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Research Article / Araştırma Makalesi

EXPERIMENTAL INVESTIGATION OF R600A REFRIGERANT FLOW INSIDE ADIABATIC CAPILLARY TUBE

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ABSTRACT

Capillary tubes are often used as an expansion component in the refrigeration systems of household refrigerators. During the flow of the refrigerant inside the capillary tube, due to pressure loss of the refrigerant, the refrigerant starts boiling and towards the end of the capillary tube, different types of two-phase regimes occur. Therefore; the refrigerant flow inside the capillary tube is a complex phenomenon and there are many experimental and numerical studies analyzing this refrigerant flow. However; in literature there are hardly any experimental studies analyzing refrigerant flow in small scale refrigeration systems using isobutane (R600a) as the refrigerant. In this study, the two-phase flow regimes of the R600a refrigerant inside a vertical adiabatic capillary tube with 0.80 mm inner diameter, under different condensation pressures subcooling degrees and capillary tube lengths, are recorded via high-speed camera; and the effects of different parameters on refrigerant mass flow are analyzed. The boundary conditions for the condensation pressure, subcooling degree and capillary tube length are determined in accordance with a small scale refrigeration system.
Keywords: Capillary tube, isobutane, two-phase flow, flow visualization.

1. INTRODUCTION

Capillary tubes are often used as an expansion component in the refrigeration systems of household refrigerators. The capillary tube, which has a diameter between 0.33-2.0 mm and a length between 2-6 m, connects the evaporator inlet to the condenser outlet. A capillary tube does not have a moving component; therefore it provides easy and cheap solution. During the compressor off periods, it balances the pressures between the condenser and the evaporator so that the compressor torque is reduced [1].

In literature there are many experimental and numerical studies about adiabatic capillary tubes. Several researchers have also collected large sets of experimental data measured with capillary tubes of different lengths and inner diameters [1,2,3,4,5,6,7]. In most of the experimental studies, the heat transferred out from the capillary tube is neglected. Earlier studies were carried out in order to analyze the flow of R-12 and R-22 refrigerants inside a capillary

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tube. After 1990, new environmental refrigerants such as R-134a, R-600a, R-290 were used in the studies.

In their studies Bolstad and Jordan found out that the effect of evaporation pressure change on refrigerant mass flow rate can be neglected [8]. Additionally; it was observed that refrigerant mass flow rate changed linearly with refrigerant subcooling degree. Moreover, they made studies on analyzing the effect of oil on refrigerant mass flow rate and observed that after the use of oil separator inside the refrigeration system, the mass flow rate decreased approximately 8%. When oil-refrigerant mixture is used, refrigerant boiling point decreases, therefore mass flow rate increases. However; unlike Bolstad and Jordan, Motta observed that when R-404a refrigerant having oil concentration of 5.7% is used, the mass flow rate decreased 6.3% [9].

In order to observe the starting of the bubble formation during boiling, some researchers visualized the flow inside a glass tube [10,11,12]. Cooper observed that the flow inside the glass capillary tube occurred in a fog flow and evaporation occurred with a delay [10]. In addition, he developed a mathematical model in order to calculate the length of the two-phase flow region. Also, he observed that refrigerant mass flow rate changed linearly with refrigerant subcooling degree.

There are studies that offer correlations which calculate mass flow rates of some refrigerants. Bansal and Rupasinghe developed an empirical correlation that is used to determine the dimensions of adiabatic and diabatic capillary tubes [13]. This correlation was derived according to the experimental results of certain ranges in literature. C.Melo analyzed the effect of capillary tube diameter, length, subcooling degree and condensation pressure on mass flow rate for R-12, R-134a and R-600a refrigerants. He formed correlations which calculate the refrigerant mass flow rate for different work ranges. Finally they compared their experimental results with the experimental results of Wolf et al. [14].

Matthias Schenk made experiments in order to analyze the mass flow rate of R600a refrigerant inside a capillary tube between 0.65 kg/h and 2.00 kg/h range. When the results of the experiments are compared with the results calculated with the numerical equations in literature, it is observed that the closest result can be achieved with the semi-algebraic equations that were developed by Hermes [15,16].

