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Experimental Investigation on R245fa Throttling Devices under High Temperature

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ABSTRACT

The experiments on mass flow rate characteristics of R245fa refrigerant flowing through throttling devices including seven capillary tubes and the electronic expansion valve were carried out under the high-temperature working conditions. By combining regression analysis with flow correlations, the design basis that is applicable to R245fa throttling devices can be obtained. By comparing the experimental data with predicted data by Jung Correlation and Kim Correlation, it can be concluded that root mean square deviations of two correlations are 3.2 % and 3.3%, respectively. The root mean square deviation for electronic expansion valve is 4.5%. The conclusions offer high-accuracy design basis for throttling devices selection of high-temperature heat pump systems using R245fa as refrigerant.

1. INTRODUCTION

As a means of waste heat recovery, high-temperature heat pump technology (HTHP) has become one of effective solutions for energy and environmental problems. Both domestic and international investigations on HTHP technology have largely been concentrated on the selection of proper working medium and the improvement of system performance. As an environment-friendly refrigerant, HFC245fa is getting more and more attention due to its low discharge temperature and high efficiency. Researchers have conducted many theoretical analyses and experiments of R245fa, such as its thermophysical properties (Dai et al., 2015), heat transfer characteristics (Ma et al., 2010; Thome, 2009), the theoretical calculation and experimental verification of cycle performance (Ma et al., 2010; Zhao et al., 2018), but the throttling characteristics of R245fa are seldom studied.

Throttling device is one of the key parts of vapor compression heat pump system, and the throttling devices of heat pump systems are mainly capillary and electronic expansion valve. Although many studies (Zhang et al., 2000; Zhao et al., 2017; Dubba and Kumar, 2016) has been conducted on flow characteristics through capillary or EEVs, most have been related to R32, R410a, R134a and R407c, and the applicable operating conditions are also conventional ones. Few literatures focus on characteristics of throttling devices using high-temperature refrigerants under high-temperature working conditions.

Therefore, it is necessary to study the correlations of capillary tubes and electronic expansion valves using high temperature refrigerant R245fa.In this paper, the mass flow rate characteristics of R245fa refrigerant flowing through capillary tubes and electronic expansion valve under varying operating conditions are studied experimentally. By combining regression analysis with the empirical correlations, the design basis which is suitable for throttling devices of R245fa is obtained.

2. EXPERIMENTAL SETUP AND OPERATIONAL CONDITIONS

2.1 Experimental setup

Figure 1 shows the schematic diagram of the experimental setup, which comprises a refrigerant cycle and heat transfer fluid cycle. The dotted line in the graph is refrigerant cycle and the real line shows heat transfer fluid cycle. T and P denote the measurement of temperature and pressure, respectively. The temperature is measured using platinum resistance thermometer (PRT) and the pressure is measured by pressure sensor. The mass flow rate of refrigerant is measured by flowmeter. The uncertainty of measuring instruments is shown in Table 1.

In Figure 1, the detachable test section is used to install the test samples of capillary tubes and electronic expansion valve. The temperature of circulating water ranges from 40 to 110°C and mass flow rate ranges from 0.5 to 2.5m^3/h. The air-cooled heat exchanger is set up to obtain different degree of subcooling.

Table 1: The uncertainty of measuring instruments

Instruments	Range	Uncertainty
PRT	0~130°C	±0.1℃
Pressure Sensor	0~5MPa	±25kPa
Flowmeter	0~5kg/min	±5g/min

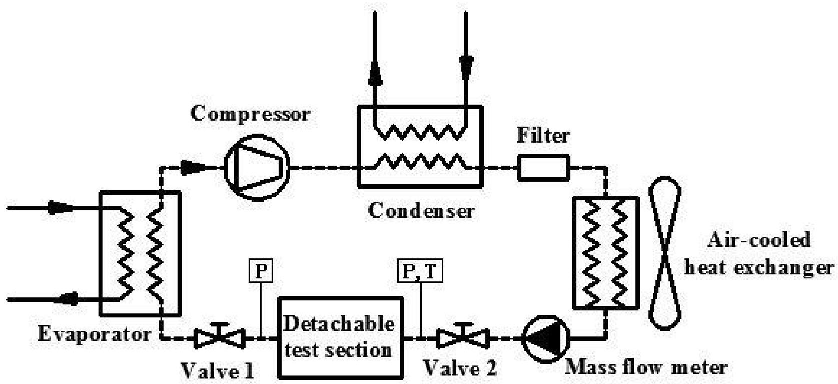

Figure 1: Schematic diagram of experimental setup

2.2 Operational conditions

In this study, seven capillary tube samples and an electronic expansion valve with orifice diameter of 2.0 mm were tested. The dimensions of capillary samples and the operational conditions are presented in Table 2 and in Table 3, and the conditions are obtained by the following methods:

(1) The pressure at the inlet or outlet of the throttling device was controlled by changing the inlet temperature and flow rate of circulating water.

