EXPERIMENTAL INVESTIGATION OF REFRIGERANT FLOW RATE WITH SPIRALLY COILED ADIABATIC CAPILLARY TUBE IN VAPOUR COMPRESSION REFRIGERATION CYCLE USING ECO FRIENDLY REFRIGERANT

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ABSTRACT

This paper represents an experimental investigation about effect of simple and twisted spirally coiled adiabatic capillary tube on the refrigerant flow rate. Several capillary tubes with different inner diameters, lengths and pitches are taken as test sections. An eco-friendly refrigerant; LPG is taken as alternative of R-134a having lesser GWP and ODP. Coiling spirally and cross sectional changes because of twist on capillary tube along the length has its influence on mass flow rate and cooling effect that can be invariably marked. Mass flow rate for different capillary tubes are measured for different degrees of sub cooling with constant inlet pressure of capillary. For comparison, the experiments have also been conducted for straight capillary tube and it has been observed that the mass flow rates in spiral coiled capillary tube are less than those in a straight one where as in twisted spiral coiled capillary tube, refrigerant flow rate is further reduced.

KEYWORDS: Spiral Capillary Tube, Straight Capillary Tube, LPG, Vapour Compression Refrigeration System

INTRODUCTION

The basic vapour compression or mechanical refrigeration cycle relies mainly on process of evaporation by absorbing large amounts of heat and releasing the same through condensation with the circulation of fluid called refrigerant. This heat which must be gained or lost during the change of state is called latent heat of vaporisation. In general, latent heat of vaporisation is more than the specific heat that is the heat lost or gained during a one degree change in temperature. Thus, there in general only two pressures are in principal, within the refrigeration system, which are relative to the evaporating and condensing temperatures which depends on the refrigerant used the temperature of the space to be cooled and the type of application. This difference in pressure is mainly achieved by installing a throttle device either manual or automatic.

The functions of the such throttling devices is to regulate the flow of high pressure liquid refrigerant from the condenser to a low pressure liquid refrigerant into the evaporator and to maintain a pressure differential between the high and low pressure sides of the refrigeration system which allows the refrigerant to vaporize under the desired low pressure in the evaporator. In capillary, the fall in pressure of the refrigerant takes place not due to the orifice but due to the small opening. It depends on the diameter of the capillary and the length of the capillary. Smaller is the diameter and more is the length of the capillary more is the drop in pressure of the refrigerant as it passes through it.

Although the device lacks active function (mechanical or electrical) to actively adjust to any sudden change in the load conditions, it is still in use as a result of its simplicity, low cost and requirement of low compressor starting torque. Capillary length ranges from 400 to 6200 mm thus; capillary tubes are normally folded in various configurations, so as to reduce the required.

The flow characteristics of refrigerants through capillary tubes have been studied extensively in past six decades, both experimentally and numerically, most of these studies mainly focused on straight capillary tubes. However in
practical applications, if this length is to be kept straight in any installation, a lot of space would be required. As a result, the capillary tubes are normally folded in various configurations, so as to reduce the required space. Since the capillary tube is to be folded in order to reduce the required space, there is the need to study the effect of capillary tube geometry on the performance of refrigeration systems. At the same time, changing cross section of the capillary at certain nodes like twists can also significantly affect the flow through it. Moreover, with the advent of new eco-friendly refrigerants, the studies on coiled capillary tubes with alternative refrigerants become all more important to select appropriate sized capillary tubes for specific applications.