In literature, there are few studies that analyze the flow of R600a refrigerant inside an adiabatic capillary tube. In C.Melo's studies, the condensation pressure of the refrigeration system was kept between 9 and 11 bar and this pressure value is much higher than the pressure inside small scale refrigeration systems. In his experiments, using capillary tubes with inner diameter of 0.61 and 0.69 mm, Matthias Schenk carried out tests keeping the refrigerant subcooling degree between 8 and 13 °C [1,15].

In this study, pressure loss and refrigerant mass flow inside a capillary tube, with 0.80 mm inner diameter and 2250 to 3750 mm length, is analyzed. The tests have been done with condensation pressure between 4.3 and 5.3 bar, subcooling degree between 3 and 6 °C. Consequently, an empirical model is derived from the experimental results.

In order to visualize the two-phase flow inside the vertical capillary tube with a high-speed camera, a glass tube is placed on the area where two-phase flow occurs.

2. EXPERIMENTAL SETUP

The schematic view of the experimental setup is shown in Fig. 1. The experimental setup is based on vapor compression system. The oil separator, which is placed at the exit of the compressor, separates the oil inside oil-refrigerant mixture and thereby avoids the circulation of oil inside refrigeration system. The oil separated by the oil separator is collected in a tank and periodically sent back to the compressor.

In the cooling system, two water baths are used to control the condensation pressure and the subcooling degree, and one water bath is used to balance the temperature change on the evaporator side. A mass flowmeter is placed on the condenser outlet of the second water bath, which is used to control the subcooling degree, to measure the mass flow rate of the refrigerant. In order to control the capillary tube and the compressor inlet temperatures separately, heaters, which are controlled by digital thermostat, are placed on both flowmeter outlet and compressor inlet. In order to filter undesired humidity and particles inside the cooling system, a dryer is placed towards the capillary tube inlet. Sight glasses are placed on the critical areas of the cooling system to watch the refrigerant flow.

The details of the selected cooling components are given in Table 1.

Table 1. Specifications of the components

Component	Parameter	Specification
Compressor	Type	Reciprocating hermetically sealed
	Motor	Inverter-driven BLDC (1200-4500 RPM)
	Cooling capacity	116 W at ASHARE conditions, 3000 RPM
Evaporator	Type	Plate fin-tube, aluminum, 2 columns, 8 rows
	Heat transfer area	0,254 m^2
Condenser	Type	Spiral Tube, steal
	Heat transfer area	0,502 m^2
Insulation for capillary tube	Type	Nitrile Rubber Pipe Insulation
	Thickness	19 mm

A capillary tube with an inner diameter of 0.80 mm and a length of 3750 mm is placed between the dryer and the evaporator. A copper capillary tube is used on the capillary tube inlet, where the refrigerant flow occurs in liquid phase. A glass capillary tube, which enables the observation of the two-phase flow, is connected to the outlet of the copper capillary tube. In order to avoid heat transfer to the environment, the capillary tube is wrapped with an insulation material. The formation of the two-phase flow, under different conditions, inside capillary tube is visualized with a high-speed camera. The experimental setup, that is used to visualize the refrigerant inside the glass capillary tube, is shown in Fig. 2. The camera shooting is carried out with 64x200 resolution and 28169 FPS (frame per second). In order to make a better visualization, a cold-light source is placed behind the glass capillary tube.

Table 2. Uncertainties of the measurements

Measured parameter	Uncertainty
Pressure	± 0.00025 bar
Temperature	± 0.2 °C
Mass flow rate	0.1%
Length	2 mm