(2) The degree of subcooling was varied by changing air flow rate of air-cooled heat exchanger.

Table 2: The operational conditions

Parameters	The capillary tube	EEV
Inlet Pressure	0.73~1.52MPa	0.70~1.76MPa
Inlet temperature	68~106℃	61~112℃
Outlet Pressure	0.26~0.67MPa	0.26~0.88MPa

Table 3: The specification of capillary tubes

No.	*d* mm	*L* mm	D_c mm
1#	1.63	500	30
2#	1.8	300	30
3#	1.8	500	50
4#	1.8	800	40
5#	2.1	400	40
6#	2.1	500	50
7#	2.4	1000	40

3. DATA ANALYSIS

3.1 The correlation of capillary tubes

The Jung correlation and the Kim correlation have been widely applied to mass flow rate predictions of capillary tubes. The two correlations are used to describe the choking flow, which indicate that the mass flow rate of refrigerant through a capillary tube is observed to be influenced by the geometry (d & L) of capillary tube, inlet conditions like pressure (P_{in}), degree of subcooling (ΔT_{sc}) and quality(x).

3.1.1 The Jung Correlation

The correlation presented by Jung (1999) has been evaluated to predict the mass flow rate. The Jung (1999)'s model as follows.

$$M = C_1 d^{C_2} L^{C_3} T_{sat}{}^{C_4} 10^{C_5 \Delta T_{sc}} \quad (1)$$

Where M is mass flow rate, d is inner diameter of capillary tube, L is length of capillary tube, T_{sat} is condensing temperature, ΔT_{sc} is degree of subcooling and C_i is constants for various refrigerants.

The experiment was carried out on the whole system; therefore, it is difficult to determine whether the tested condition is choking flow. As we know, the capillary flow rate of choking flow is not related to the outlet pressure. The data processing is analyzed by regression method with the pressure drop and without the pressure drop. The correlation formula ignoring the pressure drop is $M = C_1 d^{C_2} L^{C_3} T_{sat}{}^{C_4} 10^{C_5 \Delta T_{sc}}$ .The correlation formula considering the pressure drop is $M = C_1 d^{C_2} L^{C_3} T_{sat}{}^{C_4} 10^{C_5 \Delta T_{sc}} \Delta P^{C_6}$ .The results show that the effect of the outlet pressure on the capillary flow rate can be neglected, so the experimental test condition is choking flow.

As a result, Jung correlation can be expressed as

$$M = 0.06559 d^{2.34439} L^{-0.30186} T_{sat}{}^{0.88143} 10^{0.02086 \Delta T_{sc}} \quad (2)$$

Based on the sample data, the correlation coefficient of the model is 0.995, which indicates that there is a significantly positive correlation between the dependent variables and independent variables. Comparison of measured data and predicted data of Jung correlation is shown in Fig. 2.

3.1.2 The Kim Correlation

The dimensionless correlation presented by Kim (2002) for refrigerant mass flow rates through adiabatic capillary tubes is given as

$$\Pi_0 = a_0 \Pi_1{}^{a_1} \cdots \Pi_n{}^{a_n} \quad (3)$$

Where a_0~a_n are constants, and the definition of each Pi-group on capillary tube flow is given in Table 4. In Table 4, c_{pf} is specific heat capacity, ΔT_{sc} is degree of subcooling, d is inner diameter of capillary tube, h_{fg} is heat of vaporization, μ is viscosity, L is length of capillary tube, P_{in} is inlet pressure, and v is specific volume.

The experimental data were fitted using different numbers of dimensionless parameters, and the results are shown in table 5. R^2 is the coefficient of determination used to evaluate the regression equation, and R^2 is supposed to be close to 1.

