

2008

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Bukac, Hubert, "Analysis of Two-Stage Compression in a Scroll Compressor" (2008). *International Compressor Engineering Conference*. Paper 1875.  
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# ANALYSIS OF TWO-STAGE COMPRESSION IN A SCROLL COMPRESSOR

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## ABSTRACT

The model of two-stage compression processes, and plots of results of modeling in temperature-entropy, pressure-enthalpy and pressure-volume diagrams show advantages and disadvantages of high and low built-in compression ratios as well as the effect of large and small volume of the dome. Also of interest is the velocity of refrigerant gas during the pressure and temperature equalization. The velocity of flow during pressure and temperature equalization starts with local velocity of sound, and it decreases rapidly to zero. The short burst of gas flow with sonic velocity that is accompanied by a sudden change in pressure in the dome and in the last pocket are sources of typical noise that is inherent to all scroll compressors. Experiments have shown the scroll compressor runs most quiet when the pressure in the dome, which is approximately equal to the condensing pressure, is equal to the pressure in the last innermost pocket when the this pocket opens and co-joins with the volume of the dome.

## 1. INTRODUCTION

In an air conditioning or refrigeration system or in a heat pump, the scroll compressor can operate in two different arrangements, with or without a check valve. The check valve in the scroll compressor is actually a discharge valve, which function is the same as the function of the discharge valve in a reciprocating-piston compressor. If the scroll compressor does not have any check valve, the volume of the piping and the volume of the condenser have to be added to the volume of the dome. In this case the volume of the dome becomes very big. Thus, before the last compression pocket opens into the dome we have two volumes with different pressures and different temperatures of refrigeration vapor. In the last, innermost, pocket we have some intermediate pressure and temperature, while in the dome we have condensing pressure and discharge temperature.

At the steady-state conditions, the scroll compressor operates between evaporating and condensing pressures. The condensing pressure divided by evaporating pressures as the system compression ratio. On the other hand, the ratio of volume of suction pocket divided by the volume of discharge pocket is the built-in compression ratio. Thus, the first-stage of compression in the scroll compressor is constant-compression ratio compression. The refrigerant vapor is always raised to some intermediate pressure. As the compressor rotates, the dome changes its volume as well, and it resembles a cylinder with a clearance volume. The compression in the dome is the second-stage compression.

## 2. COMPRESSION VOLUMES

When the innermost pockets open into the dome the refrigerant vapor starts to flow back from the dome into the last pocket. The flow starts with local sonic velocity. The velocity of flow drops rapidly, and the flow ceases when the pressures equalize. This phenomenon lasts a small portion of compressor's revolution. Therefore, we can consider both volumes to be constant. From the point of view of thermodynamics, we can consider it as a mixing process at constant volume. In order to illustrate how it happens, Fig. 1 shows one full revolution of a scroll compressor in steps of  $45^\circ$ .

### 2.1 Simplified Model of Mixing Process at Constant Volume

We start at  $0^\circ$  position of the orbiting scroll as it is shown in the Fig. 1. The state of refrigerant vapor in the last, discharge, pocket has temperature  $T_i$ , absolute pressure  $p_i$ , the pocket volume is  $V_i$ , and density of refrigerant vapor is  $\rho_i$ . The conditions in the dome are temperature  $T_D$ , absolute pressure  $p_D$ , volume of the dome is  $V_D$  and density of refrigerant vapor is  $\rho_D$ . When the orbiting scroll rotates clockwise, two gaps between the tip and the wall of mating scrolls start to grow. At the position of  $45^\circ$  that gap is clearly visible. Because the pressure in the dome  $p_D$  is higher

than the pressure  $p_i$  in the last pocket the refrigerant vapor flows back from the dome into last pocket. Our goal is to calculate pressure in the dome and temperature after mixing.

