International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 9, September - 2013

CFD Flow Analysis of a Refrigerant inside Adiabatic Capillary Tube

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Abstract

Capillary tubes are widely used as a refrigerant flow control device in small refrigeration systems. Since the flow behaviour inside the capillary tube is complex, many physical models are necessary to predict the characteristics of the refrigerant flow in a capillary tube. The refrigerant leaves the compressor at high pressure and temperature and enters the condenser. After leaving the condenser the refrigerant is at medium temperature and high pressure and then it enters the Capillary tube. In the Capillary tubes the pressure and the temperature of the refrigerant is reduced drastically and suddenly. Thus us it is the throttling valve where the temperature of the refrigerant is reduced and it is then able to produce the cooling effect in the evaporator of the refrigerator or the cooling coil of the air conditioner.

In the present investigation, an attempt is made to analyze the flow Analysis of the refrigerant inside a straight capillary tube and coiled capillary tube for adiabatic flow conditions. The proposed model can predict flow characteristics in adiabatic capillary tubes for a given mass flow rate. In the present study R-22 has been used as a working fluid inside the straight capillary tube and coiled capillary tube of diameter 1.27 mm and used the same model to study the flow characteristics of refrigerant in ANSYS CFX software. It is observed from the results dryness fraction by using the helical capillary tube is better than straight capillary tube. The best suitable helical coiled design is suggested.

1. Introduction

Capillary tubes have been investigated in detail for many decades. A capillary tube is a common expansion device used in small sized refrigeration and air-conditioning systems. A capillary tube is a constant area expansion device used in a vapour-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. Capillaries substitute for more expensive and complex thermostatic valves. For instance, capillary tubes are used in some complex cooling Systems for particle detectors installed. Nevertheless, one can find other reasons for their Use in highly specialized cooling circuits.

In fact the flow through capillary tube is actually adiabatic not an isenthalpic. As the Name suggests the adiabatic capillary tubes are one in which there is no heat transfer with the surroundings or the walls of the capillary tube are thermally insulated. On the basis of Geometrical shape the capillary tubes can be classified as under:

1. Straight capillary tube
2. Coiled capillary tube

1.1 Straight Capillary Tube

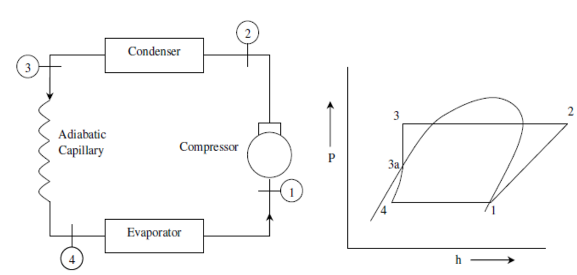


Figure 1.1 Adiabatic capillary tube (a) block diagram (b) P-h diagram

Figure 1.1a shows the vapour compression system employing the adiabatic capillary tube as an expansion device. The process 3-4 in Figure 1.1b represents the adiabatic expansion of the high pressure liquid refrigerant. The refrigerant temperature remains constant as long as it is in liquid state and as the flashing of refrigerant occurs (at point '3a') the pressure as well as temperature falls rapidly. As the flow through the capillary tube is adiabatic, the enthalpy of refrigerant remains constant till the flashing occurs. As a result of flashing, a part of enthalpy is used to increase the kinetic energy of the refrigerant. Therefore, as the vaporization progresses the enthalpy of refrigerant falls in the two-phase flow region of the capillary tube, as can be seen from the Figure 1.1b.

In adiabatic capillary tube, the refrigerant expands from high pressure side to low pressure side with no heat exchange with the surroundings. The refrigerant often enters the capillary in a sub cooled liquid state. As the liquid refrigerant flows through the capillary, the pressure drops linearly due to friction while the temperature remains constant. As the pressure of refrigerant falls below the saturation pressure a fraction of liquid refrigerant flashes into vapor. The fluid velocity increases because of the fall in density of the refrigerant due to vaporization. Thus, the entire capillary tube length seems to be divided into two distinct regions. The region near the entry is occupied by the liquid phase and the other as the two-phase liquid vapour region.