From the point of goodness-of-fit term, the effect of the dimensionless parameters Π_5 and Π_6 on capillary flow rate can be neglected according to measured data. Consequently, the empirical correlation for capillary prediction developed by employing the Kim correlation is as follows

$$\Pi_0 = 15.9602\Pi_1^{-0.2551}\Pi_2^{0.1453}\Pi_3^{0.2537}\Pi_4^{-0.2764} \quad (4)$$

Fig. 2 shows comparison of measured data and predicted data of Kim correlation. For Kim correlation, 95.5% of the predicated data deviates from experimental data within ±5%, while for Jung correlation, 90.9% of the predicated data deviates from experimental data within ±5%. The maximum relative deviations for Jung correlation and Kim correlation are -7.8% and 6%, respectively, and the RMS deviations are 3.2% and 3.3%, respectively, which means that the results of two correlations have a close stability. The relative deviation (E) and root mean square (RMS) deviation are conducted according to equation（5）and （6）, respectively.

$$E = \frac{M_{pre} - M_{\exp}}{M_{\exp}} \times 100 \quad (5)$$

$$RMS = \sqrt{\left(\sum_i E_i^2\right) \Big/ N_{\exp}} \quad (6)$$

Where M_{cal} is predicated data, M_{exp} is experimental data, N_{exp} is the total number of experimental data.

Table 4: Definition of dimensionless Pi-groups

Pi-group	Definition
Π_0	$m/(d \cdot \mu_f)$
Π_1	L/d
Π_2	$d^2 \cdot P_{in}/(\nu_f \cdot \mu_f^2)$
Π_3	$d^2 \cdot c_{pf} \cdot \Delta T_{sc}/(\nu_f^2 \cdot \mu_f^2)$
Π_4	ν_g/ν_f
Π_5	$(\mu_f - \mu_g)/\mu_g$
Π_6	$d^2 \cdot h_{fg}/(\nu_f^2 \cdot \mu_f^2)$

Table 5: The results of regression analysis

n	a_0	a_1	a_2	a_3	a_4	a_5	a_6	R^2
3	0.2750	-0.2864	0.2642	0.2661	-	-	-	0.9876
4	15.9602	-0.2551	0.1453	0.2537	-0.2764	-	-	0.9958
5	9.1973	-0.2520	0.1396	0.2524	-1.0447	1.2180	-	0.9961
6	56.4042	-0.2056	-1.1713	0.1910	-2.9808	1.6905	1.2349	0.9982

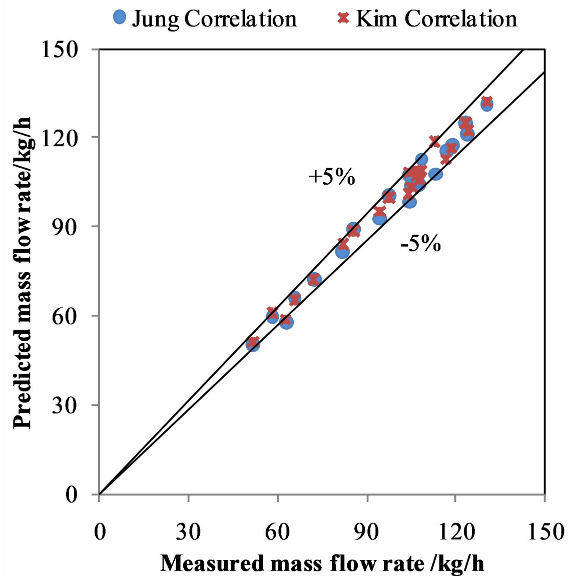

Figure 2: Comparison of measured data and predicted data for capillary tubes

3.2 The correlation of electronic expansion valve

Flow characteristics of electronic expansion valve are quite significant to system matching and system control strategy. The suppliers generally provide nitrogen or air flow characteristic curve, however the actual refrigerant flow characteristic is far from the nitrogen or air flow one. The mass flow rate of liquid that flows through an EEV is typically expressed by the hydraulic formula derived from the Bernoulli equation as shown in Eq.(7).

$$M = C_D A\sqrt{2\rho\Delta P} \tag{7}$$

Where C_D is the mass flow coefficient, ρ is refrigerant density at the EEV inlet, △P is differential pressure between the EEV inlet and outlet, and A is the flow section area. To obtain an empirical correlation for EEV mass flow rate predictions, the mass flow coefficient C_D must be determined. However, due to the complex geometrical structures, the throttling mechanisms of the EEVs are very complicated, and C_D is dependent on numerous parameters.