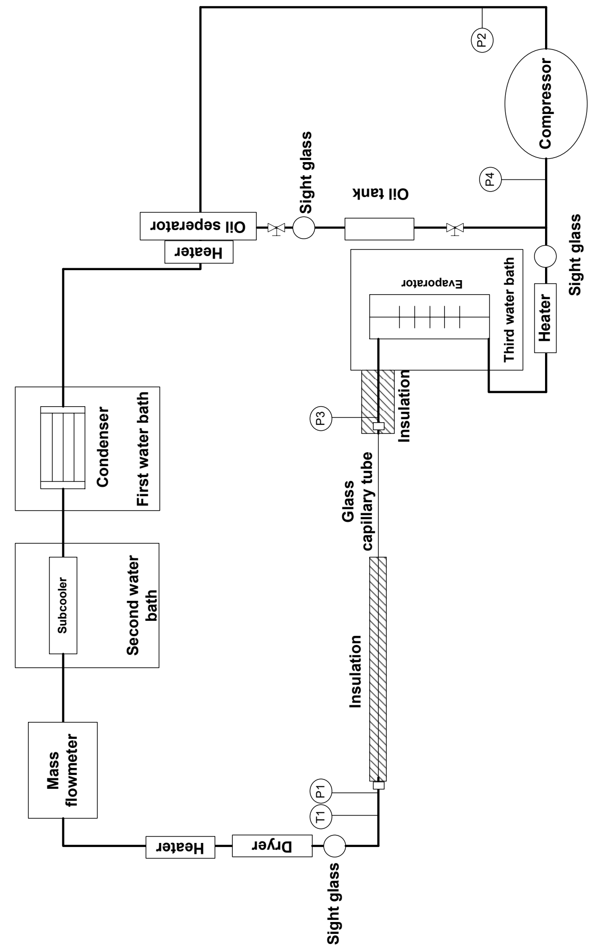


Figure 1. The schematic view of the experimental setup

A high accuracy pressure transducer (with 0.10% accuracy) is placed on each compressor inlet/outlet and capillary tube inlet/outlet. Additionally; a T type thermocouple (with ±0.2 °C sensitivity) is placed both on the inlets and outlets of each component of the refrigeration system. The calibration of thermocouples, transducers, and flowmeter were completed before the measurements. All the uncertainties of the measurements are listed in Table 2. The uncertainty analysis results are given in Table 3 for the highest and the lowest boundary conditions.

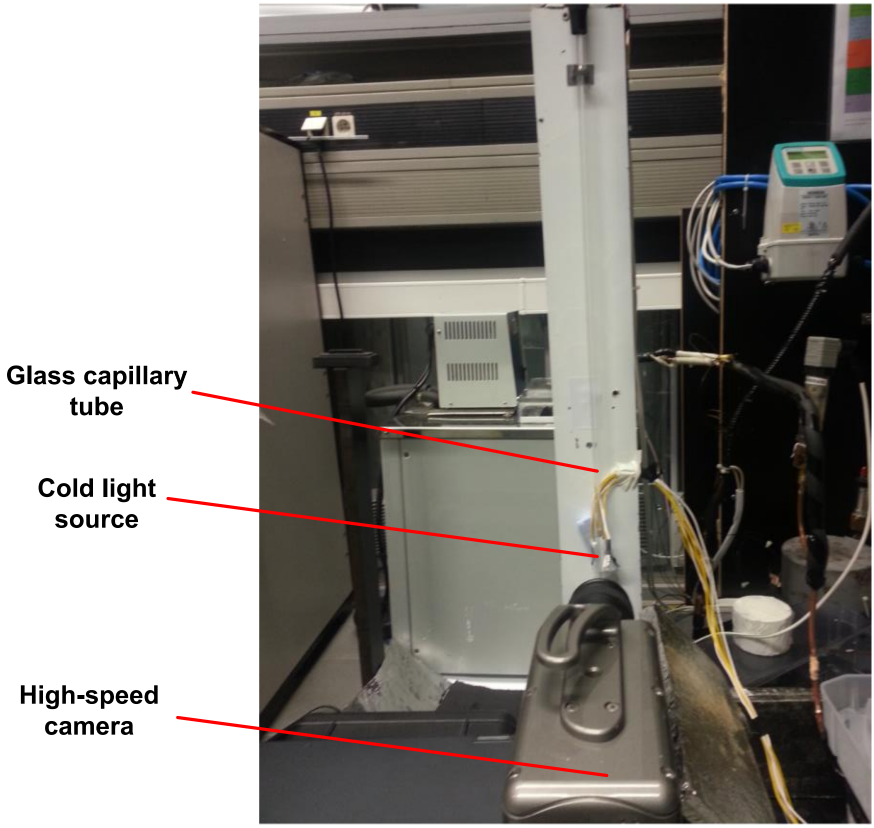


Figure 2. The experimental setup used for visualization of two-phase flow regimes inside capillary tube