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 In Figure 1.2, the variation of refrigerant temperature and pressure has been plotted against the capillary tube length. The pressure falls linearly in the liquid region of the capillary tube while the temperature remains constant as the flow through capillary tube is considered adiabatic. Further, as the pressure falls below the saturation pressure, *P*s, with the onset of vaporization both temperature and pressure starts falling rapidly until the choked flow conditions are attained.
However, in reality, after the flow reaches the saturation pressure, there is a short region in which the evaporation does not start yet and the refrigerant becomes superheated, Chen etal.[1], Chang and Ro [2]. The liquid in this region is not in thermodynamic equilibrium but under metastable condition. This region ends up quite suddenly and the liquid starts to evaporate approaching thermodynamic two-phase equilibrium conditions.

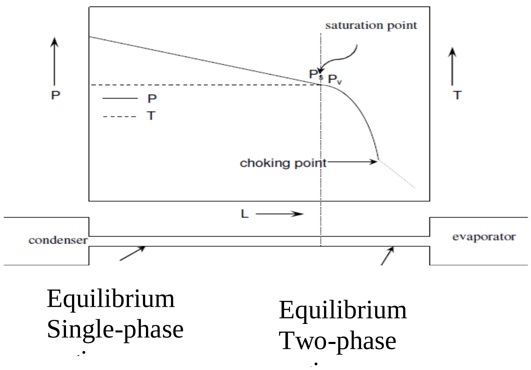


Figure 1.2 Temperature and pressure variation along the adiabatic capillary tube

1.2 Coiled Capillary Tubes

The helical capillary tubes in a domestic refrigerator or in a window air conditioner are no more a new thing. The difference between the consecutive turns of the coiled capillary tube is termed as coil pitch, denoted by '*p*'. In helical capillary tubes there are two coiling parameters one is coil pitch and another is coil diameter. Figure 1.3 shows the helical and spiral tubes depicting the geometric parameters, viz. coil pitch, coil diameter and tube diameter.

The flow through coiled tubes is complicated comparing to straight tubes. The frictional pressure drop of a single-phase fluid flow through a curved

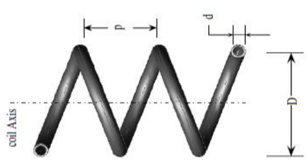


Figure 1.3 helically coiled capillary tubes

tube is larger than that for a flow through a straight tube under similar conditions. The fluid flowing in tube undergoes a centrifugal force, which results in the secondary flow, as shown in Figure 1.3. The secondary flow imposed on the main flow forms a counter-rotating helical vortex pair. The existence of secondary flow is called the Dean effect.[3]. Dean has proposed a dimensionless number called Dean Number given by the following equation:

$$\boldsymbol{De} = \boldsymbol{Re}\sqrt{\frac{d}{D}} \quad \text{.............................} \quad (1.1)$$

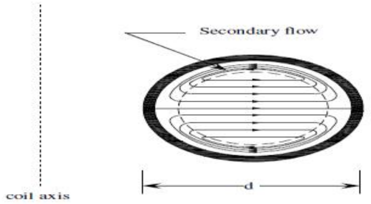


Figure 1.4 Secondary flows in the cross section of the coiled capillary tube

The flow pattern by Dean's analysis is shown in Figure 1.4. The secondary flow in the coiled capillary tube has the stabilizing effect on laminar fluid flow, resulting in higher critical Reynolds number. The critical Reynolds number increases with the increase in ratio, d/D, and is Expressed by the following relation proposed by Ito [4]:

$$\mathrm{Re}_{\mathrm{crit}} = 2000\left(\frac{\mathrm{d}}{\mathrm{d}}\right)^{0.32} \quad \text{.............................} (1.2)$$

2.Objectives of the proposed work

- To conduct experiment on adiabatic straight capillary tube.
- To develop simulation models for straight capillary using ANSYS CFX module and validate with experimental values.
- To design a helical coiled capillary tube to replace the existing straight capillary tube of experimental setup, with same length and diameter.

