

Flow Characteristics of Capillary Tube for R22 and R1270 Refrigerants

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ABSTRACT: The capillary tube is a common expansion device used in small sized refrigeration and air-conditioning systems and whose function is to reduce the high pressure in the condenser to low pressure in the evaporator and therefore drops the temperature of the refrigerant.

The main focus lies on the analysis of the refrigerant flow behavior in the capillary tube, including pressure drop, temperature and quality distribution along the tube by using a commercial code FLUENT V.6 for the simulation. The numerical results are compared with experimental results from internet web site and show a good agreement. It shows the capability of the code to simulate the flow and phase change in the capillary tube.

KEYWORDS: commercial code FLUENT V.6 simulate the flow and phase change Introduction

I. INTRODUCTION

The capillary tube is a constant area expansion device used in a vapor-compression refrigeration system located between the condenser and the evaporator and whose function is to reduce the high pressure in the condenser to low pressure in the evaporator. The capillary tube expansion devices are widely used in refrigeration equipment, especially in small units such as household refrigerators, freezers and small air conditioners. Its simplicity is the most important reason to continue using it instead of other expansion devices. It is a long copper tube (1-6 m) with a very small inner diameter. The flow inside the capillary tube of a refrigeration system can be divided into a sub-cooled liquid region from the entrance to the point in which the fluid reaches saturated conditions, and a two- phase flow region after that point until the end of the capillary tube. Many numerical and experimental investigations have been developed in order to study the refrigerant flow in capillary tubes. Normally, the numerical studies concerning capillary tubes found in the literature are targeted to the calculation of the mass flow rate through the tube for given geometry and operative conditions Bittleet. al. [1,2], Wongwises[3,4]. Experimental studies were investigated on the performance of refrigerants in-several capillary tubes length and geometry for air-conditioners Ro S. T. et. al. [5].

Another experimental study was taken under account the influence of geometrical parameters on capillary behavior i.e. the influence of length, inner diameter and type of refrigerants. The experimental device has been fully instrumented with pressure, temperature, and power sensors. The vapor-compression system was composed mainly of a compressor equipped with an accumulator, condenser, evaporator, and adjustable expansion device. Both condenser and evaporator were equipped with pre and post heat exchangers to control the flow conditions at the capillary tube test section. A straight capillary tube was installed together with various measuring stations equipped with sensors for temperature and pressure. Those sensors were necessary for measurement of the temperature and the pressure profiles along the capillary tube length, S. M. Sami et. al. [6]

II. PROBLEMS DEFINITION

The capillary tube is main element of the refrigeration system and the major (99%) refrigerating effect of the system is depends on capillary tube and it can be improve by modifying some of the geometric paremater of the capillary tube hance further gives us different temperature, pressure, and mass flow rate while refrigentfolw through the capillary tube.

III. MATHEMATICAL MODEL

A mathematical model has been developed to predict the flow of refrigerant inside a helical capillary tube. Length of helical adiabatic capillary tube can be calculated by giving the mass flow rate of particular refrigerant or vice- versa. A computer program coded in FORTRAN 77 has been developed to compute either length or mass flow rate by fixing some of parameter. The model also includes the effect of various design parameters, like capillary tube diameter,

capillary tube coil diameter, degree of sub-cooling, evaporator pressure, inlet pressure, mass flow rate. The model is based on the fundamental equations of conservation of mass, energy and momentum.

3.1 Formulation of Mathematical Model

The flow of refrigerant can be divided into two distinct regions. The single phase sub cooled region and two phase region. The mathematical model is developed by using the law of conservations of mass, energy and momentum. Moreover, the model includes the effect of the condenser and evaporator temperatures, inner diameter, and degree of sub cooling and mass flow rate of refrigerant.