Table 3. Uncertainty analysis results

Inlet/outlet parameter	Lowest	Highest
Inlet pressure of capillary tube	4.3 bar	5.3 bar
Subcooling degree	3 K	6 K
Capillary length	2250 mm	4000 mm
Calculated mass flow rate	1.805±0.01862 kg/h	1.627±0.007811 kg/h

The data acquisition system is set to collect the measurement data so that the measurements are monitored and analyzed simultaneously.

3. EXPERIMENTAL RESULTS

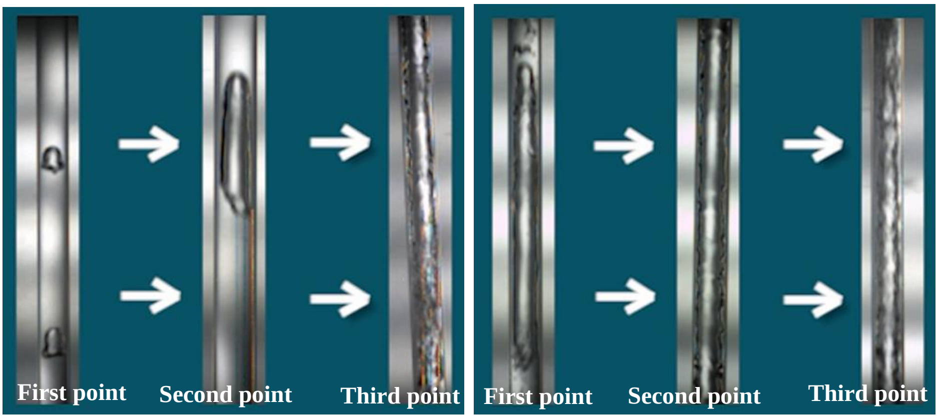
3.1. Visual Results

In this study, the effects of three factors on the formation of two-phase flow, mass flow of the refrigerant, and pressure loss inside the adiabatic capillary tube are investigated. The ranges for these three factors that are investigated in the experiments are given in Table 4.

Table 4. Experimental design parameters

D(mm)	0.80			
L(mm)	2250	2750	3250	3750
Pi(bar)	4,3	4,8	5,3	
ΔT(K)	3	4	6	

Mass flow and the flow regimes inside the capillary tube with respect to different capillary tube inlet conditions, are recorded with a high-speed camera at three different pre-defined observation points (75 cm from the capillary outlet-first observation point, 50 cm from the capillary outlet-second observation point, 25 cm from the capillary outlet-third observation point) within the last one meter of the vertical capillary tube.

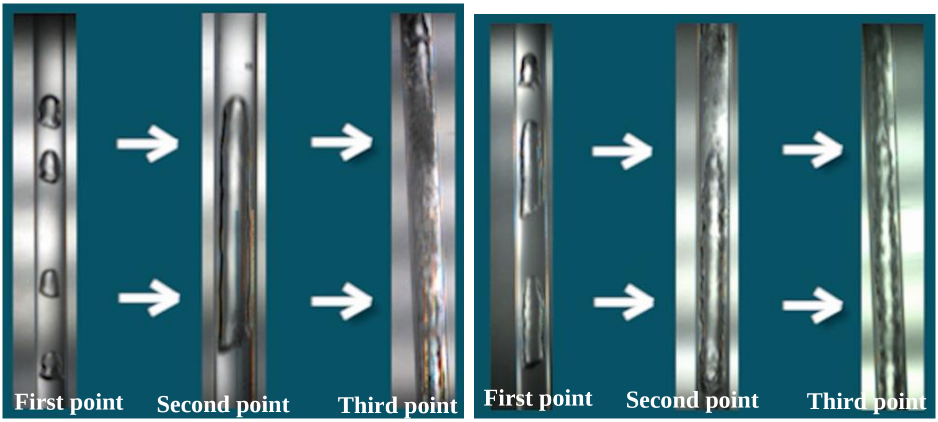


(a) (b)