3. Experimental setup

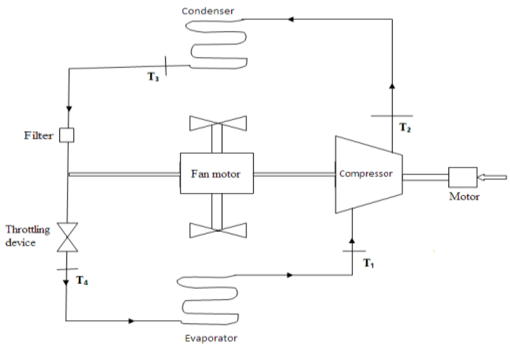


Figure 3.1 Schematic diagram of Air-conditioning system

3.1 Specifications of the system:

Compressor: 1 TR (hermitically sealed)

Condenser: Air cooled, **Evaporator**: Air cooled, **Throttling Device**: Capillary tube straight, **Refrigerant**: R-22 ($CHCLF_2$) Control **Panel**: 220 AC, Voltmeter Reading (V), Ammeter Reading (A) Main switch with 6 channel temperature indicator

$\mathbf{T_1}$ - Inlet temperature of compressor, $\mathbf{T_2}$ - Outlet temperature of compressor, $\mathbf{T_3}$ - Outlet of condenser, $\mathbf{T_4}$ - Temperature after throttling, $\mathbf{T_5}$ - Air temperature at blower outlet, $\mathbf{T_6}$ - Ambient temperature

Knobs: For filling refrigerant.

1. Throttling device : straight capillary tube of diameter 1.27 mm and length 762 mm
2. Viewer: liquid line indicator viewer after condenser before throttling

Compressor operating pressure range:

Inlet pressure: 65 – 90 (psi),

Outlet pressure: 225 -310 (psi)

The experiment is conducted on air-conditioning system with a straight capillary tube the following values are obtained

Table 3.1 Temperature readings

T_1	T_2	T_3	T_4	T_5	T_6
32 °C	63 °C	52°C	8°C	36°C	39 °C

Hence,

The capillary tube inlet temperature is T_{in} = 52 °C

And the capillary tube outlet temperature is T_{out} = 8 °C

Corresponding pressures are P_{in} = 20.328 bar and P_{out} = 6.406 bar

Mass flow rate $\dot{m}$ = 40.73 kg/h

3.2 Quality of the refrigerant

Capillary Tube Inlet Temperature (t_k) =52 °C
Capillary Tube outlet Temperature (t_0) = 8 °C
Therefore corresponding pressures are p_k =20.328 bar and p_0= 6.406 bar

From R-22 tables
$h_k = 264.97\ kj/kg$
Since $h_k = h_0$

$$x_0 = \frac{h_k - h_0}{h_{fg0}} \quad \text{.................................} \quad (3.1)$$

$$x_0 = \frac{264.97 - 209.42}{198.69}$$

$$x_0 = 0.2795$$

That is 27.95 % of refrigerant is vaporized in the capillary tube.

4. Model Analysis

4.1 Straight capillary tube

Straight capillary tube is modeled in ansys work bench. The diameter of the tube is 1.27 mm and length of the tube is 762 mm. The model of the straight capillary tube is shown in the figure

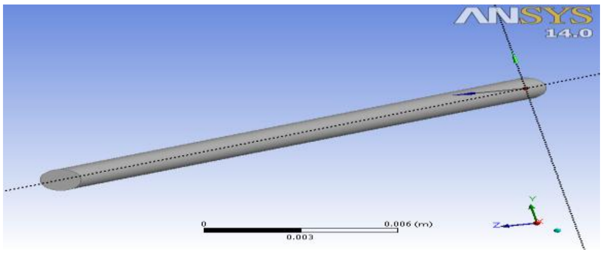


Figure 4.1 Model of the straight capillary tube

Meshing of a model is very important in ansys. Proper meshing of the model gives better results, and it reduces the iteration time for solving. The following diagram gives information meshing procedure of the model. Inflation mesh is taken outer surface of the tube.

