Investigation on the Selection of Capillary Tube for the Alternative Refrigerant R-407C

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Key words : Alternative refrigerant, Capillary tube, Flow factor, Roughness, Roughness factor, R-407C

Abstract

The capillary tube performance for R-407C is experimentally investigated. The experimental setup is a real vapor-compression refrigerating system. Mass flow rate is measured for various diameter and length while inlet pressure and degree of subcooling are changed. These data are compared with the results of a numerical model. The mass flow rate of the numerical model is about 14% less than the measured mass flow rate. It is found that mass flow rate and length for R-407C are less than those for R-22 under the same condition. Based on this experimental study and the numerical model, a set of design charts for capillary tube of R-407C is proposed.

Nomenclature

A : Cross section area [m^2]
D : Inside diameter [m]
f : Friction factor
G : Mass flux [kg/s · m^2]
h : Enthalpy [J/kg]
$\dot{m}$: Mass flow rate [kg/s]
P : Pressure [kPa]
V : Velocity [m/s]
Re : Reynolds number
z : Length [m]

Greeks symbols

ε : Roughness [μm]
μ : Viscosity [Pa · s]
π : the ratio of the circumference of a circle to its diameter
τ : Friction stress [N/m^2]

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Subscript

f : Saturated liquid
g : Saturated vapor
w : Wall side

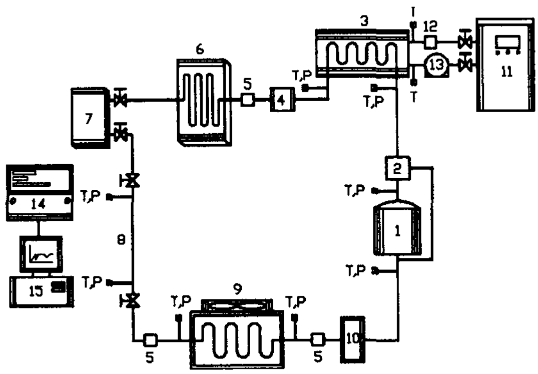
1. Introduction

R-22, which is widely used as a refrigerant in commercial and residential air-conditioning, will be phased out. The search for alternative R-22 is a hot issue in recent years. Now R-407C and R-410A seem to be the best among R-22 alternatives.[1] Therefore the manufacturers are concerned about the new design of refrigerating system for R-407C and R-410A.

The expansion device among main components of refrigeration system is very important to maximize the performance of a system since it regulates evaporating temperature and mass flow rate. There are many types of expansion devices with various characteristics. The capillary tubes are one of expansion devices. They are simple and cheap and have no moving parts. When the compressor is stopped, the refrigerant flows into the evaporator through the capillary tube so that the pressure of the high-pressure and the low-pressure side come to equilibrium. Therefore, when the compressor is restarted, the compressor doesn't experience overload. Due to such merit of capillary tubes, they have been widely used for small and medium sized refrigeration system. On the other side, the range to regulate the system capacity is relatively narrow. Therefore the selection of a proper capillary tube is essential to the optimal operation of the refrigeration system.

If a new refrigerant is charged into the old system, the COP of the system is degraded and mechanical failure may occur. Therefore the system needs to be redesigned.

Several investigators have studied capillary tube. Whitesel[2,3] tested and simulated the capillary tube performance for R-12 and R-22. He proposed a set of capillary tube design charts. Goldstein[4] developed a numerical model for the two-phase flow through a capillary tube. Chen et al.[5,6] developed a non-equilibrium drift model for the metastable flow through the capillary tube. Kim et al.[7] investigated the roughness effect of capillary tubes on the mass flow rate for R-22 and developed a numerical model. They proposed a new set of roughness corrected charts for the capillary tube design. Jung et al.[8] estimated the capillary tube performance for alternative of R-22 with numerical model. Kim and Kim[9] tested the capillary tube flow



1	Compressor	9	Evaporator
2	Oil Separator	10	Accumulator
3	Condenser	11	Isothermal Bath
4	Receiver	12	Turbine Flow Meter
5	Sight Glass	13	Pump
6	Subcooler	14	Data Acquisition System
7	Mass Flow Meter	15	Computer
8	Test Section		

Fig. 1 Schematic diagram of experimental setup.

for R-407C using the pump system that flows only refrigerant without oil. However the experimental data of capillary tube for R-407C are not so many.

