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A Generalized Correlation and Rating Charts for Mass Flow Rate through Capillary Tubes with Several Alternative Refrigerants

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Key words: Capillary tube, Mass flow rate, Correlation, Rating chart, Expansion device

ABSTRACT: A capillary tube, which is a common expansion device in small sized refrigeration and air-conditioning systems, should be redesigned properly to establish an optimum operation cycle of a refrigerating system with alternative refrigerants. Based on experimental data for R-22, R-290, and R-407C, an empirical correlation is developed to predict mass flow rate through capillary tubes. Dimensionless parameters are derived from the Buckingham Pi theorem, considering the effects of operating conditions and capillary tube geometry on mass flow rate. Approximately 97% of the present data are correlated within a relative deviation of ±10%. The present correlation also predicts the data obtained from open literature within ±15%. In addition, rating charts of refrigerant flow rate for R-12, R-22, R-134a, R-152a, R-407C, R-410A, R-290, and R-600a are developed.

Nomenclature

D : inner diameter [mm]
h_{fg} : heat of vaporization [kJ/kg]
L : length [mm]
$\dot{m}$: mass flow rate [kg/h]
P_c : critical pressure [kPa]
P_{in} : inlet pressure [kPa]
P_{sat} : saturated pressure [kPa]
T_c : critical temperature [℃]
ΔT_{sub} : degree of subcooling [℃]

Greek symbols

ρ : density [kg/m^3]
π : dimensionless parameter
σ : surface tension [N/m]
μ : viscosity [μPa·s]
Φ_1 : correction factor

Subscripts

f : saturated liquid
g : saturated vapor
mea : measured
$pred$: predicted

1. Introduction

Due to the phaseout of CFCs and HCFCs, the refrigerating systems must be optimized to satisfy design requirements for alternative refrigerants. As a result, HFC, HC, and HFC mixtures have emerged as alternatives of R-12 and R-22. A capillary tube is a constant area expansion device, which has been widely used in small vapor-compression refrigeration sys-

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tems. Since an improperly sized capillary tube can significantly reduce the performance of a refrigeration system,(1,2) the capillary tube working with alternative refrigerants must be redesigned. A flow correlation and rating charts for mass flow rate through capillary tubes with alternative refrigerants must be developed to provide an appropriate design tool.

Many researchers have extensively investigated the performance of adiabatic capillary tubes.(1,3 8) Wolf et al.(6) developed correlations for subcooled and two-phase inlet conditions by using the Buckingham Pi theorem(9) with the test data for R-22, R-134a, and R-410A. Melo et al.(7) also presented empirical correlations for adiabatic capillary tubes using the data of R-12, R-134a, and R-600a.

Most empirical correlations for predicting refrigerant mass flow rate through capillary tubes have been developed based on limited database from their own experiments. In addition, dimensionless parameters included in the existing correlations have a complicated form due to duplicated consideration of refrigerant properties as repeating variables. The objectives of this study are to develop a generalized correlation in a simple form and to generate rating charts that can be used in the prediction of mass flow rate of alternative refrigerants through adiabatic capillary tubes.

2. Experiments

The experimental setup shown in Fig. 1 was used to measure the performance of various adiabatic capillary tubes. A diaphragm pump with a variable-speed motor was used to provide a wide range of refrigerant mass flow rates. The inlet pressure of the refrigerant entering the test section was controlled by varying pump speed. Refrigerant subcooling entering the test section was regulated by a water-heated heat exchanger. The two-phase refrigerant exiting the test section was condensed and subcooled in a water/glycol cooled heat exchanger. The exit pressure of the test section was set by adjusting temperature and flow rate of the chilled water/glycol mixture entering the water/glycol cooled heat exchanger.

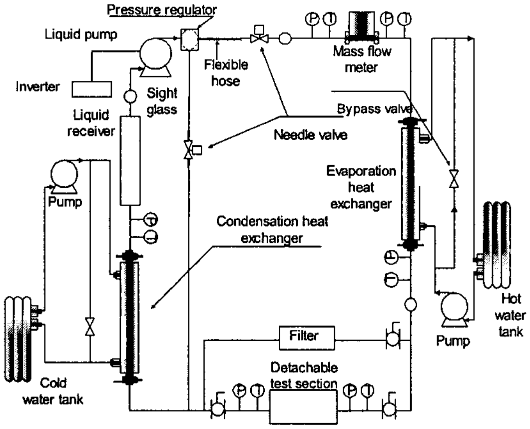

Fig. 1 Schematic diagram of the experimental setup.