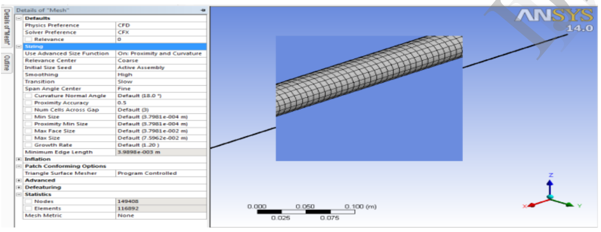


Figure 4.2 straight capillary tube meshing

4.2 Coiled capillary tube

Helical coiled tube are widely used in air-condition systems. In this project, finding a perfect model of helical coiled tube by the given operating pressures of straight capillary tube. The helical coiled capillary tube length is same as the length of the straight capillary tube. By varying pitch and number of turns we can make so many numbers of helical coiled tubes. In this project some of helical coiled tubes are taken by varying number of turns and there tested computationally. Finally a suitable design is suggested.

The difference between the consecutive turns of the coiled capillary tube is termed as coil pitch, denoted by '*p*'. In helical capillary tubes there are two coiling parameters one is coil pitch and another is coil diameter D. To finding the length helical coiled tube the following correlation is used.

From the figure 1.3 Length of the helical coiled tube $L = \sqrt{(\pi DN)^2 + (pN)^2}$ ……....…..…… (4.1)

In this present investigation spacing is taken as same for all capillary tube an it is 3 mm. there are four helical coiled capillary tube models are investigated . These model dimensional values are tabulated below.

Table 4.1 helical coiled capillary tubes models

Models	No. of turns (N)	Pitch of the coil (p) (mm)	Diameter of the coil (D)(mm)	Length of the coil (L)(mm)
1	5	3	48.5	761.98
2	10	3	24.2364	761.99
3	30	3	8.0248	762
4	40	3	5.988	761.98

The models of the helical coiled capillary tubes are shown in the figure. Helical coiled capillary tubes are designed in CATIA and it is imported to Ansys work bench.

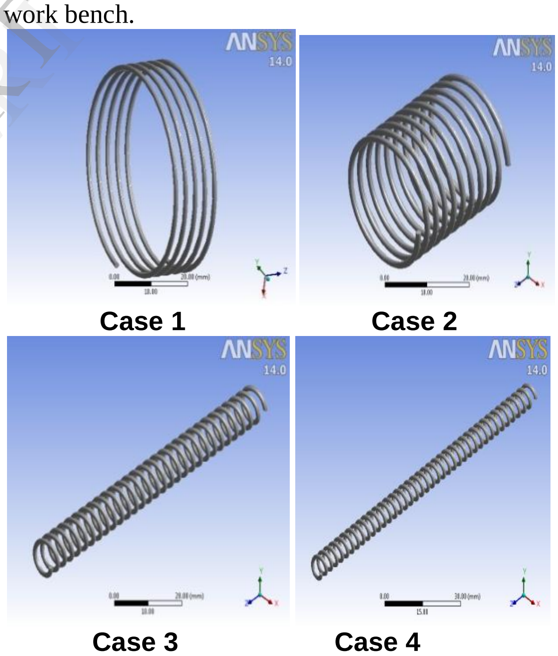


Figure 4.3 Coiled tubes

Mesh:

Meshing of a model is very important in ansys. Proper meshing of the model gives better results, and it reduces the iteration time for solving.

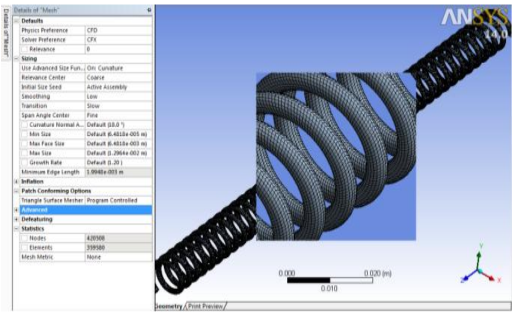


Figure 4.4 Coiled tube meshing for Case 4

The following diagram gives information meshing procedure of the model. Inflation mesh is taken outer surface of the tube. One of the mesh models as shown below.

5. CFD Results and discussion

The results obtained from the Experimental model are compared with the commercial available software ANSYS CFX module and the effect of flow properties on the refrigerant inside the straight adiabatic capillary tube. The computational results obtained from helical coiled capillary tube by changing number of turns, acceptable model is suggested.

5.1 Validation of computational results

The results obtained computational model of straight capillary tube by using ansys cfx is validated with experimental results. Once the results are validate with experimental results, then different types of helical coil capillary tube models are tested computationally by changing number of turns.

