TWO-PHASE FLOW FRICTIONAL PRESSURE DROP OF FC-14 IN HORIZONTAL TUBES

by

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Experimental measurements on the two-phase flow frictional pressure drop of tetrafluoromethane, FC-14, were carried out with a pressure of 0.4 MPa and the mass-flow rates ranging from 240-785 kg/m^{2}s. The influences of the mass-flow rate and quality on the frictional pressure drop were analyzed. The experimental results have been compared with three widely used correlations, of which proposed by Zhang and Webb (2001) gave a best agreement with the deviation in 16%.

Key words: *frictional pressure drop, horizontal tube, two-phase flow, tetrafluoromethane*

Introduction

The mixed-gases Joule-Thomson refrigerator (MJTR) has distinct advantages compared with other types. It is used for many applications, such as natural gas liquefaction, cryogenic preservation, and electronics cooling, *etc.* In this MJTR, the mixed gases with different boiling temperatures are used as the mixed-refrigerants. Tetrafluoromethane, FC-14, an important component, has a normal boiling point temperature of 145.1 K. It has been reported that using FC-14 to the mixture, the isothermal throttling effect of the mixed refrigerant can be significantly increased [1, 2]. Investigating the two-phase flow frictional pressure drop in the flow boiling process is of key importance in investigating such refrigerators. So far, the two-phase flow characteristics of FC-14 are rarely studied, especially in aspect of the two-phase flow frictional pressure drop of FC-14.

A considerable number of experimental studies and empirical correlations can be employed in flow boiling frictional pressure drop in a horizontal tube. Cheng *et al.* [3] presented an excellent review on this topic. Lockhart and Martinelli [4] presented an empirical correlation for the frictional pressure drop in liquid-gas two phase flow in horizontal pipes, and investigated four kinds of the isothermal two-phase flows, and each phase of which is in different viscous or turbulent flow regime. Friedel [5], based on a huge experimental data bank, obtained a two-phase multiplier for horizontal flow. The smallest tube diameter in the Friedel's database is 4.0 mm. Zhang and Webb [6] found that the Friedel's correlation over predicts the two-phase frictional pressure drop in small diameter tubes, especially for those at

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high reduced pressures. Then, a correlation was proposed for two-phase frictional pressure drop in small diameter tubes. This correlation predicts 119 data points with a mean deviation of 11.5%.

There are many studies concerning over the frictional pressure drop for flow boiling, but very few over FC-14. To study the subject is important for further investigating the thermal property of the mixed refrigerants. In the rest of this paper, the experimental study on the saturated flow boiling frictional pressure drop of FC-14 in a smooth tube at various conditions will be presented. The measured experimental data was compared with previously mentioned three existing corrections.

Experimental apparatus and procedure

Test facility

The details of experimental apparatus are shown in fig. 1. The apparatus consists of four main components, namely, refrigerator, data controlling and acquisition system, test sections in the loop, vacuum vessel in which the test sections are located. The refrigerator is a self-made MRJT refrigerator that can provide 1 kW cooling capacity at −110 °C. The liquid FC-14, produced by the MRJT refrigerator, is circulated by a masked magnetic pump, the speed of which can be adjusted by a speed regulator. A Coriolis mass flow meter (OVAL, ULTRA mass MKII) with an uncertainty of ±0.1% is installed in the loop after the circulation pump. An electrical pre-heater is installed in the loop before inlet of the test section to obtain a required quality. Eight 50 mm long copper tubes with an inner diameter of 6 mm and an outer diameter of 40 mm are the heating components in the loop with the DC electric heating wire coils tightly twisted around. Each side of the copper tubes are welded together by vacuum brazing technique with a 60 mm long stainless steel tube with an inner diameter of 6 mm and an outer diameter of 8 mm. The tube wall thickness is only 1 mm, so that the axial heat conduction can be ignored. The eight copper tubes and the nine stainless steel tubes make up the test Section I, the inner flow passage of which acts as a smooth tube. Test Section I is shown in fig. 2, from which all the details previously described can be found. A 186 mm long insulated copper tube section installed in the loop after test Section I with an inner diameter of 6 mm is the test Section II. Actually it can be assumed an isenthalpic copper tube installed in the vacuum vessel with a very little bit of heat leakage from the outside atmosphere. The saturated FC-14 from the pre-heater in the loop flows into the test Section I. The heat load can be input by the eight copper tubes. Two quartz glass tubes are installed at the inlet and outlet of the test Section I in the loop for visualization. The test sections inlet pressure of FC-14 in the loop is adjusted by a vapor tank. The experi-

