Flow of refrigerants through a capillary tube – A Review

Kamlendra Singh Rajput, Prof. R.C Gupta

1Research Scholar, M.E (Heat Power Engineering)
2Associate Professor, Department of Mechanical Engineering
Jabalpur Engineering College, Gokalpur, Jabalpur(M.P.)- 482011, India

Abstract: In this paper, various types of capillary tubes are explained depending upon shape and ways of working and the current researches in the field are described from the viewpoint of experimental tests, theoretical analysis as well as practical applications. The purpose of this review is to provide information about the range of input parameters like tube diameter, tube length, condensing temperature and condensing pressure, surface roughness etc. This paper also provides information about various type of refrigerant used, correlation proposed and methodology adopted in the analysis of flow through the capillary tube of different geometries operating under adiabatic flow condition. A brief discussion on the capillary tube is mention in this paper.

Keywords: Capillary tube, Refrigerant, Comparison.

1. INTRODUCTION

A capillary tube is an expansion device commonly used in the domestic refrigerators and window air conditioners. Capillary tubes are the simple tubes having diameter ranging from 0.5 mm to 2.0 mm and length of 2 m to 6 m. Capillary tubes have various advantages over the other expansion devices such as they are simple, inexpensive and causes the compressor to start at a low torque as the pressure across the capillary tube equalize during the off-cycle.

Nomenclature

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Subscripts</th>
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<tbody>
<tr>
<td>d = capillary tube internal diameter, mm</td>
<td>in = capillary tube inlet</td>
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<td>D = coil diameter, mm</td>
<td>out = outlet</td>
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<tr>
<td>( T_{sub} ) = degree of subcooling, K</td>
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<tr>
<td>e = roughness height, m</td>
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<tr>
<td>f = friction factor</td>
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<tr>
<td>L = capillary tube length, m</td>
<td></td>
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<tr>
<td>m = mass flow rate, kg/s</td>
<td></td>
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<tr>
<td>P = pressure, Pa</td>
<td></td>
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<tr>
<td>T = temperature, °C</td>
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a) Adiabatic straight capillary tubes-

In adiabatic capillary tube, as shown in Fig. 1(a), the refrigerant expands adiabatically from high pressure side to low pressure side. The refrigerant enters the capillary in a subcooled 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 falls below the saturation pressure corresponding to refrigerant temperature, a fraction of liquid refrigerant flashes into vapour. The inception of vaporization gives rise to two-phase flow in the capillary tube. This causes an increase in the vapour quality and fluid velocity which results into additional pressure drop which is called as acceleration pressure drop. The increased pressure causes the temperature of the refrigerant to fall rapidly as in the two-phase region. Fig. 1(a) shows the vapour compression system employing the adiabatic capillary tube. The process 3–4 in Fig. 1(b) represents the adiabatic expansion of the high pressure liquid refrigerant. Since the flow is adiabatic inside capillary tube, the refrigerant temperature remains constant as long as it is in liquid state and as soon as the flashing occurs the temperature falls rapidly. The process is adiabatic rather than isenthalpic and as such the enthalpy is constant till the flashing occurs. As a result of flashing, the part of total energy gets converted to kinetic energy and as such the enthalpy falls in the latter part of the capillary tube.
b) Diabatic straight capillary-

In a diabatic flow arrangement, shown in Fig. 2(a), the capillary tube is bonded with the cold compressor suction line in a counterflow heat exchange arrangement. The advantage of employing diabatic capillary tube results in higher refrigerating effect and thus a better system performance is obtained. As can be seen from the Fig. 2(b), the process of expansion as shown by the process 4–5, the temperature of the hot liquid refrigerant emerging from the condenser continues to fall due to the thermal contact with the cold suction line. Consequently, the enthalpy of the refrigerant falls continuously throughout the capillary tube length. The heat transfer from the capillary tube to the compressor suction line also causes a delay in flash point and increase in the refrigerant effect. On the other hand, on receiving heat from the capillary tube, the cold vapour in the suction line gets superheated and thus diminishing the chances of liquid entering the compressor. The two arrangements in this category are further possible, viz., lateral and concentric, shown in Figs. 2(c) and (d). In lateral configuration, the capillary tube is bonded with the compressor suction line by means of a solder joint or by wrapping copper tape, which could be wound around the two tubes whereas capillary tube occupies the core of compressor suction line in concentric configuration.
c) **Coiled capillary tubes**

The flow through coiled tubes is complicated comparing to straight tubes. Usually capillary tubes are coiled in two shapes viz., helical and spiral shown in Fig. 3(a) and (b). The frictional pressure drop of a single-phase fluid flow through a curved tube is larger than that for a flow through a straight tube under similar conditions of pressure, temperature, mass flow rates, tube diameter, tube length etc. Moreover, the single-phase fluid flow through coiled tube becomes turbulent at higher Reynolds number than the fluid flow through straight tube under identical flow conditions. The fluid in tube meets the centrifugal force, which causes the appearance of secondary flow. The secondary flow is sometimes called the Dean effect, affects the transfer of heat, momentum and mass in coiled tubes. Dean [68] has proposed a dimensionless number called Dean Number, \( \text{De} = \text{Re} \left( \frac{d}{D} \right)^{0.5} \). The secondary flow at high and low De has been shown Fig. 3c and 3d.