5.1.1 Experimental results of straight capillary tube

Experiment is conducted on air-condition system, straight capillary tube readings are obtained. The inlet temperature of the capillary tube is 52 °C and outlet temperature of the capillary tube is 8°C. The corresponding pressures are, at inlet 20.328 bar and at outlet 6.406 bar. At inlet of the capillary tube mass fraction of the R-22 liquid is 1 and mass fraction of the R-22 vapour is 0. At outlet of the capillary tube mass fraction of the R-22 liquid is 0.715 and mass fraction of the R-22 vapour is 0.285.

5.1.2 Computational results of straight capillary tube

For the study of flow properties inside the straight capillary tube R-22 is used as a working fluid. Further study the effect of fluid properties such as pressure, temperature, mass fraction of R-22 Liquid and vapour on length.

5.1.3 Comparison of computational results with experimental results

After the completion of both experimental and computational, the results obtained are tabulated below. The results are show in the table 5.1.

Table 5.1 Properties of Experimental and computational for the straight capillary tube

Properties	Experimental	computational
Inlet temperature (T_{in})	52 °C	51.3 °C
Outlet temperature(T_{out})	8 °C	9.1 °C
Inlet pressure (P_{in})	20.328 bar	20.07 bar
Outlet pressure (P_{out})	6.406 bar	6.629 bar
Inlet mass fraction liquid	1	1
Outlet mass fraction of liquid	0.7205	0.719
Inlet mass fraction of vapour	0	0
Outlet mass fraction of vapour	0.2795	0.2806

From the table 5.1 the results of both experimental and computational are approximate.
Hence the computational results are validated with experimental results.

5.1.4 Pressure variation in the straight capillary tube

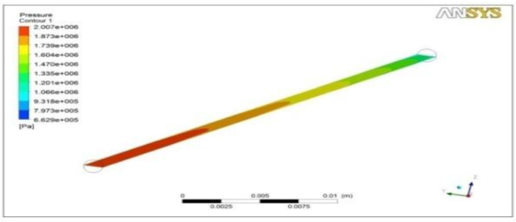


Figure 5.1 Pressure in straight capillary tube

Figure 5.1 has been drawn to compare the results of computational pressures with experimental results, to study the flow characteristics for R-22 inside the straight capillary tube. The results obtained from the existing model predict the pressures as to ANSYS CFX. As the refrigerant enters in the capillary tube its pressure drops linearly. As refrigerant enters in the two-phase region there is a sharp decrease in pressure and temperature this is due to cumulative effect of friction drop and acceleration pressure drop, which leads to more vaporization of the fluid in to two-phase region.

The pressure contours are shown in the Fig.5.1. The main function of the capillary tube is to decrease the pressure of the capillary tube so the pressure decrease is observed from 20.07 bar to 6.629 bar and from the experimental calculations, the pressures are from 20.328 bar to be decreased to 6.406 bar which is fair to be in agreement.

5.1.5 Temperature variation in the straight capillary tube

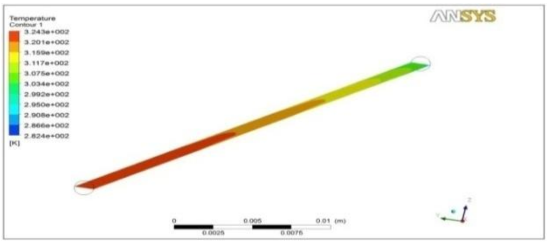


Figure 5.2 Temperature in straight capillary tube

The temperature contours are shown in the Fig.5.2. The main function of the capillary tube is to decrease the temperature of the capillary tube so the temperature decrease is observed from 52 °C to 8 °C and from the experimental calculations; the temperatures are from 51°C to be decreased to 9 °C which is fair to be in agreement.