We will make the following assumptions:

1. Both volumes,  $V_i$  and  $V_D$  remain constant.
2. The gas does not perform any volume work ( $dA = p \cdot dV = 0$ ).
3. Both volumes are thermally insulated, and there is not any exchange of heat with the surroundings ( $dQ = 0$ )
4. The gas constant of refrigerant vapor in both volumes is the same
5. No leak of refrigerant vapor either from the last pocket or from the dome.

From the first law of thermodynamics for a closed system follows

$$dQ = dU + dA \quad (1)$$

Where

$Q$  is heat [J]

$U$  is internal energy [J]

$A$  is volumetric work [N.m]

Since  $dA = 0$  the integral of Eq.(1) yields

$$U = \sum_{i=1}^2 U_i = \text{const.} \quad (2)$$

Where

$U$  is internal energy of refrigerant gas in total volume [J]

$U_i$  is internal energy of refrigerant gas in  $i$ -th volume [J]

When we substitute for internal energies in each volume into Eq.(2), we get

$$(V_i + V_D) \cdot \rho \cdot c_V \cdot T = V_i \cdot \rho_i \cdot c_{Vi} \cdot T_i + V_D \cdot \rho_D \cdot c_{VD} \cdot T_D \quad (3)$$

Where

$c_V$  is specific heat at constant volume in joint volume  $V_i + V_D$  [ $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ]

$c_{Vi}$  is specific heat at constant volume  $V_i$  [ $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ]

$c_{VD}$  is specific heat at constant volume  $V_D$  [ $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ]

$\rho$  is density in joint volume  $V_i + V_D$  [ $\text{kg} \cdot \text{m}^{-3}$ ]

$\rho_i$  is density of vapor in volume  $V_i$  [ $\text{kg} \cdot \text{m}^{-3}$ ]

$\rho_D$  is density of vapor in volume  $V_D$  [ $\text{kg} \cdot \text{m}^{-3}$ ]

$T$  is final temperature in joint volume [K]

$T_i$  is temperature of vapor in volume  $V_i$  [K]

$T_D$  is temperature of vapor in volume  $V_D$  [K]

Index  $i$  indicates values in the last pocket, index  $D$  indicates values in the dome.

The temperature of the refrigerant gas after mixing will be

$$T = \frac{V_i \cdot \rho_i \cdot c_{Vi} \cdot T_i + V_D \cdot \rho_D \cdot c_{VD} \cdot T_D}{(V_i + V_D) \cdot \rho \cdot c_V} \quad (4)$$

There two unknowns in Eq. (4), density  $\rho$  of refrigerant vapor after mixing and the specific heat after mixing.

Since we consider no leakage, the density of refrigerant vapor after mixing can be found from the law of conservation of mass.

$$\rho \cdot (V_i + V_D) = \rho_i \cdot V_i + \rho_D \cdot V_D \quad (5)$$

and

$$\rho = \frac{\rho_i \cdot V_i + \rho_D \cdot V_D}{V_i + V_D} \quad (6)$$

Specific heat at constant volume after mixing can be estimated as a weighted average of specific heats before mixing.

$$\rho \cdot (V_i + V_D) \cdot c_V = \rho_i \cdot V_i \cdot c_i + \rho_D \cdot V_D \cdot c_{VD} \quad (7)$$

and

$$c_v = \frac{\rho_i \cdot V_i \cdot c_i + \rho_D \cdot V_D \cdot c_{vD}}{V_i + V_D} \quad (8)$$

The final pressure after mixing can be found from the equation of state.

$$p \cdot (V_i + V_D) = (\rho_i \cdot V_i + \rho_D \cdot V_D) \cdot R \cdot T \quad (9)$$

and

$$p_i \cdot V_i = \rho_i \cdot V_i \cdot R_i \cdot T_i \quad (10a)$$

$$p_D \cdot V_D = \rho_D \cdot V_D \cdot R_D \cdot T_D \quad (10b)$$

When we express products  $\rho_i \cdot V_i$  and  $\rho_D \cdot V_D$  from Eqs. (10a) and (10b) and substitute them into Eq. (9), we get

$$p = \frac{T}{V_i + V_D} \left( \frac{p_i \cdot V_i}{R_i \cdot T_i} + \frac{p_D \cdot V_D}{R_D \cdot T_D} \right) \cdot R \quad (11)$$