![Coiled capillary tubes](image)

Fig. 3. Coiled capillary tubes (a) helical (b) spiral (c) Secondary flow with large De (d) with small De. [8]

2. **EXISTING RESEARCH EFFORT**

The flow characteristics of refrigerants flowing through capillary tube is matter of research because of the importance of capillary tube in low capacity refrigeration systems. Thus it is important to review the researches of this field. Some of the research work is in the field of capillary tube in low capacity refrigeration systems are as follow:

I. **Santhosh Kumar Dubba et.al (2018) [1]**

This paper presents an experimental investigation of a helically coiled capillary tube with an adiabatic flow of R-600a. The details of experimental facility for testing a capillary tube with different inlet subcooling degree and varying pressure are discussed. The effect of coil diameter, capillary length, capillary tube diameter, sub-cooling degree and inlet pressure on mass flow rate are described. The degree of subcooling at the inlet of both straight and helical capillary tube is varied from 3 to 15 °C. The experimental results confirm that, the mass flow rate in the straight capillary tube is 1.5–16 percent higher than the coiled capillary tube. A non-dimensional correlation to predict the mass flow rate through a straight and helical coiled capillary tube has been developed with a good agreement of ±20 percent of measured mass flow rate.

II. **Pravin Jadhav et.al (2017) [2]**

Numerical studies on the straight and spiral capillary tubes are addressed for the CO2 and R22 refrigerant. A homogenous one dimensional steady state adiabatic flow model is developed using fundamental principles of fluid dynamics and thermodynamics. Churchill and Ju et al. friction factor correlations are employed. Numerical result are validated with experimental results of Agrawal.
and Bhattacharya, Jabaraj et al. and Mittal et al. For similar operating condition, the mass flow rate and length of the tube is significantly larger in case of CO2 refrigerant. A reduction in mass flow rate in the spiral capillary tube is about 22% and 15% compared to straight capillary tube with CO2 and R22 refrigerants, respectively.

III. Masoud Zareh et al. (2014) [3] -

In the present study, two-phase refrigerant flow is simulated using drift flux model for straight and helical capillary tubes. The conservation equations of mass, energy, and momentum are solved using the fourth order Runge Kutta method. The effect of various parameters such as inlet pressure, inlet temperature, sub-cooling degree, and geometric dimensions are studied. The results of the present study show that for the same length and under similar conditions, mass flux through helical capillary tube with coil diameter of 40 mm are about 11% less than that through the straight tube, where the helical tube length is about 14% shorter than the straight one for the same refrigerant mass flux.

IV. Hossien Shokouhmand et al. (2014) [4] -

This paper presents a drift flux model and experimental study of choked refrigerant flow through both straight and helical adiabatic capillary tubes. The conservation equations of mass, energy, and momentum are solved using the fourth order Runge-Kutta method. This model is validated by previously published experimental data and also by test results performed and presented in this work for R-134a with average error of 5.5%. Critical mass flux variation, pressure distribution and temperature variation are obtained experimentally as well as vapor quality, vapor velocity and void fraction variation by numerical simulation. The results show that mass flux reaches a maximum amount at a specific value of evaporator pressure in choked conditions and also it is decreased by increasing the length of capillary tube. Moreover, critical mass flux increases by increasing of the tube inner diameter, condensation temperature and refrigerant degree of sub-cooling.

V. Yogesh K. Prajapati et al. (2013) [5] -

In this work a computational investigation of detailed flow structures in two-phase refrigerant flow through an adiabatic capillary tube has been presented. Finite volume method with volume of fluid method has been used in the computation. A source term has been incorporated in the governing equations to model the rate of evaporation of liquid refrigerant into vapor state. The source term effectively controls the mass transfer phenomenon during the transformation of liquid refrigerant into vapor phase. The present model has been validated with the experimental data available in the literature. The important flow properties of the single liquid and liquid-vapour mixture such as temperature, pressure, velocity, dryness fraction and flow variables at different locations of the tube and at different time levels have been presented. It has been observed that with the inception of vapour the flow properties changes drastically and a non-equilibrium state exists for some time between the two-phases.