Temperatures, pressure, and mass flow rate were measured by using thermocouples (accuracy of ±0.2℃), a pressure transducer (accuracy of ±6.9 kPa), and a mass flow meter (accuracy of ±0.2% of reading), respectively.

Table 1 shows the specification of capillary tubes and test conditions in this study. Nine capillary tubes made of copper were tested with three refrigerants: R-22, R-290, and R-407C. Test conditions were chosen to cover a wide range of operating conditions for capillary tubes used in small sized residential air-conditioners. Condensing temperature of R-407C was determined by bubble point temperature at constant pressure.

Table 1 Test conditions

Refrigerants		R22, R290, R407C
Capillary tube (mm)	Length	700, 1000, 1300
	Diameter	0.96, 1.21, 1.36
Operating temperature (℃)	Condensing	38, 45, 52
	Evaporating	7
	Subcooling	1, 4, 9, 14

3. Correlation development

A generalized correlation for the prediction of mass flow rate through capillary tubes is developed by using appropriate dimensionless parameters derived from operating conditions, capillary tube geometries, and refrigerant properties. Operating parameters considered in this study are inlet pressure, degree of subcooling, and saturation pressure corresponding to inlet temperature. The exit pressure is not included since choking conditions are generally satisfied in capillary tubes.(1,3-5) Viscosity, density, and surface tension are also contained in the correlation to consider the influences of metastable flow and pressure drop. Capillary tube diameter and length are included to consider geometric effects. The resulting relationship between mass flow rate and the selected variables is represented in a functional form as below.

$$\dot{m} = f((P_{in} - P_{sat}),\ \Delta T_{sub},\ L,\ D,\ \mu_f,\ \mu_g,\ \rho_f,\ \rho_g,\ \sigma,\ h_{fg},\ T_c) \tag{1}$$

Eight dimensionless Pi-groups are derived by combining selected variables with the four repeating variables, D, ρ_f, μ_f, and T_c. The definition of each Pi-group on capillary tube flow are given in Table 2. The generalized correlation for the dimensionless mass flow rate π_1 is generated in a power law form of the remaining Pi-groups as shown in equation (2). The coefficients and exponents of the seven independent Pi-groups are determined using a nonlinear regression technique along with the experimental data for R-22, R-290, and R-407C measured in this study.

Table 2 Dimensionless Pi-groups

Group	Parameter	Group	Parameter
π_1	$\dfrac{\dot{m}}{D^2\sqrt{\rho_f P_{in}}}$	π_5	$\dfrac{\rho_f}{\rho_g}$
π_2	$\dfrac{P_{in} - P_{sat}}{P_c}$	π_6	$\dfrac{\mu_f - \mu_g}{\mu_g}$
π_3	$\dfrac{\Delta T_{sub}}{T_c}$	π_7	$\dfrac{\sigma}{DP_{in}}$
π_4	$\dfrac{L}{D}$	π_8	$\dfrac{\rho_f h_{fg}}{P_{sat}}$

$$\pi_1 = 0.1495 \times 10^{-3}\, \pi_2^{-0.087}\, \pi_3^{0.188}\, \pi_4^{-0.412} \times \pi_5^{-0.834}\, \pi_6^{0.199}\, \pi_7^{-0.368}\, \pi_8^{0.992} \tag{2}$$

4. Correlation verification

As shown in Fig. 2, the generalized correlation is verified by comparing predicted mass flow rates using equation (2) with the measured data for R-22, R-290, and R-407C. Approximately 97% of the experimental data are correlated within a relative deviation of ±10%. Generally, the correlation yields good agreement with the measured data at all test conditions for R-22, R-290, and R-407C with average and standard deviations of 0.9% and 5.0%, respectively.

The validity of the correlation is further assessed by comparing predicted mass flow rates with R-22 using equation (2) with the measured data of Wolf et al.(6) that are not used in developing correlation. As shown in Fig. 3, approximately 98% of predicted mass flow rates are consistent with the measured data for R-22 within a relative deviation of ±10%. Even

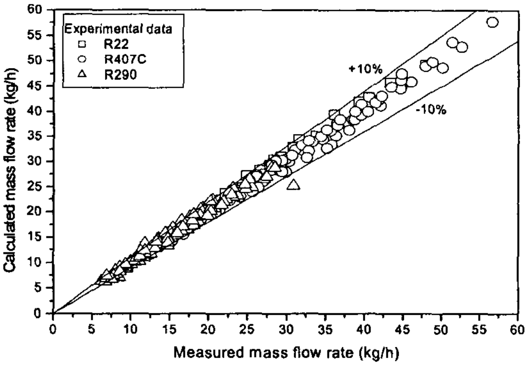

Fig. 2 Comparison of predicted mass flow rate with measured data in this study.

though Wolf et al.'s data[(6)] covers higher mass flow ranges beyond the present data used in developing the correlation, the correlation yields good prediction results for R-22 with average and standard deviations of 0.9% and 5.7%, respectively.