Some of the investigations made in earlier decades regarding capillary tubes suggested some of the interesting effects and applications. Mikol (1963) carried out an extensive experimental investigation on the capillary tube to explore the various flow phenomena like Meta stability and choking. They developed a friction factor correlation by flowing water through the same capillary tube. The effect of coiling on the refrigerant mass flow rate of the refrigerant has been discussed by a few investigators. Kuehl and Goldschmidt (1990) have conducted experiments on the flow of R-22 through adiabatic capillary tubes of straight and coiled geometries. They have concluded that because of the coiling of capillary tube, the refrigerant mass flow rate was reduced by not more than 5%. Kim et al. (2002) have studied the flow of R-22 and its alternatives, viz., R-407C and R-410A through the straight and helically coiled adiabatic capillary tubes. They have observed 9% reduction in refrigerant mass flow rate through a coiled tube in comparison to that in straight tube of same length. Zhou and Zhang (2006a) conducted an experimental investigation on helically coiled capillary tubes for the flow of refrigerant R-22. In addition, a numerical model using Mori and Nakayama friction factor correlation (Mori and Nakayama, 1967) was also proposed. It was concluded that for the mean coil diameter beyond 300 mm, the change in mass flow rate was insignificant. It was also observed that the refrigerant mass flow rate through a helical capillary tube with coil diameter of 40 mm was approximately 10% less than that of the straight capillary tube. Further, Zhou and Zhang (2006b) confirmed the hysteresis in refrigerant mass flow rate with increasing and decreasing inlet subcooling in an adiabatic helical capillary tube. The hysteresis effect was more prominent in helical capillary tube than that in straight tube due to the disturbance generated from the secondary flows caused by the centrifugal force. It was also found that in the coiled capillary tube the refrigerant flashed earlier with decreased coil diameter as reduction in coil diameter caused the pressure drop to increase. However, for validation of the numerical model with the experimental data, the increasing subcooling data should be taken into account due to their consistency and reproducibility. Deodhar et al. (2006) have conducted an experimental and numerical investigation on R-134a refrigerant through straight and helically coiled capillary tube. Experiments carried out on helically coiled capillary tubes indicate an increase in resistance to the flow due to coiling. Mass flow rate through a capillary tube of capillary tube of coil diameter of 20 mm is lower by about 9 to 19 percent than that through the straight capillary tube. Park et al. (2007) studied the flow of R-22 and its alternatives, R-407C and R-410A, through coiled adiabatic capillary. It been has revealed a slightly higher drop in mass flow rates of the coiled capillary tubes compared to those in straight capillary tubes as reported by Kim et al. (2002) and Zhou and Zhang (2006a). It was found by Park et al. (2007) that the mass flow rate of the coiled capillary tubes was decreased by 5 to16% in comparison to that for the straight capillary tubes. They also proposed a generalized mass flow rate correlation for helically coiled capillary tubes based on Buckingham-π theorem. In addition, a numerical model based on homogenous two-phase flow model was presented using Ito (1959) friction factor correlation for single phase flow and Giri’s equation for two-phase flow (Gorasia et al., 1991). Valladares (2007) also presented a numerical simulation model for the coiled capillary tubes based on the finite volume formulation. The solution was carried out using an implicit step-by-step numerical scheme. The calculation of mass flow rate was made iteratively using Newton–Raphson Algorithm. Khan et al. (2007) have proposed the numerical model for the computation of length of adiabatic spiral capillary tube. The model for spiral
capillary tube is compared with the model for straight capillary tube operating under similar conditions. It has been found that because of coiling the length of the capillary tube is reduced considerably for a given set of conditions. Khan et al. (2008a) investigated the effect of the coiling on the mass flow rate of R-134a in helical capillary tube by varying the coil pitch in the range 20-60 mm for the coil diameter of 140 mm. They observed that the coiling of capillary tube reduces the mass flow rate by 5-15 percent as compared to those of straight capillary tube operating under similar conditions. Khan et al. (2008b) also examined the flow characteristics of R-134a in spiral capillary tube having coil pitch of 20, 40 and 60 mm. They concluded that the mass flow rate in spiral capillary tube is 5-15 percent less than that in straight capillary tube. They also developed a non-dimensional correlation to predict the mass flow rate of R-134a in spiral capillary tube. Mittal et al. (2009) proposed a homogenous model for the adiabatic flow of the refrigerant through the spiral capillary tube and the effect of pitch of the spiral on the mass flow rate of refrigerant. A comparison of the flow characteristics of refrigerant R22 and its alternatives, i.e., R407C and R410A has been made at different operating conditions and it has been found that the flow characteristics of R22 and R407C are almost similar for a given condenser pressure and degree of sub cooling at the inlet of sub cooling. Zhou et al. (2012) investigates the inlet pressure fluctuations for the coiled adiabatic capillary tubes. It has been found that pressure fluctuation for coiled capillary tubes is much more prominent than for straight ones.