VI. Sukkarin Chingulpitak et al. (2011) [6] -

This paper presents a numerical investigation of the flow characteristics of helical capillary tubes compared with straight capillary tubes. This model is validated by comparing it with the experimental data of both straight and helical capillary tubes. Comparisons of the predicted results between the straight and helical capillary tubes are presented. The results show that the refrigerant flowing through the straight capillary tube provides a slightly lower pressure drop than that in the helical capillary tube, which resulted in a total tube length that was longer by about 20%. In addition, for the same tube length, the mass flowrate in the helical capillary tube with a coil diameter of 40 mm is 9% less than that in the straight tube. Finally, the results obtained from the present model show reasonable agreement with the experimental data of helical capillary tubes and can also be applied to predict the flow characteristics of straight capillary tubes by changing to straight tube friction factors, for which Churchill’s equation was used in the present study.

VII. M.K. Mittal et al. (2010) [7] -

This paper presents an experimental investigation of coiling effect on the flow of R-407C in an adiabatic helical capillary tube. It has been observed that the coiling of capillary tube significantly influences the mass flow rate of R-407C through the adiabatic helical capillary tube. For the sake of comparison, the experiments have also been conducted for straight capillary tube and it has been observed that the mass flow rates in coiled capillary tube are 5–10 percent less than those in a straight one. The data obtained from the experiments have been analysed and non-dimensional correlations for the prediction of mass flow rate of R-407C in straight and helical capillary tube have been developed. The proposed correlations predict our experimental data in an error band of ±10 percent. The predictions by developed correlations are also in good agreement with the data of other investigators.

VIII. Mohd. Kaleem Khan et al. (2008) [8] -

An experimental investigation was carried out to evaluate the flow characteristics of refrigerant R-134a through an adiabatic helically coiled capillary tube. The effect of various physical parameters like diameter and length of capillary tube, coil pitch, and inlet subcooling on the mass flow rate of R-134a was investigated. Moreover, the refrigerant mass flow rate through an instrumented capillary tube was also compared to that through a no instrumented capillary tube. It was found that the provision of taps for pressure
measurement on the capillary tube surface has a negligible effect on the mass flow rate of R-134a. Further, the coil pitch had a significant effect on the performance of the adiabatic helically coiled capillary tube. It was established that the coil pitch significantly influenced the mass flow rate through the adiabatic helically coiled capillary tube. It was concluded that the effect of coiling of the capillary tube reduces the mass flow rate by 5% to 15%, as compared to those of the straight capillary tube operating under similar conditions.

IX. P.K. Bansal et.al (2004) [9] -

This paper presents a homogeneous simulation model for choked flow conditions for pure refrigerants (R134a, R600a) in adiabatic capillary tubes. The model is based on the first principles of thermodynamics and fluid mechanics and some empirical relations. This study presents fresh look at the classical fluid flow problem, known as Fanno flow for refrigerant flow in capillary tubes. A new diagram called the full range simulation diagram has been developed that presents a better way to understand the choked flow phenomenon graphically. The diagram is useful for design and analysis of refrigerant flow in capillary tubes. The model has been validated with published experimental data for R22, R134a and R600a and is found to agree to within ±7%.

X. Wong wises et.al (2001) [10] -

This paper provides a result of simulation using an adiabatic capillary model which is developed to study flow characteristic in adiabatic capillary tubes used as a refrigerant control device in refrigerating systems, the developed model is considered as an effective tools of capillary tubes design and optimization of systems using newer alternative refrigerants the model is validated by comparing with experimental data of Li et al and Mikol for R12 and Melo et al R134a. In particular it has been possible to compare the various pairs of refrigerants it is found that the conventional refrigerant give longer capillary length than alternative refrigerant. For all pairs, the conventional refrigerant consistently give lower pressure drops for single phase and two phase flow rate which resulted in longer tube lengths. In addition, an example of capillary tube selection chart developed from the present numerical simulation as shown. The chart can be practically used to select the capillary tube size from the flow rate and the flow condition or to determine mass flow rate directly from a given tube and flow condition. The results of this study are of technological importance for the efficient design when systems are assigned to utilize various alternative refrigerants.


This paper presents theoretical comparison of the flow characteristics of many pairs of refrigerants flowing through adiabatic capillary tubes. The two-phase flow model developed was based on homogeneous flow assumption. Two-phase friction factor was determined from Colebrook correlation. The viscosity model was also based on the recommendations from the previous literature. For all pairs, numerical results showed that the traditional refrigerants consistently gave lower pressure drops for both single phase and two-phase flow than the environmentally acceptable alternative refrigerants which resulted in longer tube lengths.