Figure 3. Two-phase flow regimes under a and b conditions
a) P_i=4.3 bar, ΔT=6 K, L=2750 mm, b) P_i=4.3 bar, ΔT=3 K, L=2750 mm

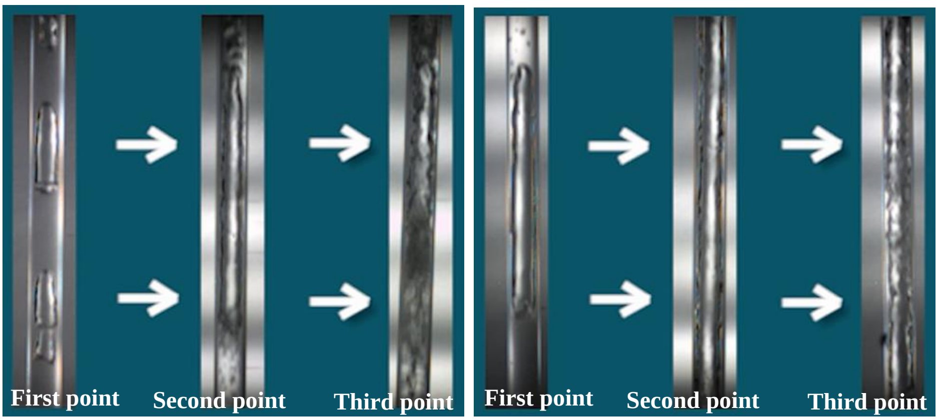
In Fig. 3, the formation of two-phase flow, under different subcooling degrees, same capillary tube length and same capillary tube inlet pressure are shown. As shown in Fig. 3a, due to the effect of pressure decrease, bubble formation starts at the first observation point and the flow occurs in bubbly type flow. At the second observation point, as the velocities of the bubbles increase, the bubbles combine with each other and form a slug type flow. At the third observation point, towards the end of the capillary tube, flow regime turns into annular type flow.

As shown in Fig. 3b, when the subcooling degree is decreased, it is observed that the formation of two-phase flow starts earlier. Therefore at the first observation point, annular flow type is seen instead of bubbly flow.



(a) (b)

Figure 4. Two-phase flow regimes under a and b conditions
a) P_i=4.3 bar, ΔT=6 K, L=2750 mm, b) P_i=5.3 bar, ΔT=6 K, L=2750 mm



(a) (b)

Figure 5. Two-phase flow regimes under a and b conditions
a) P_i=4.8 bar, ΔT=4 K, L=2250 mm, b) P_i=4.8 bar, ΔT=4 K, L=2750 mm

In Fig. 4, the formation of two-phase flow, under different capillary tube inlet pressure, same subcooling degree and same capillary tube length is shown. When Fig. 4a and Fig. 4b are compared, it is observed that when the capillary tube inlet pressure is increased, the formation of two-phase flow starts earlier. As the capillary tube pressure increases, the refrigerant mass flow rate also increases, and consequently the boiling of the refrigerant starts earlier.

In Fig. 5, the formation of two-phase flow, under different capillary tube lengths, same subcooling degree and same capillary tube inlet pressure is shown. When Fig. 5a and Fig. 5b are compared, it is observed that when the capillary tube length is increased, the formation of two-phase flow starts earlier.

3.2. Analysis of the Experimental Data

The effects of three factors on refrigerant mass flow rate and pressure loss inside the capillary tube are shown in Figs. 6, 7, and 8.

As shown in Fig. 6, under same subcooling degree and same capillary tube inlet pressure, as the capillary tube length increases, the refrigerant mass flow rate decreases linearly. As the capillary tube length increases, the length of two-phase flow region also increases and as a result of the accelerated pressure decrease inside the two-phase flow region, the forces resisting on the flow increase. Consequently, refrigerant mass flow rate decreases.