5.1.6 Mass fraction contour of Liquid and vapour

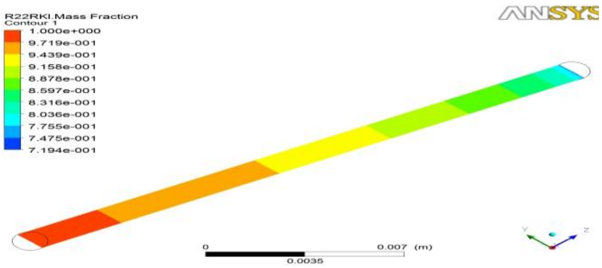


Figure 5.3 (a) liquid mass fraction in straight capillary tube

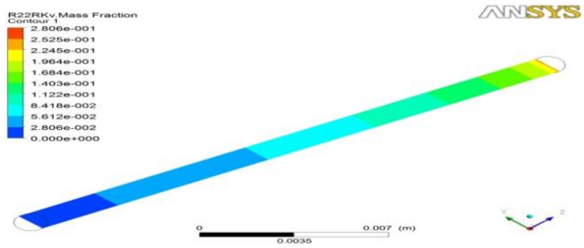


Figure 5.3 (b) Vapour mass fractions in straight capillary tube

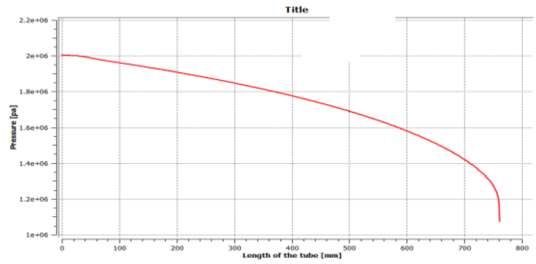
The liquid mass fraction contours are shown in the Fig. 5.3 (a). The main function of the capillary tube is to decrease the mass fraction of the capillary tube so the mass fraction of liquid decrease is observed 1 to 0.7194 and the Experimental calculations are measured to be from 1 to 0.715 which is fair to be in agreement.

The vapour mass fraction contours are shown in the Fig.5.3 (b). The main function of the capillary tube is to increase in mass fraction of vapour of the capillary tube so the Mass fraction of liquid increase is observed from 0 to 0.2806 and the experimental calculations are measured to be from 0 to 0.2795 increase is observed which is fair to be in agreement.

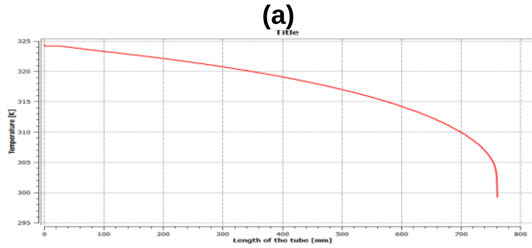
5.1.7 Graphs

The fluid properties of R22 along the length are plotted below.

5.1.7.1 Pressure and temperature graphs of straight capillary tube



(a)



(b)

Figure 5.4 (a) Pressure graph of straight capillary tube along the length
(b) Temperature graph of straight capillary tube along the length

As shown in the figure 5.4 (a) and (b) the pressure and temperature decreases linearly up to certain length from inlet to outlet. The flow reaches before the exit point the pressure and temperature decreases drastically.

5.1.7.2 Vapour mass fraction graph of straight capillary tube

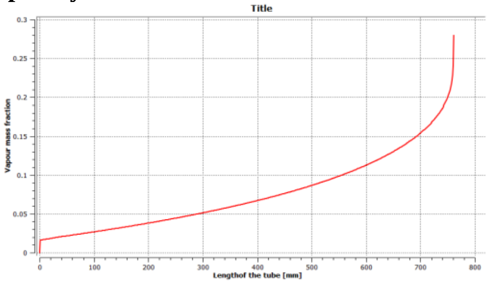


Figure 5.5 vapour mass fraction graph of straight capillary tube

From the graphs fig 5.5, mass fraction of vapour is increase from inlet to outlet hence mass fraction of liquid decreases from inlet to outlet.

5.2 Design of helical coiled capillary tubes

For the study of flow properties inside the coiled capillary tube R-22 is used as a working fluid. Further study the effect of fluid properties such as pressure, temperature, mass fraction on length. In this project the straight capillary tube length as 762 mm and it is replaced, with this same length of helical coiled tube by varying with pitch and number of turns.