Table 1: The existing research work and different process parameters.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Title, Authors Name and Year</th>
<th>Refrigerants</th>
<th>Range of Parameters</th>
<th>Type</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Adiabatic flow characteristics of R-600a inside a helically coiled capillary tube. Santhosh Kumar Dubba (2018)</td>
<td>R-600a</td>
<td>( d = 1.12 \text{–} 1.52 \text{ mm} ), ( L = 2.8 \text{–} 4.6 \text{ m} ), ( D = 0, 60 % ) to 80mm, ( P_m = 620.5, 668.7, 724 ) KPa, ( T_{sub} = 3–15 \text{ °C} )</td>
<td>Straight and Helical capillary tube</td>
<td>The experimental results confirm that, the mass flow rate in the straight capillary tube is 1.5–16 percent higher than the coiled capillary tube.</td>
</tr>
<tr>
<td>2</td>
<td>A comparative study of straight and spiral adiabatic capillary tube. Pravin Jadhav (2017)</td>
<td>R-744 R-22</td>
<td>( T_{in} = 313K ), ( P_{in} = 100 \text{bar} ), ( e = 0.00576 \text{ mm} )</td>
<td>Straight and Spiral capillary tube</td>
<td>For similar operating condition, the mass flow rate and length of the tube is significantly larger in case of R744 refrigerant. A reduction in mass flow rate in the spiral capillary tube is about 22% and 15% compared to straight capillary tube with R744 and R22 refrigerants, respectively.</td>
</tr>
</tbody>
</table>
| 3 | Numerical simulation and experimental analysis of refrigerants flow through adiabatic helical capillary tube. Masoud Zareh (2014) | R-12,R-134a,R-22 | d=1.4 mm  
$P_m=1200$KPa  
$T_m=40^\circ$C  
$e=.0003$mm  
$D_c=40$-100mm | Straight and Helical capillary tube | For the same length and under similar conditions, mass flux through helical capillary tube with coil diameter of 40 mm are about 11% less than that through the straight tube, where the helical tube length is about 14% shorter than the straight one for the same refrigerant mass flux. |
| 4 | Experimental investigation and numerical simulation of choked refrigerant flow through helical adiabatic capillary tube. Hossien Shokouhmand(2014) | R-134a | d=1.397 mm  
$P_m=1204$KPa  
$T_m=44.9^\circ$C  
$D_c=40$-100mm | Straight and Helical capillary tube | Under the same conditions, critical mass flux through helical tube with coil diameter of 40 mm is about 16% less than of straight one. The mass flux in steady and choked conditions through coiled capillary tube are equal approximately. |
| 5 | Numerical Investigation of Refrigerant flow through an adiabatic capillary tube. Yogesh K. Prajapati(2013) | R-12, R-134a | d=0.66 mm  
$P_m=8.37$ bar  
$T_m=298.22$K  
$e=1.98$ μm  
$T_{sub}=9.5$ K  
$M=3.726$ kg/h | Straight capillary Tube | For the same geometry and input parameters R134a flashes earlier than R12. Therefore, shorter tube is required while using R134a. The dryness fraction development i.e. the inception point of vapour phase inside the tube has been captured. Initially vaporization starts at downstream location gradually it shifted towards upstream with flow time. |
| 6 | A comparison of flow characteristics of refrigerants flowing through adiabatic straight and helical capillary tubes. Sukkarin Chingulpitak(2011) | R-407C  
R-134a | L=1.52 - 3.05 m  
$T_{in}=37.8$ - 54.4°C  
$d=0.84$mm  
$T_{sub}=16.7^\circ$C | Helical and straight capillary tube | The results show that the refrigerant flowing through the straight capillary tube provides a slightly lower pressure drop than that in the helical capillary tube, which resulted in a total tube length that was longer by about 20%. |
| 7 | An experimental study of the flow of R-407C in an adiabatic helical capillary tube. M.K. Mittal (2010) | R-407C | d=1.02, 1.27, 1.52mm  
$e=1.19, 1.91, 2.52$ μm  
$L=1.0, 1.5, 2.0$m  
$D_c=60, 100, 140, 0$mm  
$T_{sub}=3$–12K  
$P_m=1470, 1640, 1860$KPa | Straight and Helical capillary tube | Mass flow rates in coiled capillary tube are 5–10 percent less than those in a straight tube. |
| 8 | Experimental Study of the Flow of R-134a | d=1.12-1.63 mm  
$T_{sub}=10^\circ$C | Straight and Helical | The effect of coiling of the capillary |
3. CONCLUSION

The following conclusions are drawn based on the literature review on flow of refrigerants through the capillary tubes:

- The optimum refrigerant charge as well as the capillary length lead to a capillary based refrigeration system to work with better coefficient of performance.
- The length of capillary tube required for helical is smaller for same pressure drop under identical condition.
- The mass flow rate required will be less in case of helical capillary tube with respect to straight capillary tube by 5-15%.
- It can also be found that lower pressure drop is obtained by using the traditional refrigerant for both single phase and two phase flow which resulted in longer tube lengths.

REFERENCES