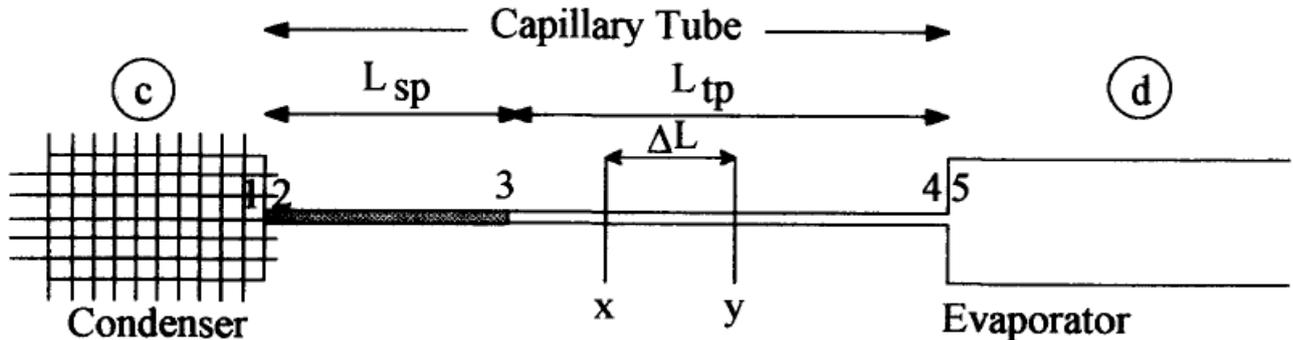


Figure 2: Simplified diagram of the adiabatic capillary tube

As shown in fig 3.1, the entry diagram of refrigerant commence at point 1 from the condenser. In the capillary tube there is some pressure drop due to entry of the refrigerant from the condenser to the capillary tube. The portion between points 2 and 3 is the single-phase sub cooled liquid region and the portion between points 3 and 4 is the two-phase region where liquid and vapour coexist. From 2 to 3 refrigerant remains in single liquid phase and vapors starts to form as it enters in two phase region. In single region pressure drop is linear and due to friction that experience by the fluid while passing through the tube. And in the two-phase region of the capillary tube, the temperature and pressure of refrigerant starts falling rapidly till the evaporator pressure or the choking point is attained.

The expansion process from point 1 to 5 is shown in figure.3 on temperature-entropy (T-S) and pressure-enthalpy (P-H) diagrams simultaneously.

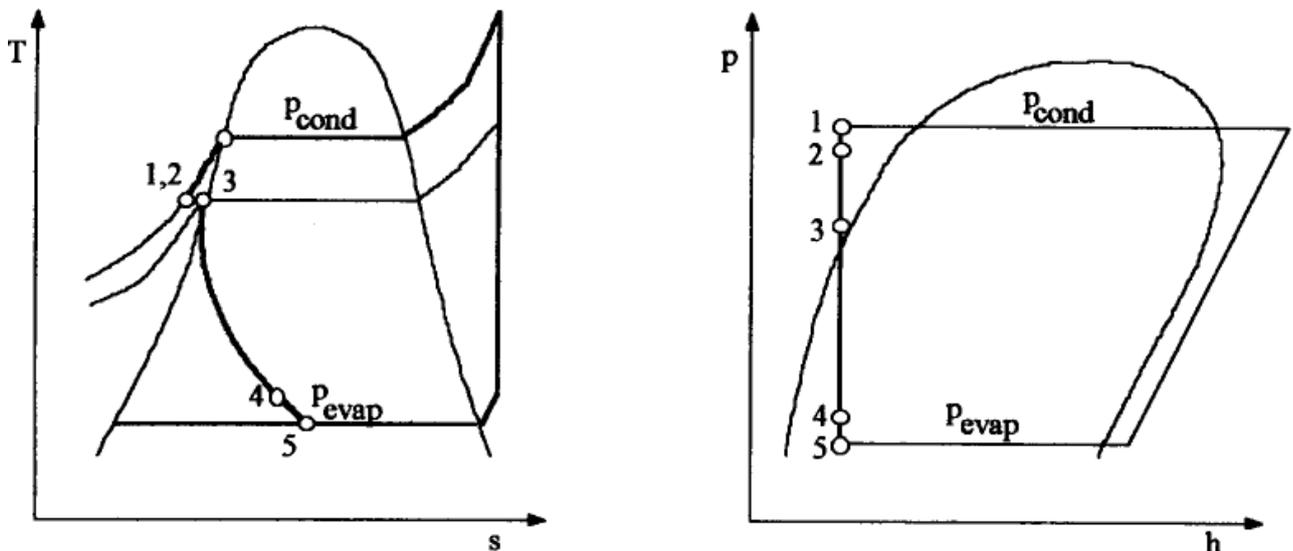


Figure 3: T-S and P-H diagram of capillary tube

Thus refrigerant flow has been divided into three distinct regions as follows:

- 1 – 2 represents pressure drop at entrance due to sudden contraction of area.
- 2 – 3 represents single-phase sub cooled flow region. 3 – 4 represents liquid-vapour two-phase flow region.
- 3 – 4 represents liquid-vapour two-phase flow region.