Where

$R$  is gas constant of the refrigerant vapor after mixing [ $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ]

$R_i$  is gas constant of the refrigerant vapor in volume  $V_i$  before mixing [ $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ]

$R_D$  is gas constant of the refrigerant vapor in volume  $V_D$  before mixing [ $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ]

**Remark:** We can find gas constant at given pressure and temperature from Mayer's relation  $R = c_p - c_v$ . Specific heats at constant pressure and constant volume for many refrigerants are readily available from REFPROP.

## 2.2 Enthalpy of Mixing Process at Constant Volume in the Scroll Compressor

Fig.1 shows the refrigerant vapor flows through very narrow passage. It is actually a throttling process. In this simplified analysis we consider Joule-Thomson's effect to be negligible. Therefore, the pressure equalization between the last pocket and the dome does not change enthalpy. The sum of enthalpies in both volumes before mixing is equal to the enthalpy in combined volume after mixing. Thus, we can write

$$\rho \cdot (V_i + V_D) \cdot h = \rho_i \cdot V_i \cdot h_i + \rho_D \cdot V_D \cdot h_D = \text{const} \quad (11)$$

$$h = \frac{\rho_i \cdot V_i \cdot h_i + \rho_D \cdot V_D \cdot h_D}{\rho \cdot (V_i + V_D)} \quad (12)$$

Where

$h$  is enthalpy of refrigerant vapor after mixing [ $\text{J} \cdot \text{kg}^{-1}$ ]

$h_i$  is enthalpy of refrigerant vapor in the last pocket before mixing [ $\text{J} \cdot \text{kg}^{-1}$ ]

$h_D$  is enthalpy of refrigerant vapor in the dome before mixing [ $\text{J} \cdot \text{kg}^{-1}$ ]

**Remark:** If we consider friction in flowing gas the enthalpy will not be constant.

## 3. MIXING AT CONSTANT VOLUME IN THERMODYNAMIC CYCLE DIAGRAMS

A two-stage compression in the scroll compressor can be visualized in different thermodynamic cycle diagrams. Of interest are temperature-entropy (T-s), pressure-enthalpy (p-h) and pressure-volume (p-V) diagrams.

### 3.1 The T-s Diagram

The mixing process at constant volume occurs between two isentropic compressions. The first one is the isentropic compression in pockets and the second one in the isentropic compression in the dome. In the Fig.2, the isentropic compression in a reciprocating piston compressor is between points 1 and 2. The isentropic compression in the pockets happens between points 1 and 3, and between points 1 and 6. Point 3 indicates smaller built-in compression ratio while the point 6 indicates higher built in compression ratio. The mixing occurs between points 3 and 4, and between points 6 and 7. The bigger volume of the dome shifts point 4 and 7 up.

### 3.2 The p-h Diagram

In the Fig.3 we can see mixing process in the p-h diagram. The meaning of depicted points is the same as it is in T-s

diagram. The bigger volume of the dome shifts points 4 and 7 closer to conditions in the dome rather than those in the discharging pockets.

### 3.3 The p-v diagram

The p-V diagram is shown in Fig.4. For the sake of comparison the compression line between point 1 and 2 corresponds to an equivalent ideal reciprocating-piston compressor. The compression in the scroll compressor takes two and half a revolution and it is between points 1 and 3. When the last pocket opens into the dome the mixing process takes place, and point 4 indicates pressure and volume after mixing. In a hypothetical case of a scroll compressor with zero volume of the dome, point 4 would be identical with the point 3.