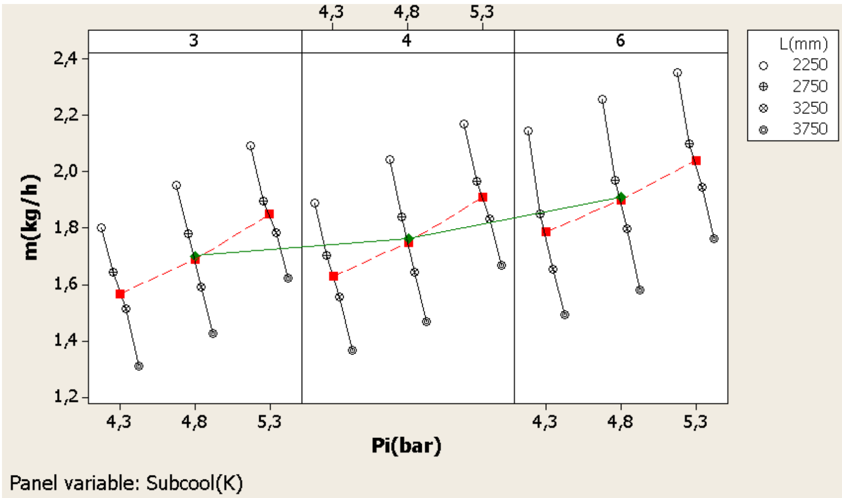


Figure 6. The variation of the mass flow rate under different capillary tube inlet pressures, capillary tube lengths and subcooling degrees

When subcooling degree and capillary tube length are kept constant, as the capillary tube inlet pressure increases, the refrigerant mass flow rate increases linearly and as a result the length of two-phase flow also increases.

When capillary tube inlet pressure and capillary tube length are kept constant, as the subcooling degree increases, the refrigerant mass flow rate increases linearly and as a result the length of two-phase flow decreases. Consequently, the pressure loss inside capillary tube decreases so the refrigerant mass flow rate increases.

As shown in Fig. 7, when subcooling degree and capillary tube inlet pressure are kept constant, as the capillary tube length increases, pressure loss inside capillary tube also increases. When capillary tube length and subcooling degree are kept constant, as the capillary inlet pressure increases, the pressure loss inside capillary tube also increases.

As the capillary tube length increases, the length of two-phase flow also increases and as a result of the accelerated pressure decrease inside the two-phase flow region, the forces resisting on the flow increase. Consequently, the refrigerant mass flow rate decreases. When the capillary tube length and the capillary tube inlet pressure are kept constant, as the subcooling degree increases, the pressure loss inside capillary tube stays almost same.

The ratings of the factors affecting the mass flow rate are shown in Fig. 8. As shown in the figure, it is observed that, the capillary tube length has the most dominant effect on the change of mass flow rate. The capillary tube inlet pressure and the subcooling degree are the other two dominant factors, respectively.

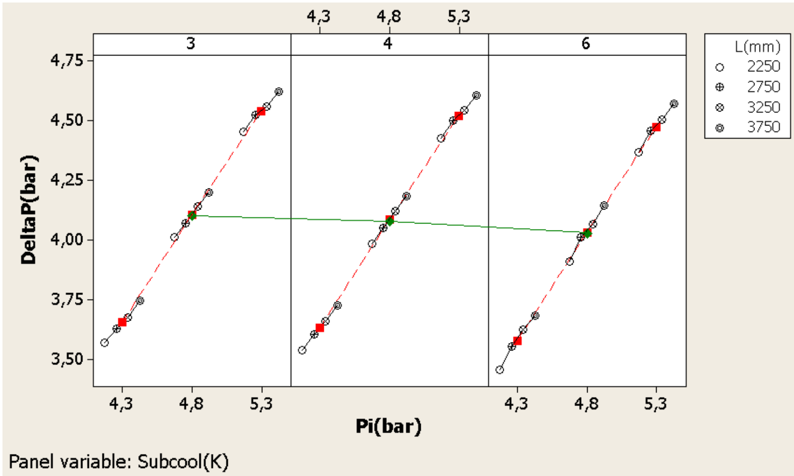


Figure 7. The variation of the pressure loss inside capillary tube under different conditions

