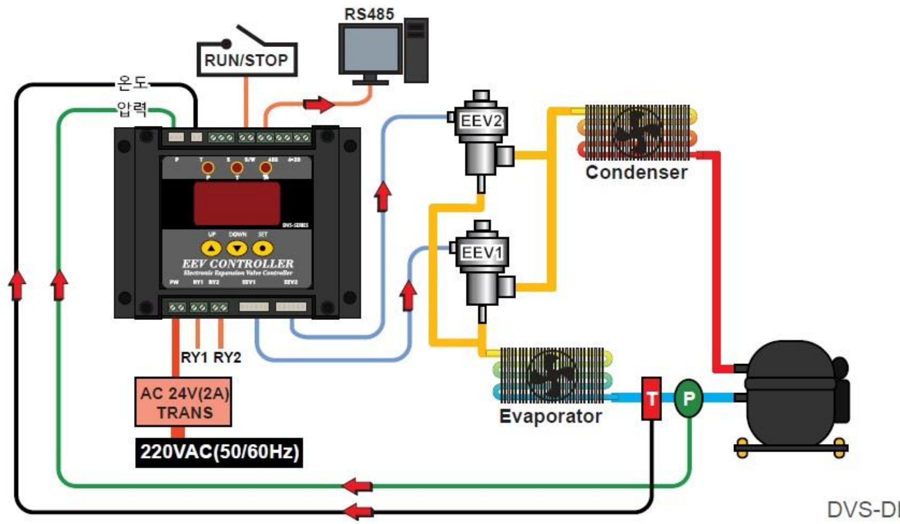
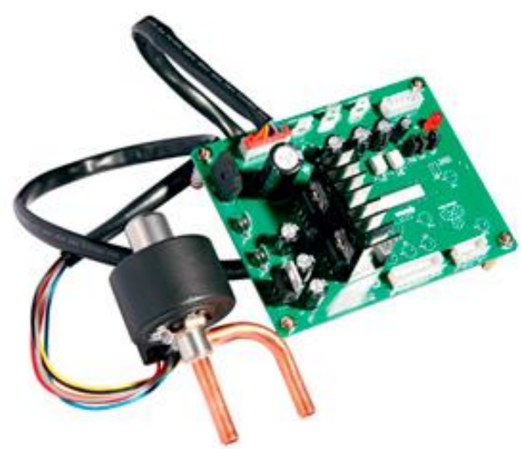
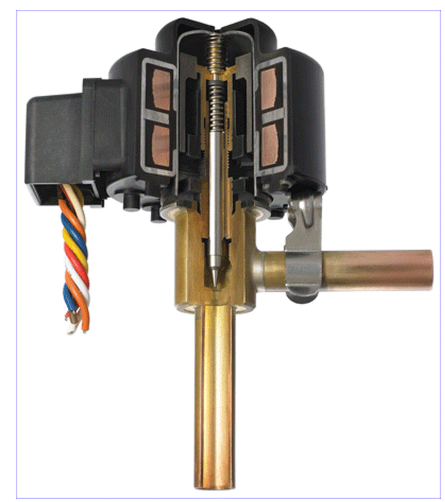


FIGURE An electric expansion valve





Electric Expansion Valve

❑ Sensing the presence of liquid

- ➢ Temperature and resistance of the thermistor
- ➢ Current flow through the heater
- ➢ Valve opening

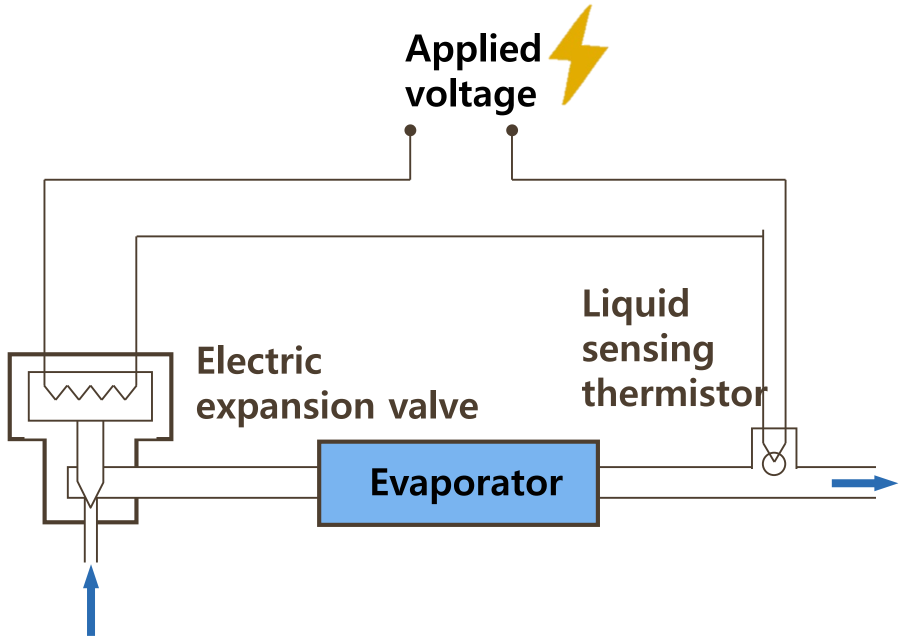


FIGURE An electric expansion valve

Question and Answer Session