### 3.4 The critical pressure diagram

Fig.5 the central line shows pressure in the last pocket as a function of evaporating pressure. The upper and lower lines are lines of critical pressures. At the steady state conditions the pressure in the dome is much higher than the pressure in the last pocket. Therefore, the pressure equalization starts with the flow of refrigerant vapor from the dome back into the last pocket. The flow starts with the local velocity of sound. At compressor startup the pressure in the dome is equal to the evaporating pressure, and it is much lower than the pressure in the last pocket, and the refrigerant vapor will start to flow out of the pocket into the dome. In this case the flow starts also with the velocity of sound. As the orbiting scroll rotates the gap between tips of vanes and walls of scrolls increases rapidly and the pressure equalizes. In the Fig.5 these pressures indicated as pressures after mixing.

The critical pressure ratio depends on isentropic coefficient, and it is equal to

$$C_{\text{crit}} = \frac{P_{\text{crit}}}{p} = \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}} \quad (13)$$

Where

$C_{\text{crit}}$  is critical pressure ratio [ ]

$P_{\text{crit}}$  is critical pressure [kPa]

$k$  is isentropic coefficient [ ]

Experiment have shown that a scroll compressor runs most quite when the pressure in the dome is equal to the pressure in the last pocket

## 4. CONCLUSIONS

The simplified analysis of two-stage compression in the scroll compressor shows that it is desirable to have volume of the dome as small as possible and the built-in compression ratio as high as possible. This will result in improved COP of the compressor and its lower noise.

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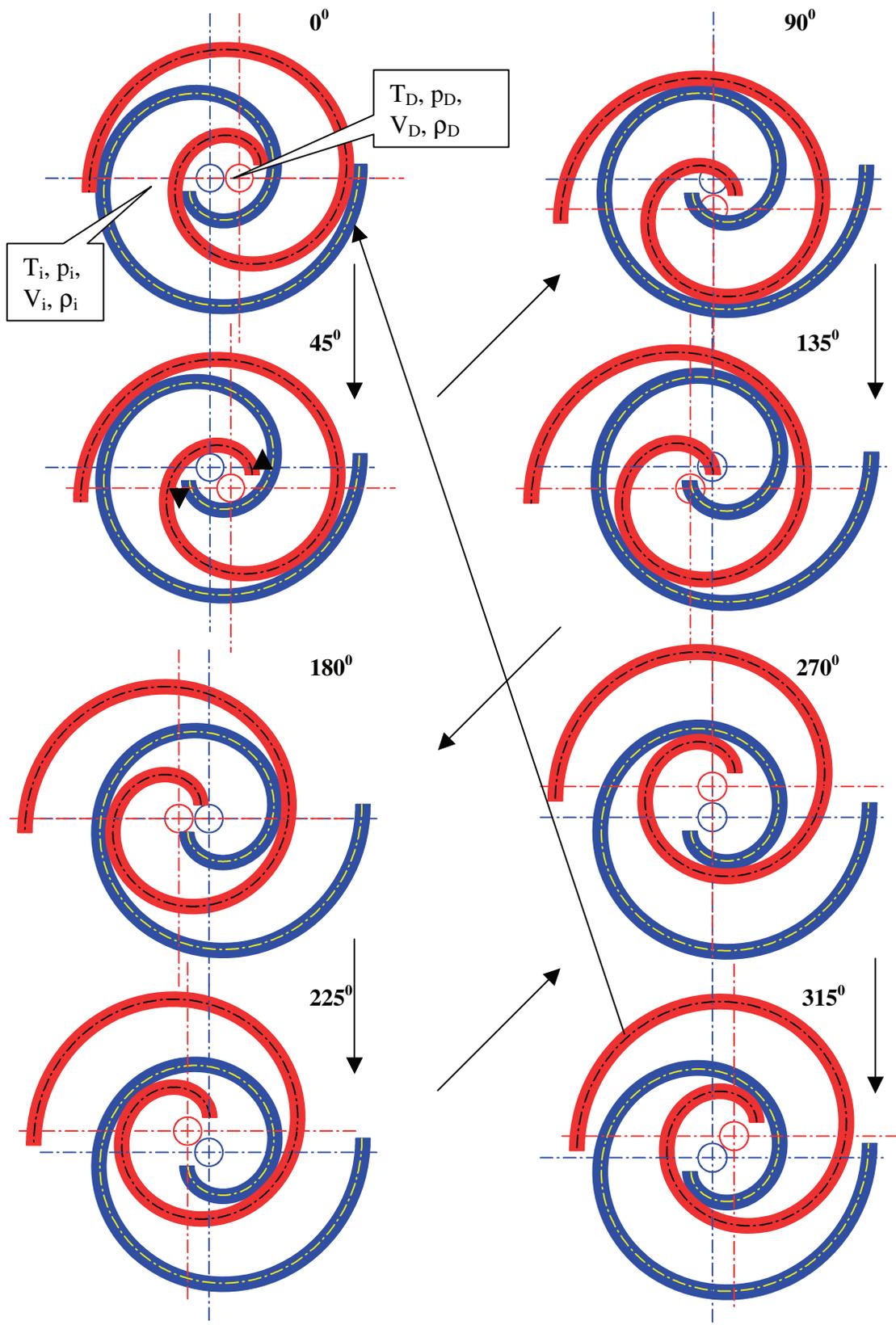