Table 5.2 Experimental results of straight capillary tube and Computational results of Helical coiled capillary tube

Properties	Exp.	Case 1	Case 2	Case 3	Case 4
Inlet temp. (T_{in}), °C	52	52	46	49	52
Outlet temp. (T_{out}) °C	8	8	8	7	7. 3
Inlet pre. (P_{in}), bar	20.32	17.6	17.53	19.0	20.28
Outlet pre. (P_{out}), bar	6.406	6.406	6.37	6.181	6.2112
Inlet mass fraction of liquid	1	1	1	1	1
Outlet mass fraction of liquid	0.72	0.713	0.712	0.70	0.708
Inlet mass fraction of vapour	0	0	0	0	0
Outlet mass fraction of vapour	0.279	0.286	0.287	0.29	0.291

A suitable design of helical coiled tube is suggested without changing the inlet and outlet parameters of pressure and temperature. Hence the vaporization of refrigerant increases in the capillary tube. By solving the above four cases the following results are obtained. These results are tabulated below. Computational results of straight capillary tube is compared with the four case of helical coiled capillary tube a proper design should be selected

As shown in the table 5.2 fours cases of helical capillary tubes are analyzed in ANSYS CFX.

In Case 1 the drop in temperature is 44 °C and this temperature drop is coincide with experimental temperature drop 44 °C .The pressure drop is 11.194 bar and this pressure is not coincide with experimental pressure drop 13.922 bar.

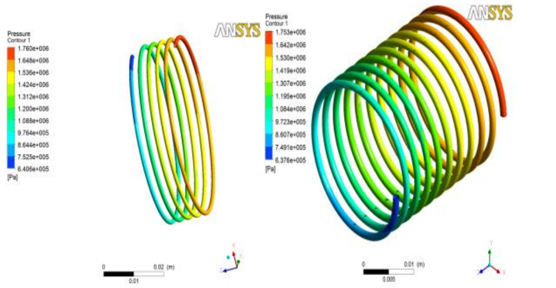
In Case 2 the drop in temperature is 38 °C and this temperature drop is not inline with experimental temperature drop 44 °C .The pressure drop is 11.163 bar and this pressure is not coincide with experimental pressure drop 13.922 bar.

In Case 3 the drop in temperature is 42 °C and this temperature drop is not inline with experimental temperature drop 44 °C .The pressure drop is 12.891 bar and this pressure is not coincide with experimental pressure drop 13.922 bar.

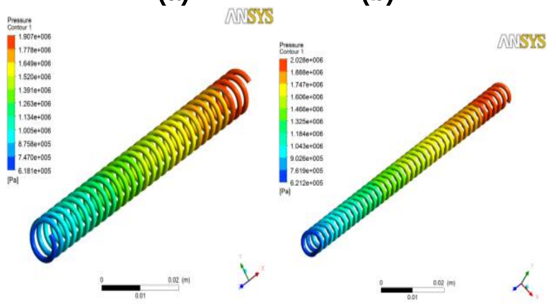
In Case 4 the drop in temperature is 44.7 °C and this temperature drop is inline with experimental temperature drop 44 °C .The pressure drop is 12.891 bar and this pressure is coincide with experimental pressure drop 14.7 bar.

From above tables the properties of fourth case of the helical coiled capillary tube is similar to experimental values of the straight capillary tube. Hence, fourth case suitable for replacing straight capillary tube with helical coiled capillary tube. Case 4 has 40 turns with 3 mm pitch is suggested. The results of 40turns coil are as follows.

5.2.1 Pressure contours of helical coiled capillary tubes



(a) **(b)**

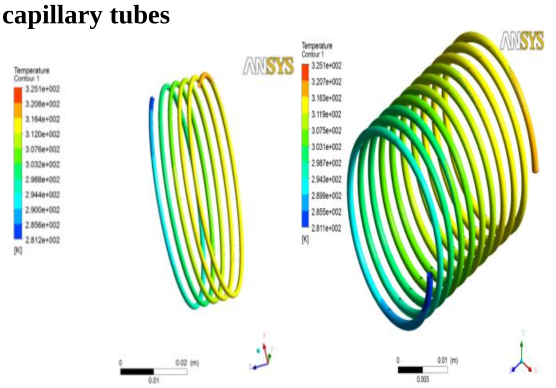


(c) **(d)**

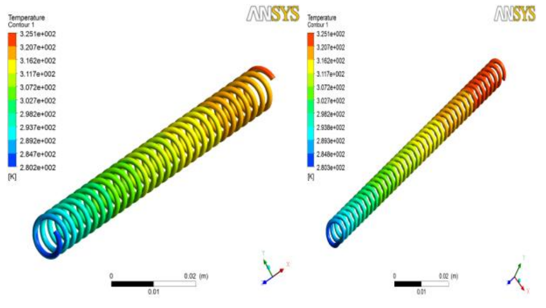
Figure 5.6 Pressure contours of helical coiled capillary tube
(a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4