The objective of this study is to test a capillary tube performance for R-407C and to propose a set of design charts for capillary tube.

2. Experimental Apparatus

Figure 1 is the schematic diagram of the experimental setup for the capillary tube test. The experimental setup is composed of compressor, condenser, evaporator, and capillary tube as the vapor compression system is. The compressor is the reciprocal type of 3 hp. An inverter is used to vary the speed of the compressor and consequently the mass flow rate. An accumulator is placed before the compressor in order to prevent the saturated liquid from coming into the compressor. After the compressor, an oil separator is placed to keep the refrigerant oil flowing into the capillary tube.

The condenser is a shell and tube type designed for this experiment. The thermal load of the condenser is controlled by flow rate and temperature of cooling water. The temperature of cooling water is controlled by an isothermal-bath.

The thermal load of the evaporator is supplied from heated air and the capacity is from 2.15 to 3.29 kJ/s.

A sight glass is installed before the subcooler to see if the state at the inlet to the flow meter is liquid or not.

Several capillary tubes of different diameters are selected and their inner diameters and roughness are measured by pin gage and stylus roughness gage, respectively. The specifications of the tubes are listed in the Table 1. The degree of subcooling at the inlet of capillary tube is controlled by a subcooler.

A Coriolis effect mass flow meter is used to measure the mass flow rate. In order to prevent vapor from flowing into the flow meter, it is located after the subcooler and just before the subcooler the phase is checked through the sight glass.

T-type thermocouples are used for temperature measurements. The temperature signals are transferred to PC through Data Acquisition System(DAS) by RS-232C communication. The thermocouples are located at the inlet and outlet of the compressor, condenser, evaporator, and the capillary tube. Particularly, several thermocouples are placed on the surface of the capillary tube to investigate the temperature variation along the tube. These thermocouples are installed on the surface of the tube to avoid the effect on the roughness and the interruption of the refrigerant flow.

The pressures at the inlet and outlet of the capillary tube are measured using the precision Burdon tube gage, the accuracy of which is 0.1% of full scale. The specifications of measuring devices are listed in the Table 2.

Table 1 Specifications of capillary tubes

	Inside diameter (mm)	Length (mm)	Roughness (μm)
Capillary tube	1.243	700	2.0514
		900	
		1100	
	1.524	700	4.5478
		900	
		1100	
	1.720	700	3.3355
		900	
		1100	

3. Experimental Procedure

The experimental procedure is:

a. Once a new capillary tube is installed, the capillary tube is evacuated enough to remove any moisture and air.
b. Refrigerant is charged into the experimental system.
c. The auxiliary equipment such as constant temperature bath is run to get the required condition.
d. When the auxiliary equipment reaches at the required condition, the refrigeration system is run.
e. The refrigerant system is run sufficiently enough until it reaches at a steady state.
f. When the system is at a steady state, temperature, pressure, and mass flow rate are recorded.
g. As inlet condition of capillary tube and its length and inner diameter are hanged, the above a-f procedures are repeated.

4. Numerical Model

A numerical model is developed for the calculation of the capillary tube for R-407C. The capillary tube flow is divided into a single-phase and a two-phase flow region. The model is based on the following assumptions:

a. Flow in the capillary tube is one-dimensional, steady, and homogenous.
b. Flow is adiabatic.
c. The tube is a horizontal, straight, and constant inner diameter tube.
d. The friction coefficient inside the tube is constant.