With growing environmental hazards, one of the serious threats to the environment is the stratospheric ozone layer depletion. The stratospheric ozone layer plays a beneficial role by absorbing most of the biologically damaging ultraviolet sunlight called UV-B coming towards the Earth. Ozone also plays a key role in the temperature regulation of the Earth’s Atmosphere. The ozone depleting compounds (i.e., CFCs and HCFCs) contain reactive gaseous atoms of chlorine or bromine. Although, the CFC and HCFC molecules are heavier than the molecules of air, the atmospheric air-circulation takes these compounds to the stratosphere over a period of time. Thus, in the present environmentally conscious age, it has been pointed out that production, leakage, disposal, etc. of CFCs and HCFCs refrigerants has an adverse effect on our environment by contributing towards ozone layer depletion and green- house effect. Thus, due to slow improvement of efficiency and concern for the environment, efforts are now being directed to develop eco friendly alternative refrigeration systems. LPG is ozone-safe blend of three hydrocarbons (30% propane, 55% n-butane, 15% iso butane) and exhibits properties similar to that of R12 and there is not any single study reported in literature suggesting the study of flow of LPG through coiled capillary tube. Therefore, in order to strengthen the work of LPG as refrigerant, the present study has been done by different operating conditions and different geometrical parameters of capillary tube.

**EXPERIMENTAL SETUP AND PROCEDURE**

The experimental facility as shown below consists of a simple vapour compression refrigeration system charged with LPG as a refrigerant. The evaporator and condenser are shell and tube type adiabatic heat exchangers. Refrigerant flows through copper tubes of inside diameter as ¼ inch throughout the condenser, evaporator and connecting lines. All connecting tubes of refrigerant are well insulated by polyurethane cellular foam. Water can flow through the insulated shell of each of the evaporator and condenser and there is an arrangement for control and measurement of water flow rate through each. Hand operated valves and connectors are provided before and after the capillary tube to facilitate its replacement.

The temperature of refrigerant at various points is measured with PT-100 (strongly insulated along length of tubes by means of polyurethane cellular foam). Pressure of refrigerant is measured and indicated by separate dial gauges at four points before and after each of the evaporator and condenser. Mass flow rate of refrigerant liquid after condenser is indicated by a glass tube Rotameter fitted in the refrigerant line after condenser. A digital wattmeter gives the instant value of power consumption of compressor and also the total energy consumed during whole trial.
Spirally coiled capillary tubes as Test sections used in the experimental investigation are used by keeping pitch as area of interest. Three capillary coil diameters i.e., 1.12 mm, 1.40 mm and 1.52 mm are used and three different pitch of the spiral geometry are used. Lengths of capillary tubes used in the experiment are 2.9 m, 3.7 m, and 4.5 m. Different pitches of the spiral shaped are taken as solid, 1 cm, 2cm.

The capillaries are provided with twists at 15cm apart along the length to produce twisted test sections of capillaries. This makes total 72 test sections including both simple capillary and twisted type capillary. The pressure at capillary inlet test section is adjusted to 760 KPa. The sub cooling at inlet of capillary are randomly set in the range 1°C to 12°C.

RESULTS AND DISCUSSIONS

The refrigerant mass flow rate in capillary tubes and its thermo-fluid-dynamic behaviour depends on capillary tube length, capillary tube diameter, capillary tube inlet pressure, degree of sub cooling, cross section of capillary tube and nature of refrigerant.