To extend application limits of the correlation imposed by data source, the predicted mass flow rates using equation (2) are compared with the measured data reported by previous investigators[(4,6,7)] with R-12, R-134a, R-152a, R-410A, and R-600a that are not used in the development of the present correlation. Figure 4 shows the comparison of the predicted with measured mass flow rates. Approximately 96.4 % of the data are correlated within a relative deviation of ±15%. The present correlation predicts the data for HFC refrigerants (R-134a, R-152a, R-410A, R-407C) from present data and open literature ranging from −10 to +15 % at all test conditions. Relative deviations of the experimental data for HC refrigerants (R-290, R-600a) from the predicted values are from −17 to +15%.

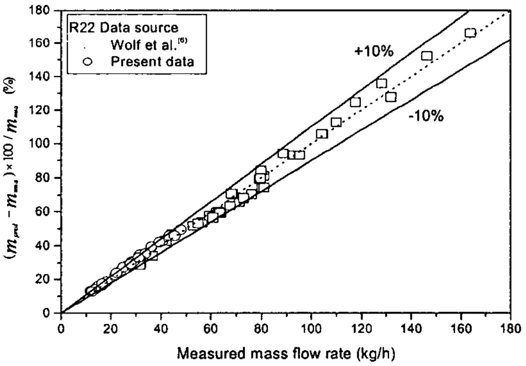

Fig. 3 Comparison of predicted mass flow rate with measured data for R-22.

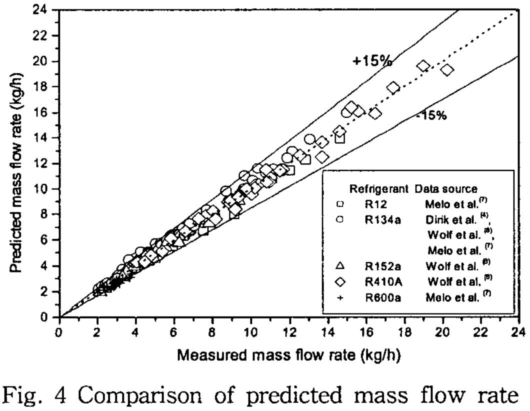

Fig. 4 Comparison of predicted mass flow rate with measured data in open literature.

5. Rating charts

Rating charts for predicting refrigerant mass flow rate through adiabatic capillary tubes are developed based on the present correlation. They are similar to rating charts developed by Wolf et al.[(6)] Two quantities used in the prediction of the refrigerant flow rate are the flow rate for a reference capillary tube ($\dot{m}_r$) and

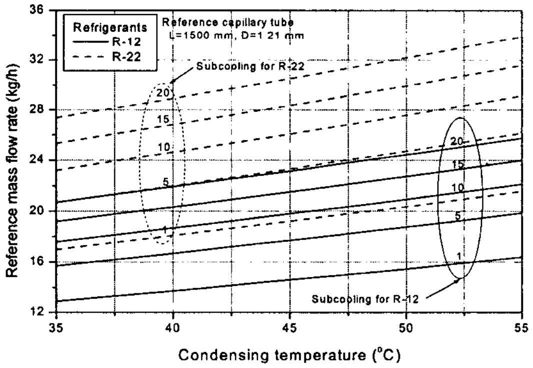

Fig. 5 Reference mass flow rates for R-12 and R-22.

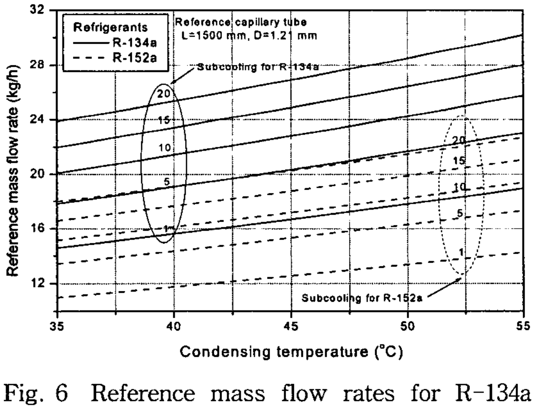

Fig. 6 Reference mass flow rates for R-134a and R-152a.