R-407C is non-azeotropic mixture. The dew point temperature of non-azeotropic mixtures is not equal to the bubble point temperature at the same pressure. Either one of the two temperatures is needed in the numerical model and the bubble point temperature is used. The thermodynamic properties for R-22 and R-407C are calculated from REFPROP.[10]

Table 2 Specifications of measuring equipment

Equipment	Specfication
Micro motion mass flowmeter (Refrigerant)	Maker : OVAL Model : D012S-SS-200 Range : 0~300 kg/h Accuracy : 0.1% of full scale
Data acquisition system	Maker : Yokogawa Model : 3890 Range : -200~400 ℃ Accuracy : 0.1 ℃
Electronic digital flowmeter (Water)	Maker : Great Plains Industries, Inc. Model : 07S31GM Range : 10~190 *l* /min Accuracy : ±1.5% of full scale
Pressure gauge	Maker : Heise Range : 0~4 MPa Resolution : 5 kPa
Inverter	Maker : LG Model : SV037GS-2 Capacity : 6 kVA Current : 16A Freqency : 0.5~360 Hz

4.1 Single flow region

The refrigerant is liquid at single-phase flow region. The temperature is constant and the pressure drops linearly. Governing equations are as follows:

a. Continuity equation

$$\frac{\dot{m}}{A} = G = \rho V = const \tag{1}$$

b. Momentum equation

$$-AdP-\tau_w(\pi d)dz=0 \quad (2)$$

c. Energy equation

$$h=const. \quad (3)$$

4.2 Two-phase flow region

Both the saturated liquid and the saturated vapor are present at two-phase flow region. The pressure and temperature drop per unit length increases as the flow comes to the end of the tube. Governing equations are as follows:

a. Continuity equation

$$\dot{m}=\dot{m}_f+\dot{m}_g \quad (4)$$

b. Momentum equation

$$-AdP-\tau_w(\pi d)dz=d(\dot{m}V)_f+d(\dot{m}V)_g \quad (5)$$

c. Energy equation

$$(\dot{m}h)_f+(\dot{m}h)_g+\frac{(\dot{m}V^2)_f+(\dot{m}V^2)_g}{2}=0 \quad (6)$$

4.3 Friction factor and viscosity

The friction factor and viscosity of two-phase flow region are important in the numerical model. The friction factor is affected by roughness. In this work, the friction factor is calculated from following correlation.[11]

$$f=\left[1.14-2\log_{10}\left(\frac{\varepsilon}{D}+\frac{21.25}{Re^{0.9}}\right)\right]^{-2} \quad (7)$$

Where ε is roughness, D is tube diameter, and Re is Reynolds number. This correlation is approximation of Colebrook-White correlation within 0.5%.

The viscosity of two-phase flow is calculated by the Cicchitti model.[12]

$$\mu=x\mu_g+(1-x)\mu_f \quad (8)$$

Where x is quality.

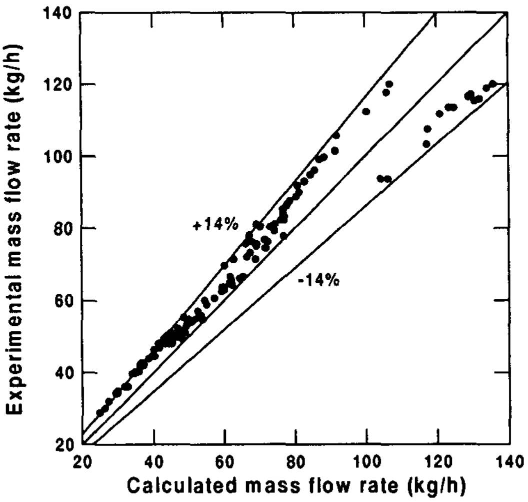
5. Results and Discussion

Experimental apparatus for the capillary tube performance is designed and setup in order to test the capillary tube performance for R-407C which have the best potential among R-22 alternatives. Experiments are conducted with various diameters and length of capillary tube. Experimental results are compared to results from numerical model.