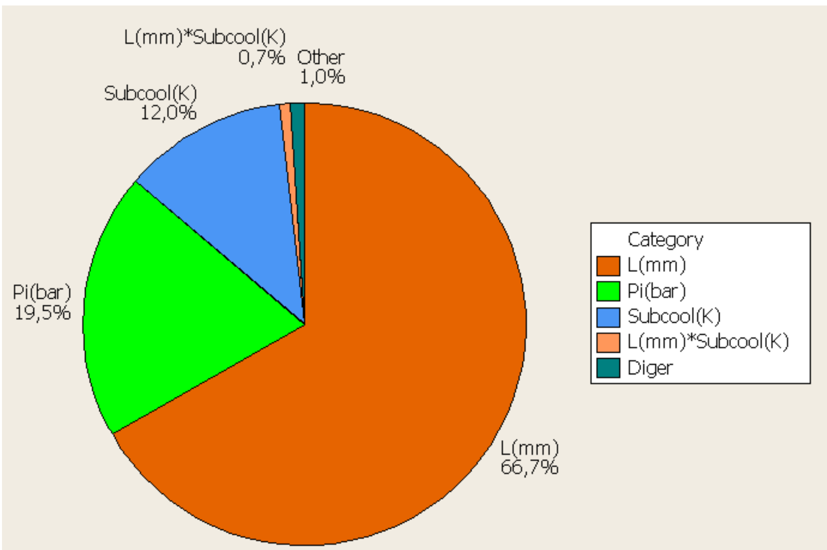


Figure 8. The ratings of the factors affecting the mass flow rate

3.3. Proposed Empirical Correlation and Comparison with Available Correlations

Empirical correlation for the refrigerant mass flow rate given below in Eq. (1), is derived by full factorial design, including all statistically significant effects.

$$\dot{m}_{emp} = 0.877260 - 2.30201 \cdot L \cdot 10^{-4} + 0.271392 \cdot P_i + 0.162828 \cdot \Delta T - 3.10362 \cdot 10^{-5} \cdot L \cdot \Delta T \tag{1}$$

The measured and calculated mass flow rates inside the capillary tube with 0.80 mm inner diameter, under different capillary tube length, capillary tube inlet pressure, and subcooling degree are given together in Fig. 9. As a result of the comparison between the model results and the experimental results, it is observed that the experimental results are within an error band of ±5%.

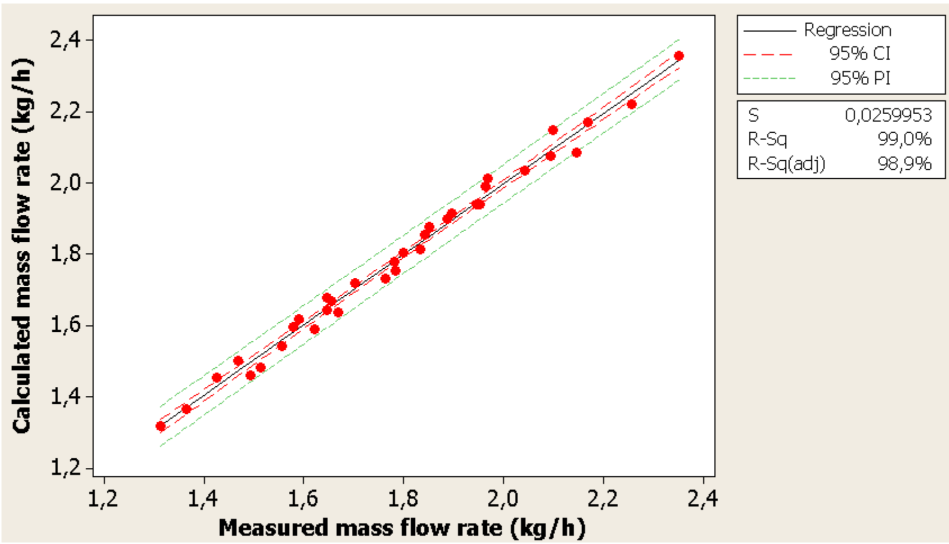


Figure 9. Prediction of the experimental data by Eq. (1)

Several scientists developed empirical correlations and algebraic equations in order to predict refrigerant mass flow rate inside adiabatic capillary tube. Yang and Zhang derived the correlation with a neural network approach [17]. The predictions of their correlation are within a ±20% range of the experimental results of Melo and Mathias Schenk on R600a [1,15]. On the other hand, the algebraic equation developed by Hermes provides predictions within an ±10% error band of the experimental results of Melo and Mathias Schenk on R600a [1,15,16].