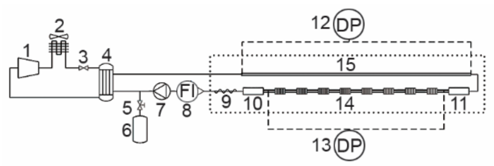

Figure. 1 Schematic diagram of the experimental apparatus and the details of the components; *1 – compressor, 2 – condenser, 3 – throttling valve, 4 – liquefaction heat exchanger, 5 – manual globe valve, 6 – buffer, 7 – magnetic pump, 8 – Coriolis flow-meter, 9 – electric heater (EH), 10-11 – glass tube, 12-13 – 3351 digital pressure (DP) transmitter, 14 – test Section I, 15 – test Section II*

Figure 2. Photo of experimental Section I

ment is carried out under a steady state, which means that the test sections inlet pressure, temperature and mass flow rate are all kept still for a few hours.

Measurements

The two-phase flow frictional pressure drop of FC-14 along each test section are measured by the digital differential pressure transmitters. The heat flux, input into the test Section I by the DC electric heating wire coils twisted around the eight copper tubes, are calculated by the DC voltage and current which are measured by a digital multimeter (Keithley 2700, USA) and an amperometer (HUAYI SH1844, China), respectively. The amperometer has an uncertainty of ±0.5% with the measurement range of 0-5 A and the Keithley 2700 digital multimeter has an accuracy of ±0.005% with the measurement range of 0-60 V.

The photograph of test Section I is shown in fig. 2. Three four-wire Pt100 thermometers are inserted into the wall at the inlet of each copper tube and one four-wire Pt100 thermometer is attached to surface of each stainless steel tube. So there are 33 thermometers totally and 17 temperature acquisition locations along the test Section I. The thermometers are calibrated in a proper range with an uncertainty of ±0.1 K. Three piezoelectric pressure transducers (YUHANG ZQ503, China) are installed to measure the inlet and outlet pressures of the test sections with a pronounced accuracy of ±0.1% and a measurement range of 0-0.5MPa. The pressure drops between the inlet and outlet of the two test sections are measured with differential pressure transducers (HSB 3351DP, China) with an uncertainty of ±0.1% and a measurement range of 0-10 kPa. The mass-flow rate is measured by a Coriolis mass-flow meter installed in the loop before the test sections outside the vacuum vessel with a pronounced uncertainty of ±0.1% and a measurement range of 0-180 kg/h.

When the steady-state condition reached, the data will be recorded by a computerized data acquisition system, which is consisting of 40 channels. The data is continuously monitored and recorded for every 50 second. Once, the steady-state conditions were reached, the temperature, pressure and mass-flow rate of the FC-14 in the test sections could be kept steady for a few hours. Mostly, the steady-state conditions kept for more than 20 minutes would be considered to be reached. The pressure transducers, differential pressure transducers, thermometers, flow meters and other associated instrumentations are all calibrated before testing.

Experimental uncertainty

The uncertainties of the measurements are calculated using the methods suggested by NIST [7]. The combined uncertainties, taken to represent the estimated standard deviation of the results, are obtained by combining the concerned individual standard uncertainties. The individual standard uncertainties of the measurements are summarized in tab. 1.

The heat flux, Q, was obtained by measuring the values of the voltage and the consequent current. So the combined uncertainty of Q are evaluated about ±0.5%. The combined standard uncertainty of the momentum pressure drop mainly depends on the uncertainties of the steam quality, x, and the mass-flow rate. The combined uncertainty of the steam quality x is less than ±0.3%.