Fig.1: Rotation of scroll compressor

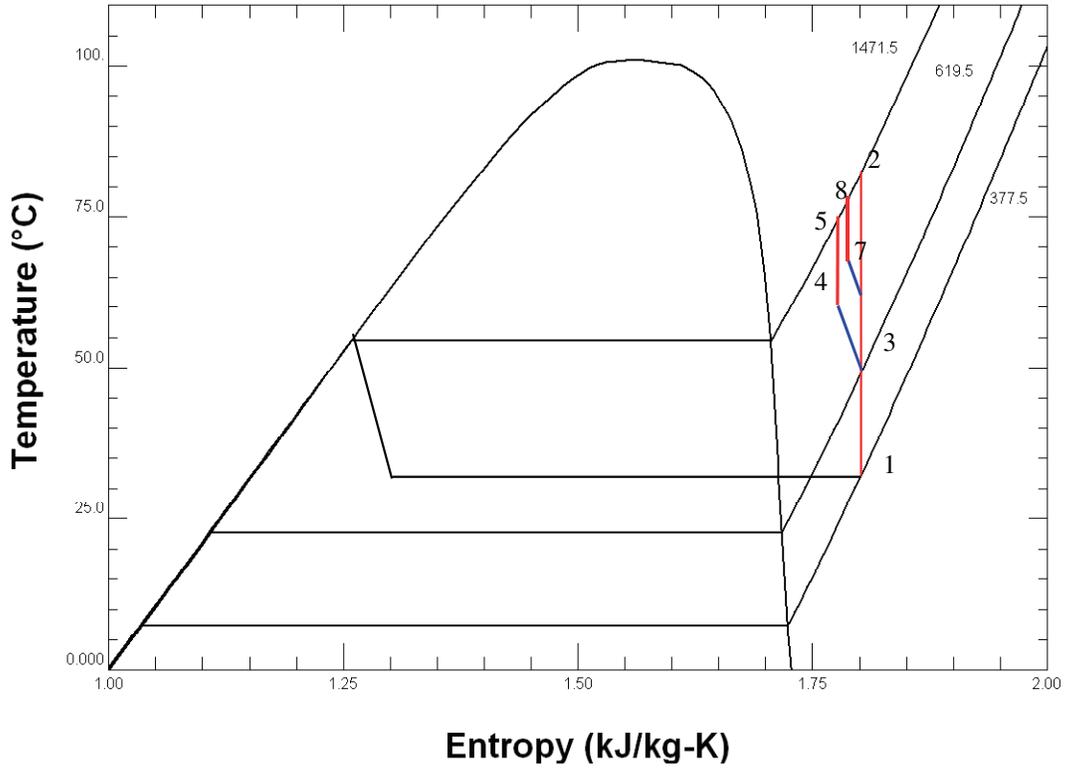


Fig.2: The T-s diagram