The flow through capillary tube is based on the following assumptions

- The horizontal helical coiled tube has constant diameter
- Oil free refrigerant
- The inner diameter and surface roughness of the capillary tube are constant
- Adiabatic and homogeneous two-phase flow
- Non-metastable liquid region
- One dimensional steady flow
- Thermodynamic equilibrium through the capillary tube

Consider an infinitesimal fluid element of length ‘dL’ within the capillary tube, shown in Fig.3.3 and applying the equations of conservation of mass, momentum and energy.

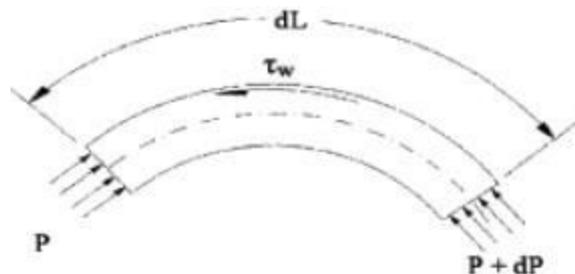


Figure 4: Free body diagram of fluid element of adiabatic helical capillary tube

Mass Balance

Continuity equation results into the following equation. [32]

$$m = \rho VA \quad OR \quad G = m / A = \rho V \tag{3.1}$$

Momentum Balance

On applying the principle of momentum conservation and second law gives

$$P.A - (P + dP).A - \tau_w(\pi d)dL = mdV \tag{3.2}$$

on simplification, the Equation (3.2) reduces to the following Equation

$$dL = -\frac{2d}{f} \left(\frac{\rho dP}{G^2} + \frac{dV}{V} \right) \tag{3.3}$$

Taking log of both sides of Equation (3.1) and then differentiating and simplifying

$$-\frac{dV}{V} = \frac{d\rho}{\rho} \tag{3.4}$$

Equation (3.3) reduces to

$$dL = \frac{2d}{f} \left(\frac{\rho dP}{G^2} - \frac{d\rho}{\rho} \right) \tag{3.5}$$

Energy Balance

On applying the steady flow energy equation for adiabatic flow with no external work and neglecting the elevation difference we have

$$\delta q - \delta w = dh + VdV + g dz \tag{3.6}$$

3.1.1 Single Phase Region

In order to calculate the single phase length, the pressure drop at inlet due to sudden contraction is considered. Liquid is incompressible (density constant) and capillary tube area is constant.

By integrating equation (3.5) length of single phase region is given by The Pressure drop at the entrance is given by

$$P_1 - P_2 = k \frac{\rho V^2}{2} \tag{3.7}$$

Where k is the entrance loss coefficient (K = 1.5). The steady flow equation between point 2 and 3 can be expressed as:

$$\frac{P_2}{\rho_2 g} + \frac{V_2^2}{2g} + Z_2 = \frac{P_3}{\rho_3 g} + \frac{V_3^2}{2g} + Z_3 + f_{sp} \frac{L_{sp}}{d_i} \frac{V^2}{2g} \tag{3.8}$$

As we know fluid is incompressible so

$$m = \rho VA = \rho_2 AV_2 = \rho_3 AV_3 \tag{3.9}$$

By rearranging equation (3.8) and (3.9) we have

$$P_2 = P_3 + \rho g(Z_3 - Z_2) + \left(\frac{f_{sp} L_{sp}}{d_i} \right) \left(\frac{\rho V^2}{2} \right) \tag{3.10}$$