Wile D.D. (1965) proposed an empirical correlation to calculate the dimensionless mass flow coefficient and it is expressed as follows

$$C_D = 0.02005\sqrt{\rho} + 0.634v \tag{8}$$

In this study, the mass flow rate of R245fa flowing through an EEV with varying inlet pressure, degree of subcooling, and degree of EEV opening was investigated. And then mass flow coefficient C_D is calculated according to Eq.(8). The flow section area of each opening is calculated using the air flow characteristic curve of the electronic expansion valve provided by the manufacturer (Liang et al., 2015).

The measured data were used to validate Eq. (8). As a result, the mass flow coefficient C_D modified is given as follows:

$$C_D = 1.21(0.02005\sqrt{\rho} + 0.634v) \tag{9}$$

The range of mass flow coefficient C_D is from 0.76 to 0.9 based on texted conditions. Comparison of measured data and predicted data of EEV mass flow rate is shown in Fig. 3.The relative deviation between measured mass flow rate and predicted mass flow rate is 9.3%, and the RMS deviation is 4.5%. At the same time, the experimental data also show that the dimensionless mass flow coefficient C_D should be developed by taking the flow section area of EEV, the properties of R245fa itself, and operating conditions into consideration.

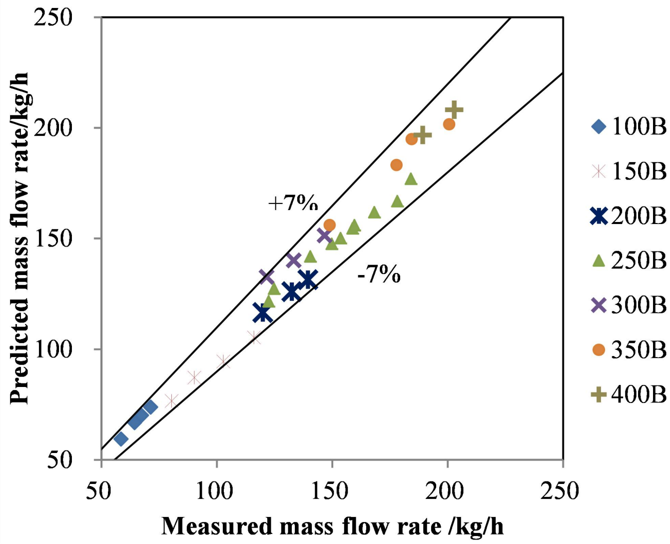

Figure 3: Comparison of measured data and predicted data for EEV

4. CONCLUSIONS

The mass flow rate characteristics of R245fa refrigerant flowing through capillary tubes and EEVs with different operational conditions under high temperature were studied experimentally. The design basis of throttling devices with R245fa as refrigerant under high temperature is obtained. The main conclusions are as follows:

(1) Based on experimental data, the coefficient of empirical correlation for R245fa flowing through capillary tubes was carried out by using regression analysis. The maximum relative deviations for Jung correlation and Kim correlation are -7.8% and 6%, respectively, and the RMS deviations are 3.2% and 3.3%, respectively. Whereas Kim correlation is involved with refrigerant property which brings inconvenience of calculating, Jung correlation is recommended to predict flow rate of R245fa flowing through capillary tubes.

$$M = 0.06559 d^{2.34439} L^{-0.30186} T_{sat}{}^{0.88143} 10^{0.02086 \Delta T_{sc}}$$

(2) Based on experimental data, the mass flow coefficient C_D modified is given as follows:

$$C_D = 1.21(0.02005\sqrt{\rho} + 0.634v)$$

The relative deviation between measured mass flow rate and predicted mass flow rate is 9.3%, and the RMS deviation is 4.5%.

The conclusions offer design basis for throttling devices selection of high-temperature heat pump systems with R245fa as refrigerant. However, there are some limitations in the range and quantity of tested conditions. Further research is required to provide more experimental data and wider operational conditions to validate the accuracy of the design basis.

NOMENCLATURE

M	Mass flow rate	(g/s)
d	Inner diameter	(mm)
L	Length	(m)
T_{sat}	Saturated temperature	(℃)
$\triangle T_{sc}$	The degree of subcooling	(℃)
c_p	Specific heat capacity	(J/(kg·K))
h_{fg}	Heat of vaporization	(J/kg)

μ	Dynamic viscosity	(kg/(m·s))
v	Specific volume	(m^3/kg)
ρ	Density	(kg/m^3)
A	Flow area	(m^2)

Subscript

f	Saturated liquid
g	Saturated vapor

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