Measurement and calculation methods

The directly measured pressure drop consists of three components, the static pressure drop, the momentum pressure drop and the frictional pressure drop. The expression is given:

$$\Delta P_{\mathrm{total}} = \Delta P_{\mathrm{static}} + \Delta P_{\mathrm{mom}} + \Delta P_{\mathrm{f}} \tag{1}$$

Table 1. The uncertainties of measurements

Parameters	Instruments	Range	Uncertainties
Temperature	PT100 thermometers	60-300 [K]	±0.1 [K]
Tube diameter	Calipers	0-130 [mm]	±0.02 [mm]
Pressure	ZQ503 piezoelectric pressure transducers	0-0.5 [MPa]	±0.5 [kPa]
Differential pressure	3351DP differential pressure transducer	0-0.01 [MPa]	±0.01 [kPa]
Mass Flow-rate	ULTRA mass MKII Coriolis mass flow-meter	0-180 [kgh^{-1}]	±0.1%
DC voltage	JC 1765	0-60 [V]	±0.005%
DC current	SH1844 amperometers	0-5 [A]	±0.5%

The test sections are positioned horizontally, so the static pressure drop $\Delta P_{\mathrm{static}}$ is 0.

The momentum pressure drop, caused by the kinetic energy loss, is calculated:

$$\Delta P_{\mathrm{mom}} = m_{\mathrm{total}}^2 \left\{ \left[\frac{(1-x)^2}{\rho_{\mathrm{L}}(1-\varepsilon)} + \frac{x^2}{\rho_{\mathrm{G}}{}^{\varepsilon}} \right]_{\mathrm{out}} - \left[\frac{(1-x)^2}{\rho_{\mathrm{L}}(1-\varepsilon)} + \frac{x^2}{\rho_{\mathrm{G}}{}^{\varepsilon}} \right]_{\mathrm{in}} \right\} \tag{2}$$

The calculation formula of void fraction is an improved model by Stephan [8] based on Rouhani and Axelsson [9] 's horizontal tube drifting flow density model:

$$\varepsilon = \frac{x}{\rho_{\mathrm{G}}} \left\{ [1 + 0.12(1-x)] \left(\frac{x}{\rho_{\mathrm{G}}} + \frac{1-x}{\rho_{\mathrm{L}}} \right) + \frac{1.18(1-x)\left[\mathrm{g}\sigma(\rho_{\mathrm{L}} - \rho_{\mathrm{G}}) \right]^{0.25}}{m_{\mathrm{total}}^2 \rho_{\mathrm{L}}^{0.5}} \right\}^{-1} \tag{3}$$

where m_{total} [kgm^{-2}s^{-1}] is the total vapor-liquid mass-flow rate, x – the steam quality, ρ_{L} and ρ_{G} – the density of liquid and vapor, respectively, and σ [Nm^{-1}] – the surface tension.

The vapor quality, x, at the outlet of test Section I and inlet of Section II is calculated based on the energy balance:

$$x = \frac{Q - C_{\mathrm{p}} m_{\mathrm{total}} A (T_{\mathrm{sat}} - T_{\mathrm{i}})}{m_{\mathrm{total}} A R_{\mathrm{LV}}} \tag{4}$$

where C_p [Jkg^{-1}K^{-1}] is the specific heat at constant pressure of FC-14. The thermodynamic and transport properties of FC-14 are evaluated using a NIST database of Refprop v8.0 [10].

Results and discussion

The test Section II is considered to be an adiabatic copper tube, which is different from the test Section I. But the heat power of the test Section I is set to be zero in this paper, so the vapor quality is assumed to be constant through the test Section I and II installed in the vacuum vessel. The total pressure drop, the frictional pressure drop and the momentum pressure drop of test Section I and II together versus the inlet quality are shown in fig. 3. The rang of the inlet vapor quality, x, is from 0 to 0.25, and the total mass-flow rate, m_{total}, is from 240 kg/m^{2}s to 785 kg/m^{2}s. The vapor quality, x, is adjusted by the pre-heater. The frictional pressure drop can be attributed to the effect of the fluid property and the inner surface roughness of the tubes [11]. Generally, the flow boiling frictional pressure drop is governed mainly by two important mechanisms: the boiling and the mass flow rate.