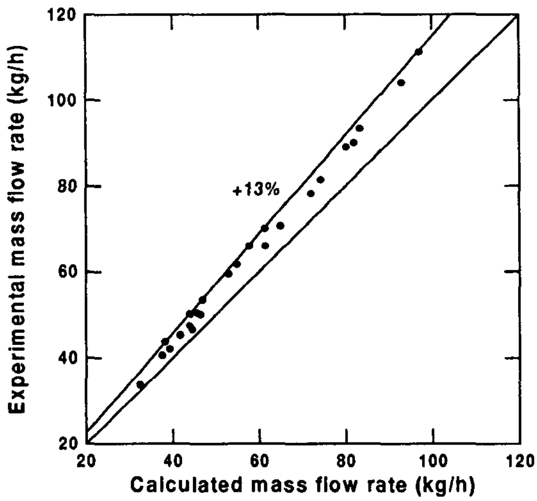
The measured mass flow rates are compared to the calculated values for R-407C and R-22 in Fig. 2(a) and (b), respectively. The experimental data for R-22 are obtained from the previous work of Kim et al.[7] Figure 2 shows that the calculated data are in agreement with the measured data within ±14% and +13% for R-407C and R-22, respectively. For both R-22 and R-407C, the measured mass flow rate is consistently larger than the calculated data over the whole range. But one type of capillary tube (d=1.72 mm, L=700 mm) shows a trend which is contradictory to above results. The experiments for it are conducted repeatly a few times to find the reason for incoincidence. But the same results are obtained and it could have not been clearly explained and needs for further investigation.

The reason why the measured values are greater than the calculated values is due to the effect of oil and the effect of flash point delay that are not considered in the numerical model.

Although there is an oil separator in this experimental setup, some of the oil is not separated from the refrigerant. The residual oil dissolved in the refrigerant reduces the vapor pressure of the pure refrigerant. The decrease



(a) R-407C



(b) R-22

Fig. 2 Comparison of measured mass flow rates with calculated mass flow rates for R-407C and R-22.

of vapor pressure results in the increase of the single phase region and then the amount of pressure drop decreases. Therefore, under the same conditions of the inlet and the outlet, the mass flow rate increases.

If the flash point is delayed the single phase region is lengthened and two-phase region is shortened. The major portion of pressure drop occurs at the two-phase region. The shorter the two-phase region is, the smaller the pressure drop is. It results in the increase of mass flow rate. And the effect of flash point delay is expected larger than the effect of oil in this study.

The main variables to decide the capillary tube performance are length, diameter, and roughness of tube and mass flow rate, degree of subcooling, and inlet pressure of refrigerant. Therefore the characteristic of capillary tube can be adjusted by the following five methods:

a. Variation of mass flow rate with roughness
b. Variation of mass flow rate with length
c. Variation of mass flow rate with diameter
d. Variation of mass flow rate with inlet pressure of capillary tube
e. Variation of mass flow rate with degree of subcooling at inlet of tube

If the length and diameter of capillary tube were chosen, the performance of capillary tube will be affected by the inlet pressure and the degree of subcooling. Hence to compare the capillary tube performance for refrigerants, the inlet pressure and the degree of subcooling must surely be same for each refrigerants. But to get simultaneously the same inlet pressure and degree of subcooling for each refrigerant through experiment is very difficult. Therefore the capillary tube performance for R-22 and R-407C is compared using the numerical model.

Figure 3 represents the mass flow rate vs the absolute roughness of capillary tube. As the roughness increases, the mass flow rate decreases for both R-22 and R-407C. The mass

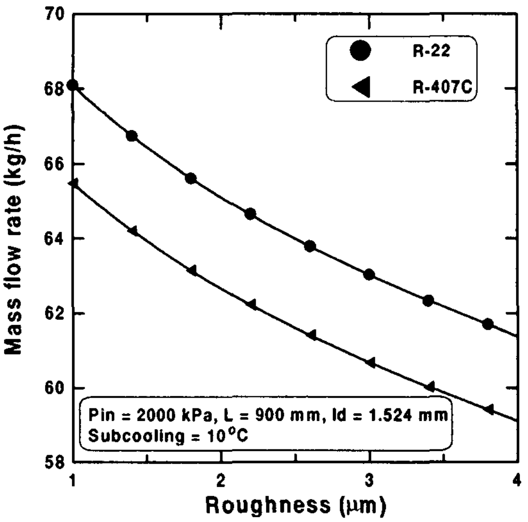


Fig. 3 Variation of mass flow rate with roughness.