Friction factor for straight capillary tube [3]

$$f_{sp} = \frac{0.33}{Re^{(0.25)}} \tag{3.11}$$

Where, $Re = \frac{VD}{\mu v}$



For coiled capillary tube by M&N and Giri Method [32] For liquid region (M&N) equation

$$f_{sp} = \frac{0.192(d/D)^{0.5}}{[Re(d/D)]^{2.5 \frac{1}{5}}} \times \left\{ 1 + \frac{0.068}{[Re(d/D)]^{2.5 \frac{1}{5}}} \right\} \quad 3.12$$

For two phase region (Giri) equation

$$f_{tp} = \frac{1.1258}{[Re^{0.1988}(D/d)^{0.5889}]} \quad 3.13$$

By M&N Method

$$f_{sp,tp} = \frac{0.192(d/D)^{0.5}}{[Re(d/D)]^{2.5 \frac{1}{5}}} \times \left\{ 1 + \frac{0.068}{[Re(d/D)]^{2.5 \frac{1}{5}}} \right\} \quad 3.14$$

For same elevation we have $Z_2=Z_3$, Substituting equation (3.10) into (3.7) which gives:

$$L_{sp} = \frac{d_i}{f_{sp}} \left[\frac{2\rho}{G^2} (P_1 - P_2) \right] \quad 3.15$$

3.1.2 Two Phase Flow Region

In this region vapour and liquid fluid flows through helical adiabatic capillary tube. Refrigerant fluid flow is homogeneous means vapour and liquid move with same velocity. In two phase region capillary tube has been divided into number of elements. The following equations are based on the control volume consideration in two phase region.

By conservation of mass

$$m = \frac{AV_i}{v_i} = \frac{AV_{i+1}}{v_{i+1}} \quad 3.1$$

Where v_i is the specific volume of fluid at any point.

By neglecting the elevation difference, the conservation of energy for steady state adiabatic condition without external work can be expressed as follows:

$$\left(h_3 + \frac{v_3^2}{2} + gZ_3 \right) = \left(h_i + \frac{v_i^2}{2} + gZ_i \right) \quad 3.17$$

$$h + \frac{v^2}{2} = const \quad 3.18$$

Where h and V are the enthalpy and velocity of fluid at any point, respectively. Due to fact that as the refrigerant flows through the capillary tube, the pressure gradually drops and the liquid flashes into vapours arising from the reduced pressure.

$$h = h_f(1 - x) + h_g x \quad 3.19$$

$$v = v_f(1 - x) + v_g x \quad 3.20$$

$$m = \rho AV = const$$

$$V = \frac{m}{\rho A} = \frac{G}{\rho} = GV \quad 3.21$$

The energy balance between point 3 and 4 can be calculated by putting the equation 3.19,3.20 and 3.21 into equation 3.18 and is given by

$$h_3 + \frac{v_3^2}{2} = h_{f4} + (h_{g4} - h_{f4})x + \frac{[v_{f2} + (v_{g4} - v_{f4})x]^2 (G^2)}{2} \quad 3.22$$

Everything in equation 3.22 is known except x , which can be solved by the quadratic equation [3]

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad 3.23$$

Where,

$$a = \frac{(v_{g4} - v_{f4})^2 G^2}{2}$$

$$b = (h_{g4} - h_{f4}) + v_{f4}(v_{h4} - v_{f2})G^2$$

$$c = (h_{f4} - h_3) + \frac{G^2}{2} v_{f4}^2 - \frac{v_3^2}{2}$$

Again conservation of momentum can be expressed by using the element of fluid shown in figure.4.

$$\left(P \frac{\pi d_i^2}{4} \right) - (P + dP) \frac{\pi d_i^2}{4} - \tau_w \pi d_i dL = mdV \quad 3.24$$

Where τ_w is the wall shear stress and is given by

$$\tau_w = \frac{f_{tp} \rho V^2}{8} \tag{3.25}$$

By putting equation 3.25 in Equation 3.24, we have

$$-\frac{\pi d_i^2}{4} dP - \frac{f_{tp}}{8} \rho V^2 d_i \pi dL = mdV \tag{3.26}$$

After modification

$$dL = -\frac{d_i}{f_{tp}} \left[\frac{2dP}{\rho V^2} + \frac{2mdV}{\rho AV^2} \right]$$

For constant mass flow rate

$$-\frac{dV}{V} = \frac{d\rho}{\rho}$$

By putting equation 3.28 into 3.27, we get

$$dL = \frac{2d_i}{f_{tp}} \left[\frac{-\rho dP}{\rho V^2} + \frac{d\rho}{\rho} \right]$$