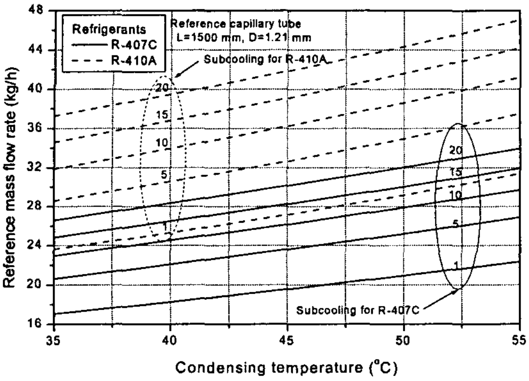

Fig. 7 Reference mass flow rates for R-407C and R-410A.

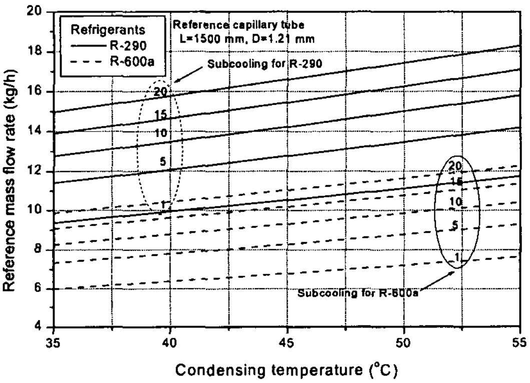

Fig. 8 Reference mass flow rates for R-290 and R-600a.

the geometric correction factor (Φ_1). The actual mass flow rate ($\dot{m}_a$) is determined by multiplying these two quantities as given by

$$\dot{m}_a = \dot{m}_r \cdot \Phi_1 \tag{3}$$

Figures 5, 6, 7 and 8 are reference mass flow rates for eight refrigerants, which are R-12, R-22, R-134a, R-152a, R-407C, R-410A, R-290, and R-600a, as a function of condensing temperature and inlet subcooling for a reference capillary tube with a length of 1,500 mm and a diameter of 1.21 mm. The x-axis of the charts is expressed in terms of condensing temperature instead of inlet pressure or condensing pressure to retain the same operating

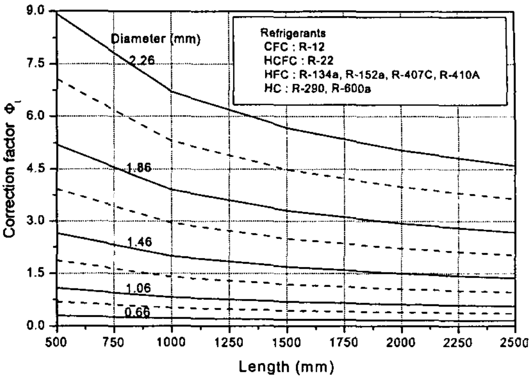

Fig. 9 Correction factor for geometry.

range of x-axis for various refrigerants. Figure 9 shows a geometric correction factor for all refrigerants included in this study. After determining the correction factor from Fig. 9 at a given capillary tube geometry, multiplying this factor with the reference mass flow from Figs. 5 through 8 for given inlet conditions yields the actual mass flow rate. It should be noted that the charts are constructed on the assumption of choking conditions.

The accuracy of the charts cannot be guaranteed when the charts are extrapolated beyond the application limits of the correlation. Limitations on the application of the present correlation include capillary tube lengths from 508 to 2,500 mm, capillary tube inner diameters from 0.66 to 2.22 mm, condensing temperatures from 35 to 55℃, and inlet subcoolings from 1 to 18.9℃. The working fluids can be extended to R-12, R-134a, R-152a, R-410A, and R-600a.

6. Conclusions

The performance of capillary tubes with R-22, R-290, and R-407C were measured by varying tube inlet conditions and tube geometries. Based on the experimental data, a generalized correlation to predict refrigerant mass flow rate through capillary tubes is developed by implementing dimensionless parameters generated using the Buckingham Pi theorem. The generalized correlation yields good agreement with the present data for R-22, R-290, and R-407C with average and standard deviations of 0.9% and 5.0%, respectively. The present correlation predicts the existing data for R-12, R-134a, R-152a, R-410a, and R-600a with relative deviations from −10 to +15% at all conditions. In addition, rating charts for the reference mass flow rate and the geometric correction factor are generated for R-12, R-22, R-134a, R-152a, R-407C, R-410A, R-290, and R-600a.

Acknowledgements

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