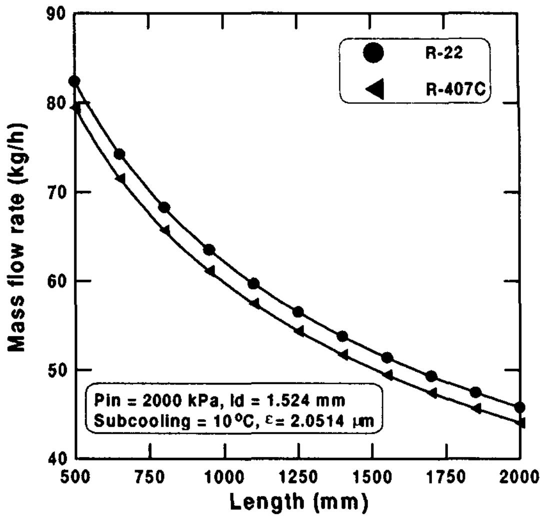


Fig. 4 Variation of mass flow rate with length.

flow rate of R-407C is about 4% less than that of R-22 under the same roughness.

The effect of length on mass flow rate is presented in Fig. 4. As the length of capillary tube increases, the mass flow rate decreases for both R-22 and R-407C. The mass flow rate of R-407C is about 4% less than that of R-22 under the same length of capillary tube. And the length of capillary tube of R-407C is about 10% less than that of R-22 under the same mass flow rate.

Figure 5 shows the mass flow rate vs the diameter of capillary tube. As the tube diameter increases from 1.0 mm to 3.0 mm, the mass flow rate increases from 30 kg/h to 350 kg/h. And the mass flow rate of R-407C is less than that of R-22 under the same diameter of capillary tube.

Figure 6 shows the mass flow rate vs the inlet pressure. As the inlet pressure increases, the mass flow rate increases. The mass flow rate of R-407C is from 3% to 4% less than that of R-22 under the same inlet pressure.

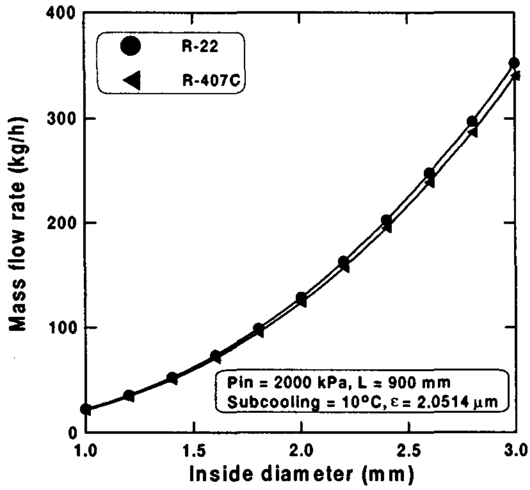


Fig. 5 Variation of mass flow rate with inside diameter.

Figure 7 represents the mass flow rate vs the degree of subcooling. As the degree of subcooling increases, the mass flow rate increases. The mass flow rate of R-407C is less than that of R-22 under the same subcooling.