The cumulative effect of coil pitch, capillary tube diameter, inlet sub cooling, twisted nodes and capillary tube length on the refrigerant mass flow rate has been arranged in tabular orientations as shown:
Effect of Capillary Tube Length and Shape of Capillary on Mass Flow Rate

The length of the capillary tube has a significant impact on the mass flow rate of the refrigerant across cycle. It can be found that when the length of the capillary of a particular diameter is increased, mass flow rate decreases, refer fig., 1.1 at a constant inlet pressure and sub cooling rate. Also, when straight capillary tube is shaped spirally, the mass flow rate of the system falls which can be further reduced by providing locational twists across the length of the capillary tube.

![mass flow rate vs length of capillary](image)

This is mainly caused due to increase in frictional resistance across the capillary length. For the capillary diameter 1.12mm and length 2.9 m of simple straight capillary, the mass flow rate is decreased by 4.3%, 8.6 % and 15.13%, when these are turned into spiral shape of pitches 2mm, 1mm and 0mm respectively.

Similarly, for length 3.7m a fall of 2.43%, 7.14% and 14.28% in mass flow rate is recorded. To verify the behaviour of mass flow rate, another capillary length 4.5m, is subjected to similar operating parameters and an overall decrease of 2.83%, 5.67% and 11.34% was found, this shows the effect of spiral geometry of capillary. This is mainly due to action of centrifugal force acting along the spiral shape of the capillary.

For the capillary diameter 1.40mm and length 2.9m straight capillary and spiral capillaries of pitches 2mm,1mm and 0mm, the mass flow rate decreased by 2.57%, 2.82% and 4.41% respectively. Similarly, for capillary of length 3.7m and diameter 1.40mm, the mass flow rate is reduced by 1.54%, 3.045% and 4.76%, when compared to straight capillary respectively. For the capillary tube of length 4.5m, mass flow rate is reduced by 4.56%, 5.08% respectively, when the straight capillary is turned into spiral shape.

When capillary tube of 1.52mm is taken of different lengths and moulded into spiral shape from straight, significant reduction in mass flow rate is found as compared to straight capillary. For, capillary length 4.5m in such a capillary, mass flow rate reduces to 1.91%, 2.83% and 2.85% respectively, when straight capillary is turned into spiral capillary of 2mm pitch, 1mm pitch and zero pitch respectively.
A similar approach was taken for twisted straight capillary tube having same diameters and lengths as shown in fig., 1.2. A decrease of 11.4% and 14.5% was recorded on increasing the length from 2.9m to 3.7m and 4.5m respectively for capillary diameter 1.12mm. For a capillary tube diameter of 1.40mm, decrease of 11.3% and 8.46% is found respectively.

In case of capillary size 1.52mm, 10.48% and 3.52% fall in mass flow rate is recorded when increasing the length from 2.9m to 3.7m and 4.5m respectively. Also, the mass flow rate decreases further when the straight capillary with twist is moulded into spiral shape as discussed above in case of capillaries without twisted nodes.

A comparison is shown in fig. 1.3 with straight capillary of dia. 1.52mm without any twist and with twist. It has been found that the effect of twists has a greater influence on mass flow rate as compared to simple capillary tube. While increasing the length from 2.9m to 3.7m, mass flow rate decreases to 8.61% in case of simple straight capillary tube which is further more reduced to 13.80% when the same capillary is provided twisted nodes across the length of capillary. Similarly, when the same capillary is turned into spiral shape, an overall reduction of 19.4% is found when twisted capillary is further turned to spiral shape as shown in fig. 1.4.
It has been concluded from above graphical representations that with increase in length of capillary tubes irrespective of internal diameters, mass flow rate decreases. Smaller is the capillary tube diameter more is the percentage decrease in mass flow rate. Therefore, for a given compressor capacity, length of the capillary can be optimised so as to save the material of the capillary and a more compact unit. Also, compressor capacity can be lowered for a particular length of capillary tube in order to minimize the power required to drive the unit. Further, use of locational twisted capillary tube can further decrease mass flow rate through the refrigeration system and can be applied for more material and power savings as suggested earlier as shown in fig., 1.3.