In two phase region Reynolds number is given by

$$Re_{tp} = \frac{Vd}{\mu_{tp} v_{tp}} \tag{3.30}$$

Where μ_{tp} is the two phase viscosity which can be calculated by two phase viscosity models, but in present study cicchitti viscosity model is used.

$$\mu_{tp} = x\mu_g + (1-x)\mu_f \tag{3.31}$$

Velocity (V) is given by

$$V = Gv_{tp} = (xv_g + (1-x)v_f) \tag{3.32}$$

Two phase length can be calculated by integrating the equation

$$L_{tp} = 2d \left[\frac{-1}{G^2} \int_{P_s}^{P_s \max} \frac{\rho}{f_{tp}} dP + \int_{P_s}^{P_s \max} \frac{d\rho}{\rho f_{tp}} \right] \tag{3.33}$$

And capillary length of each section is given by

$$\Delta L_i = \frac{2d_i}{f_{tp,i}} \left[\frac{-\rho_i \Delta P}{G^2} + \frac{\Delta \rho}{\rho_i} \right] \tag{3.34}$$

Where, ρ_i and f_{tp} , are mean density and mean friction factor respectively over the ‘ith’ element in two phase region. And final length will be sum of single phase and two phase length.

$$L = L_{sp} + L_{tp} \tag{3.35}$$

V. RESULT AND DISCUSSION

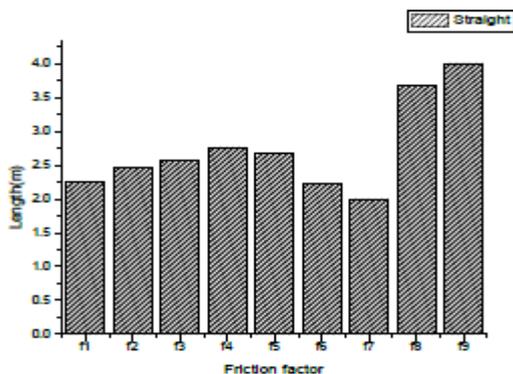


Figure 6 : Variation of Capillary tube Length with Friction factor for Straight capillary Tube (d=1.6mm, tc=40°C, te=5°C, w=0.01kg/sec for R22)

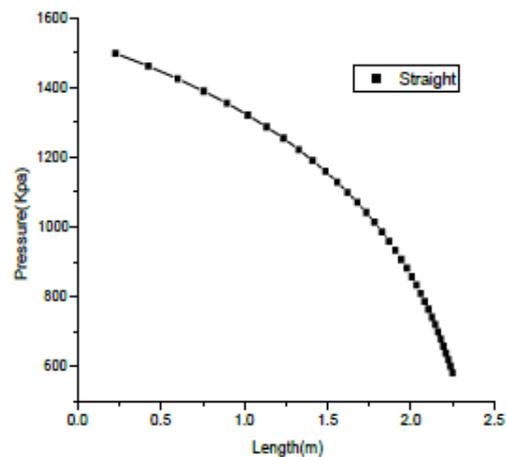


Figure 7 : Pressure Variation for Straight capillary Tube along the axial length (d=1.6mm, tc=40°C, te=5°C, w=0.01kg/sec for R22)

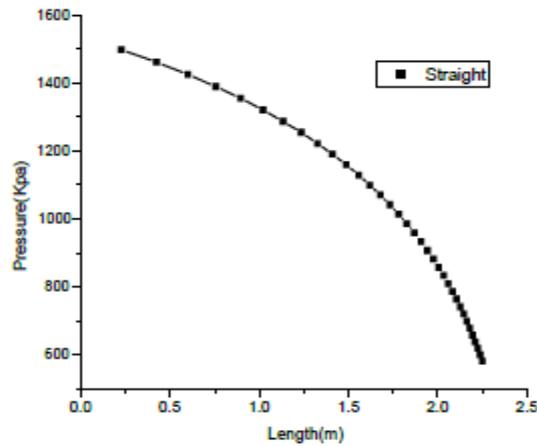


Figure 8: Variation of capillary tube length for straight capillary tube with different Mass flow rate.