In the comparison of R-22 and R-407C, under the same conditions, the mass flow rate

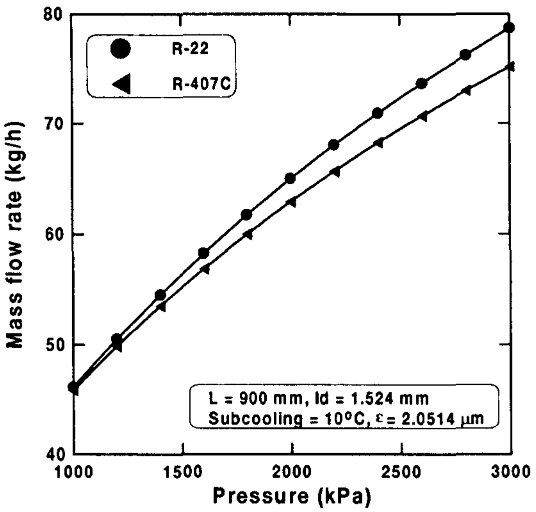


Fig. 6 Variation of mass flow rate with inlet pressure.

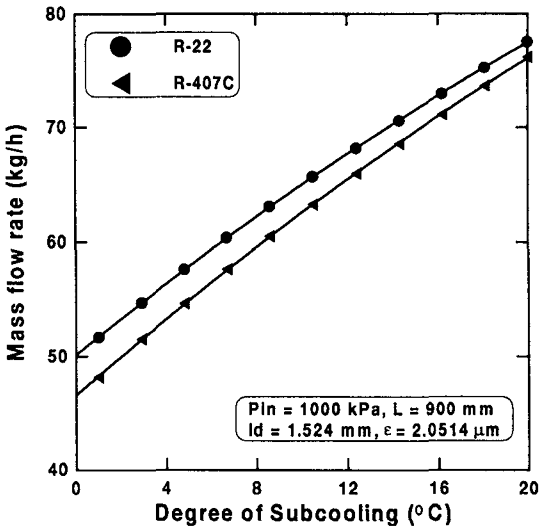


Fig. 7 Variation of mass flow rate with degree of subcooling.

of R-407C is about 4% less than that of R-22. And under the same conditions, the tube length of R-407C is about 10% shorter than that of R-22.

Based on the above results, a set of design charts for capillary tube of R-407C is proposed for the standard capillary tube of ASHRAE. Figures 8, 9, and 10 are a set of design charts for capillary tube of R-407C. Figure 8 is for a standard capillary tube. Figure 9 is for the flow factor, and Fig. 10 is for the roughness correction factor. ASHRAE standard capillary tube and the conditions are in Table 3. The mass flow rate of capillary tubes can be calculated as follows. These equations were proposed by Kim et al.[7]

$$\dot{m} = \phi_1 \phi_2 \, \dot{m}_{standard} \tag{9}$$

$$\phi_1 = \frac{\dot{m}(L, d, \varepsilon_{standard})}{\dot{m}(L_{standard}, d_{standard}, \varepsilon_{standard})} \tag{10}$$

$$\phi_2 = \frac{\dot{m}(L_{standard}, d_{standard}, \varepsilon)}{\dot{m}(L_{standard}, d_{standard}, \varepsilon_{standard})} \tag{11}$$

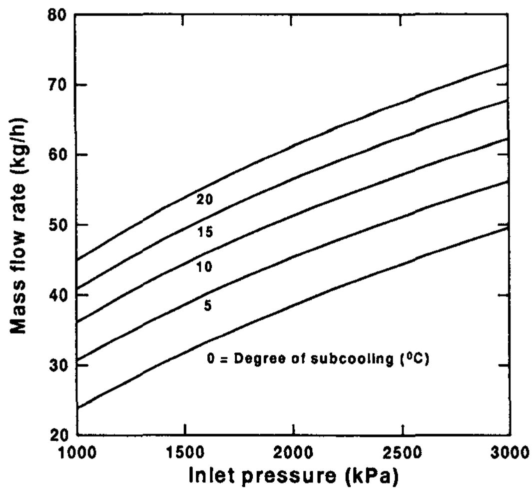


Fig. 8 Mass flow rate as a function of inlet pressure for various subcoolings for a standard caillary tube (R-407C).