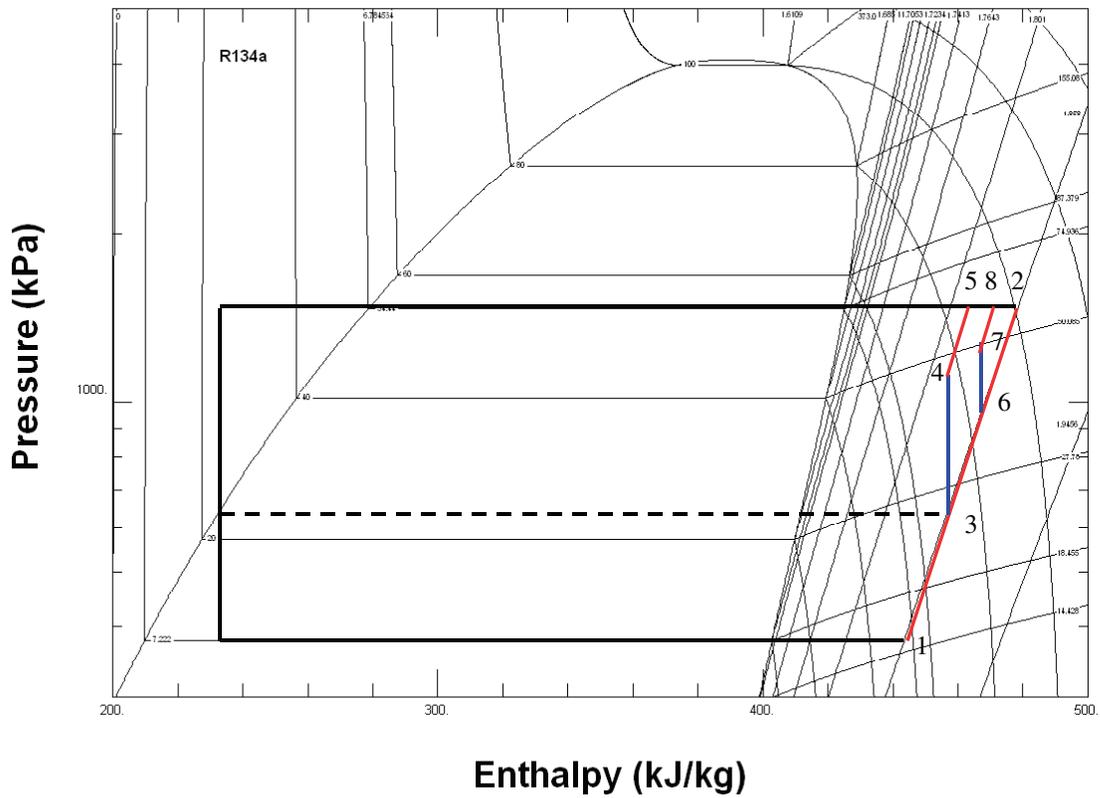


Fig.3: The p-h diagram

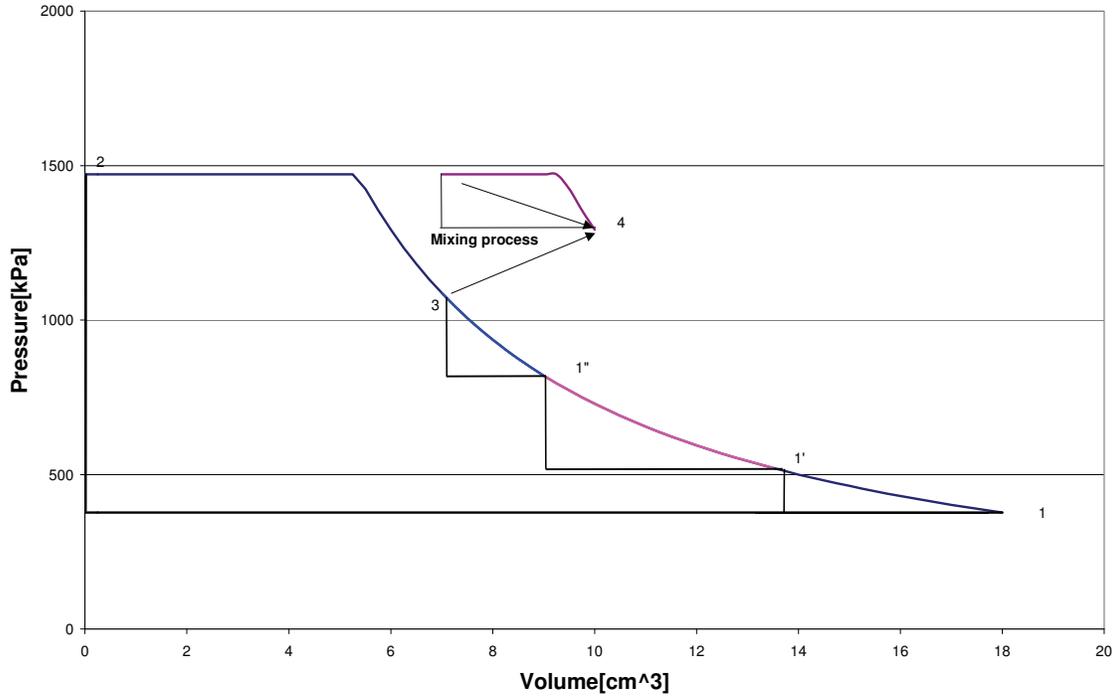