In Fig. 10 the experimental results of this study is compared with both the results of the Hermes equation and Eq. (1). As it can be seen in the figure, the experimental results and the empirical correlation derived in this study, which provided predictions within an error band of ±5%, a better level of agreement is achieved in comparison with Hermes equation.

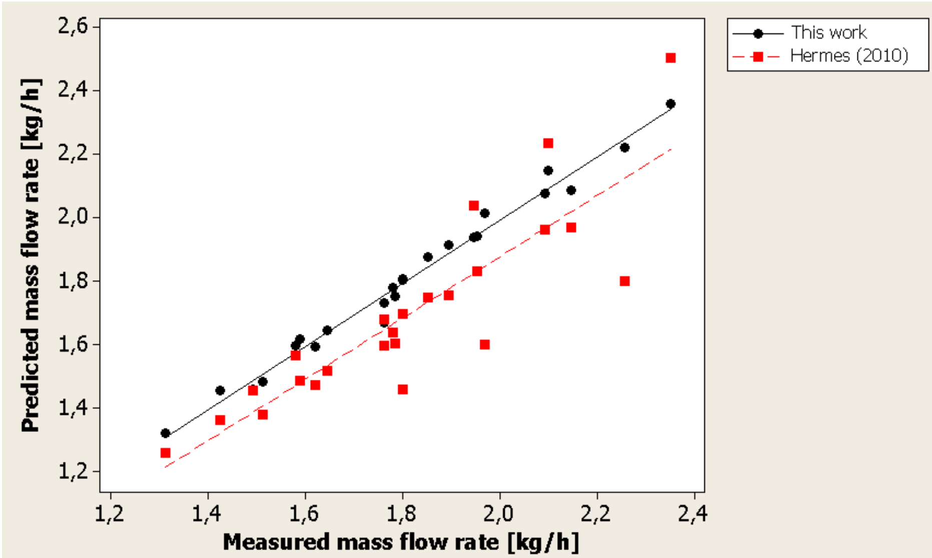


Figure 10. Prediction of the experimental data by Hermes Equation and Eq. (1)

4. CONCLUSIONS

In this study, the effects of different capillary tube inlet pressures, subcooling degrees and capillary tube lengths, on formation of flow regimes and mass flow of R600a refrigerant inside adiabatic capillary tube with 0.80 mm inner diameter are investigated and analyzed by using the ranges that are not experimented in current literature studies. As a result of the experiments; it is observed that; when either the capillary tube length or the inlet pressure of capillary increases, the formation of two-phase flow starts earlier. On the other hand; when the subcooling degree increases, flash point of the refrigerant is delayed.

An empirical correlation is derived by using the experimental results. When the refrigerant mass flow rates calculated with this correlation are compared with the values obtained by experimental results, it is observed that the calculated mass flow rates are within an error band of ±5%. The correlation can be used as a strong tool to define refrigerant mass flow rate inside vapor compression refrigeration system using isobutane.

Experimental studies on isobutane refrigerant flow inside both adiabatic and non-adiabatic capillary tubes having at least two different diameters must be improved in future literature.

Nomenclature

FPS	frame per second	(-)
L	length of capillary tube	(mm)
D	inner diameter of capillary tube	(mm)
T	temperature	(°C)
$\dot{m}$	mass flow rate	(kg h-1)
P	pressure	(bar)
ΔT	subcooling degree	(K)

Subscripts

i	inlet of capillary tube
emp	empirical
1	capillary tube inlet
2	compressor outlet
3	capillary tube outlet
4	compressor inlet

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