As show in the figure 5.6. Case 4 is acceptable design for helical capillary tube by replacing straight capillary tube. The pressure contours are observed form the above Fig.5.6 (d) .the main function of the capillary tube is to decrease the pressure of the capillary tube so the pressure has been decreased from 20.0688 bar to 6.2119 bar and the Experimental calculations are from 20.328 bar to be decreased to 6.406 bar which is fair to be in agreement.

5.2.2 Temperature contours of helical coiled capillary tubes



(a) **(b)**

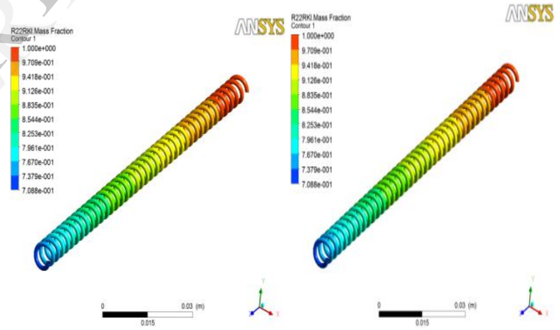


(c) **(d)**

Figure 5.7 Temperature contours of helical coiled capillary tube
(a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4

The temperature contours for case 4 is shown in Fig.5.5 (d). The main function of the capillary tube is to decrease the temperature of the capillary tube so the temperature has been decreased from 52 °C to 7.3 °C and the experimental calculations are from 52°C to be decreased to 8 °C which is fair to be in agreement, that is case 4.

5.2.3 Mass fraction contours of liquid and vapour for Case 4:



(a) (b)

Figure 5.8 (a) Liquid mass fraction in helical capillary tube (b) Vapour fraction in helical capillary tube

The liquid mass fraction contours are observed form the above Fig.5.8.the main function of the capillary tube is to decrease the mass fraction of the capillary tube so the mass fraction of liquid has been decreased from 1 to 0.7085 and the experimental calculations are said to be from 1 to be decreased to 0.715 which is fair to be in agreement.

The vapour mass fraction contours are observed form the above Fig.5.6 the main function of the capillary tube is to Increase the mass fraction of vapour of the capillary tube so the mass fraction of liquid has been increased from 0 to 0.29155 and the experimental calculations are said to be from 0 to be increased to 0.285 which is fair to be in agreement.

5.2.4 Mass flow average of R-22 vapour mass fraction in outlet

Table 5.3 Vapour mass fraction of helical capillary tube

Case	Turns	Mass fraction of vapour
1	5	0.28647
2	10	0.287
3	30	0.2920
4	40	0.29155

From the table 5.3 increases in mass fraction of vapour is observed at outlet.

6. Conclusions

The following conclusions can be drawn

- The computational results of straight capillary tube is inline with experimental values of the straight capillary tube, hence the computational results are validated.
- Four types of helical capillary tube are analyzed to replace the existing straight capillary tube. Case 4 pressures and temperatures are coinciding with pressures and temperatures of straight capillary tube.
- The behavior of the refrigerant flow with the phase change during the throttling process in the capillary tube is predicted in ANSYS CFX.
- Helical coiled capillary tube is designed to replace the existing straight capillary tube, four different helical models are analysed to achieve the suitable one to replace the straight capillary tube of experimental setup.
- It is suggested that straight capillary tube can be replaced with helical coiled capillary tube having 40 turns and pitch 3mm

7. Nomenclature

d capillary tube internal diameter, m

D coil diameter, m

L capillary tube length, m

m mass flow rate, kg/s

P pressure, bar

p pitch, mm

T temperature, °C

ρ Density, kg/m^3, h Enthalpy kj/kg

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