VI. CONCLUSION

As the study focused on three geometry of capillary tube such as straight, helical, spiral. It is important to know the length of the capillary tube required for give operating condition. Present study considers the two refrigerants R22 and R1270 Numerical simulation will be performed with taking in to account the geometric dimension of all three types of capillary tube in addition to it parameters likes condenser temperature, evaporator temperature, mass flow rate of refrigerants are also considering.

By using numerical investigation the variation of capillary tube length for given operating condition and geometric condition can be obtained and it is compare with the remaining helical and spiral capillary tube.

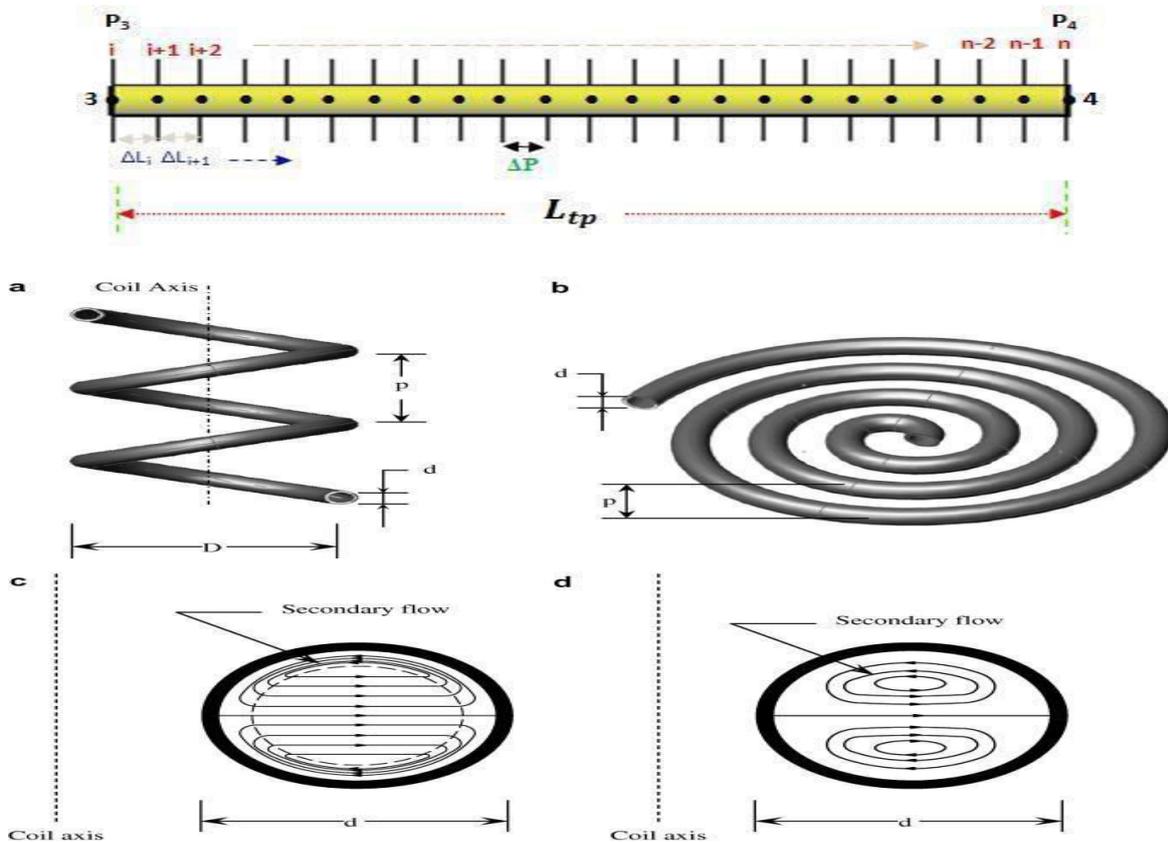


Figure 9: Straight capillary tube, Helical capillary tube, spiral capillary tube.

As the research paper suggests the three different viscosity model, the variation of all these three models need to be performed. Pressure and temperature variation of refrigerants inside the capillary tube are also performed. Results which are trying to obtain by using numerical simulation will be validated with Fluent analysis which can be carried out in Ansys software with required boundary conditions.

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