Effect of radial pitch on mass flow rate through the capillary tube

![Twisted nodes](image)

The spiral shaped capillary tube has a significant effect on the mass flow rate when compared with straight capillary test section. So, the effect of radial pitch on the spiral geometry derives interest towards next area of investigation in this experiment. Different test sections of spiral geometry are fabricated and the radial pitch is taken as zero, 1cm and 2cm cm respectively. The length of the capillaries is taken as 4.5m, 3.7m and 2.9m.

It has been observed from experimental investigation that mass flow rate through spiral capillary tube rises on increasing the radial pitch as shown in fig., 2.1. The effect of pitch is found maximum on smallest capillary tube diameter i.e. 1.12mm and goes on decreasing when larger capillary diameters are taken as 1.40mm and 1.52mm in this experiment.
Thus, pitch of the spiral geometry can be significantly adjusted so as to decrease the mass flow rate through the cycle providing the same pressure difference across the capillary. Thus, a smaller compressor unit is to be implied for spiral geometries having lower radial pitch resulting to be more energy efficient.

On increasing the radial pitch of spiral capillary of dia.1.12mm and length 4.5m from 0cm to 1 cm, the mass flow rate across the capillary is found to be increased by 9% which further increases to 11.2% if radial pitch is increased to 2cm. Similarly, for spiral capillary tube of length 4.5m and dia. 1.40mm, the mass flow rate increases by 5.1% and 6.8% respectively for radial pitches 1cm and 2cm respectively. For a capillary tube of dia. 1.52mm and length 4.5m, spirally shaped, effect of increasing radial pitch to 1cm and 2 cm is investigated to be 2.8% and 5.4% respectively.

Also, on capillary having locational twists the mass flow rate is lesser through the capillary as compared to the normal spiral capillary tube. At the same time mass flow rate of the locational twisted capillary tube also increases on increasing the radial pitch of the spiral capillary. For a capillary of dia. 1.12mm, with locational twists, mass flow rate increases to 2.2% and 5.6% for an increase in pitch from 0 to 1cm and 2cm, which are less in percentage rise as compared to non twisted capillary tube as shown in fig., 2.2.

Effect of capillary diameter on mass flow rate

It has been observed that with the increase in capillary diameter, mass flow rate of the refrigerant also increases. This is mainly due to the lesser contact of the capillary walls with the refrigerant flow as the passage area increases.
The above fig. 3.1 shows that mass flow rate through the cycle increases when diameter of capillary is increased. For the capillaries of length 4.5m in this experimental work, mass flow rate increases to 35.68% when the diameter of the capillary is increased from 1.12mm to 1.40mm. If the capillary diameter is raised to 1.52mm, the mass flow rate is enhanced by 47%. For capillary length 3.7m, the mass flow rate is enhanced by 39% and 49%, when the diameter of the capillary is increased from 1.12mm to 1.40mm and 1.52mm respectively. It has been observed that effect of diameter is more prominent in the smaller capillary lengths. While increasing the same diameter proportions, a 39% and 51% increase in mass flow rate is accompanied with the capillaries of length 2.9m.

CONCLUSIONS

The whole experiment is concluded as:

1. While using LPG as a refrigerant; mass flow rate across capillaries of different lengths and diameters can be decreased up to 12% by turning the straight capillary into spiral shape having radial pitch ranging from zero to 2cm. This mass flow rate is further reduced up to 18% by providing the locational twists (15cm apart) along the length of capillary.

2. The increase in length of the capillary by 0.8m results in decrease of mass flow rate up to 10%. This reduction in mass flow rate can be achieved up to 14% by using twisted capillary length. This effect is more prominent while using capillaries of diameter less than 1.40mm.

3. The refrigerant flow rate across the capillary can be increased up to 52% by increasing the capillary diameter from 1.12mm to 1.52mm using different lengths with LPG as working fluid.

REFERENCES