6. Conclusion

The vapor compression system is constructed to test the performance of capillary tube

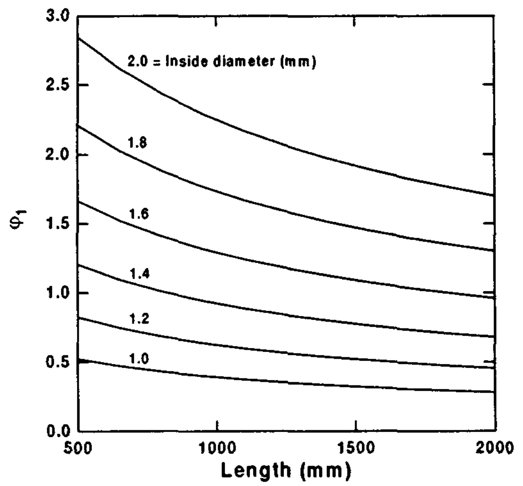


Fig. 9 Flow factor of capillary tube (R-407C).

Table 3 ASHRAE standard and the conditions of capillary tube selection chart

ASHRAE standard	Length = 2030 mm
	Inside diameter = 1.63 mm
	Roughness = 2.5 μm
Conditions	Pressure = 2000 kPa
	Degree of subcooling = 5 ℃

for R-22 and R-407C. The experiments are conducted with various size of capillary tube and inlet conditions. The numerical model is also developed and compared with experimental values.

The calculated mass flow rate was about 14% less than the measured mass flow rate. The reason why the calculated values are less than the measured values may be due to the effect of oil and the effect of flash point delay.

In the comparison of the calculated results from the numerical model for R-22 and R-407C, the mass flow rate of R-407C is about 4% less than that of R-22 under the same

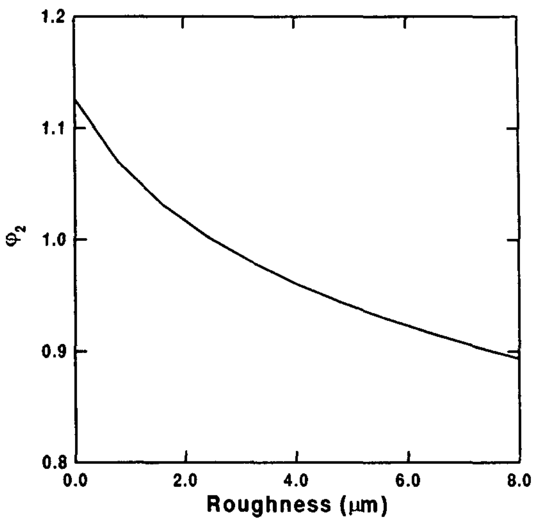


Fig. 10 Roughness factor of capillary tube (R-407C).

conditions. Also, the tube length of R-407C is about 10% shorter than that of R-22.

A set of design charts for capillary tube is proposed for R-407C. These design charts can predict the mass flow rate in the capillary tube for R-407C within 15% .

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Appendix

Example 1

Pressure at capillary tube inlet is 1,836.5 kPa and the degree of subcooling is 2℃. What is the mass flow rate of R-407C through the capillary tube with d=1.7 mm, L=900 mm, and ε=3.3355 ㎛?

Solution

The mass flow rate of standard capillary tube is 39.3 kg/h from Fig. 9. The flow factor for 900 mm length and 1.72 inner diameter is 1.62 from Fig. 10. And the roughness factor for 3.3355 ㎛ roughness is 0.98 from Fig. 11. Therefore the mass flow rate of R-407C is 62.4 kg/h (=39.3×1.62×0.98).

Example 2

Pressure at capillary tube inlet is 2,000 kPa and the degree of subcooling is 5℃. What is the inner diameter of the capillary tube to pass 40 kg/h with d=1.4 mm and ε=3.0 ㎛?

Solution

The mass flow rate of standard capillary tube is 45.4 kg/h from Fig. 9. The roughness factor for 3.0 ㎛ roughness is 0.985 from Fig. 11. Therefore the flow factor is 0.89 (=40.0 / 45.4 / 0.985). The length should be 1,060 mm from Fig. 9 when flow factor is 0.89 and diameter is 1.4 mm.