Fig.4: The p-V diagram

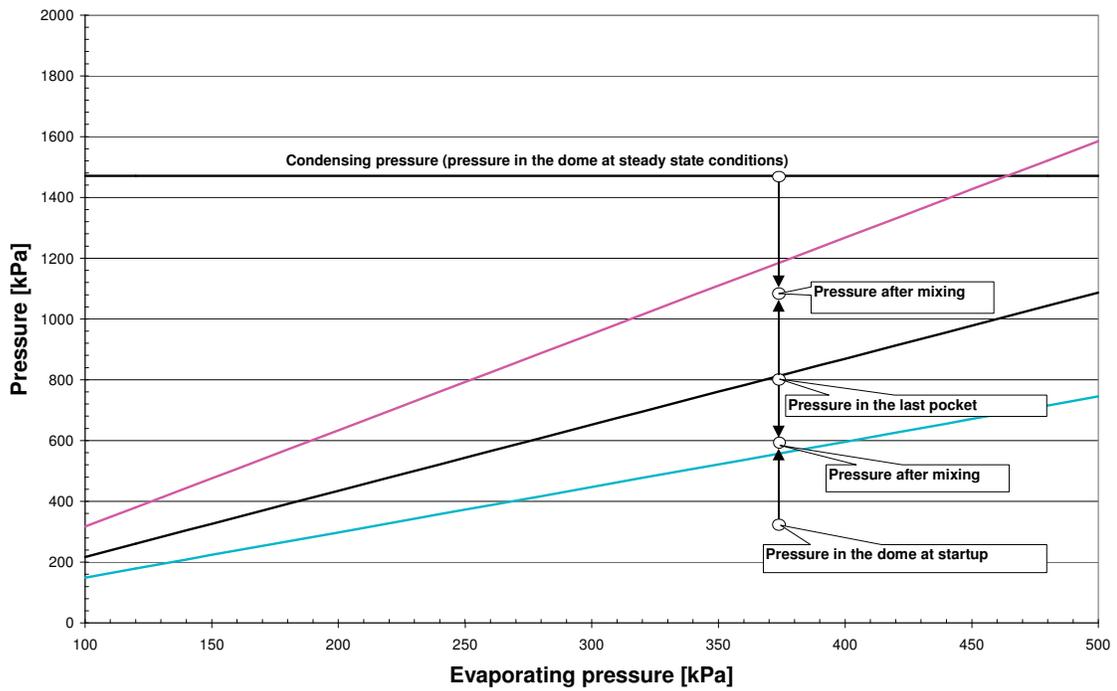


Fig.5: The critical pressure diagram