The frictional pressure gradient *vs.* the inlet quality of the test Section I with a variety of mass-flow rates are plotted in figs. 4 and 5, respectively. It is an increased trend of the frictional pressure drop with an increased inlet vapor quality. The frictional pressure gradient of the test Section I is higher than that of the test Section II at the same inlet vapor quality. The slope of the frictional pressure drop lines increase with the increasing of the mass-flow rate.

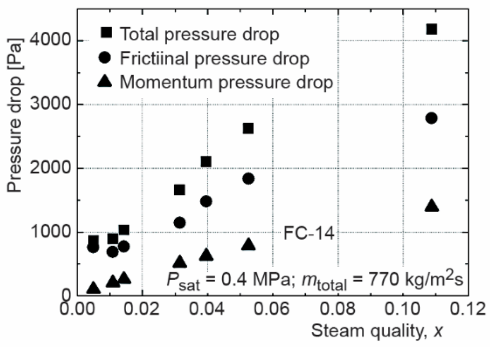

Figure 3. The total pressure drop, frictional pressure drop and momentum pressure drop

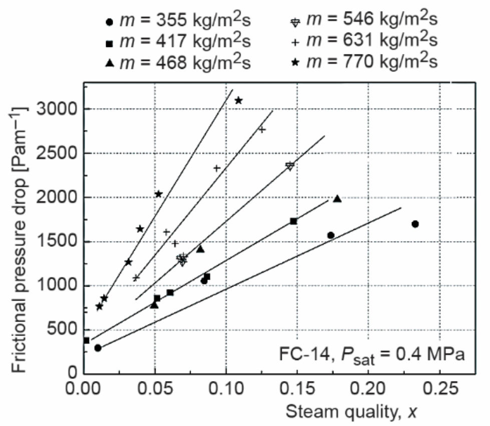

Figure 4. Pressure drop gradient *vs.* flow quality at various mass flux through test Section I

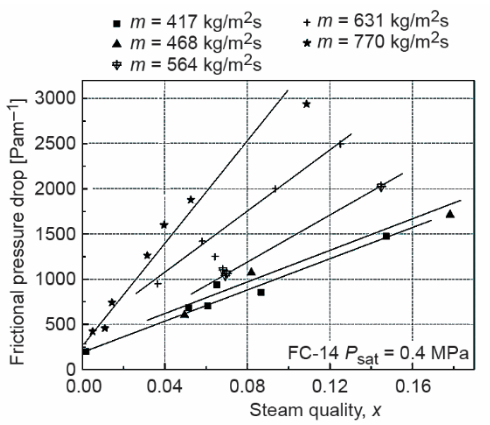

Figure 5. Pressure drop gradient *vs.* flow quality at various mass flux through test Section II

Existing correlations

Several models and correlations are reported in the literatures for predicting the two phase flow frictional pressure drop in small tubes, of which three models are applied to compare with the present experimental data measured in this paper. The comparisons with the test Section II are shown in figs. 6-8. The mean absolute deviations (MAD) [12] of the correlations are summarized in tab. 2, which is defined:

$$MAD = \frac{1}{M}\sum\frac{\left|\Delta P_{\text{pred}} - \Delta P_{\text{exp}}\right|}{\Delta P_{\text{exp}}}\cdot 100\% \tag{4}$$

Thereinto, Zhang and Webb's [6] correlation gives a best agreement with a total mean absolute deviation of 16% shown in tab. 2. Moreover, the author's reference, type of channels, fluids and the MAD are all listed in tab. 2 and more details are listed in the Appendix.

Table 2. Correlations used for comparison

Author	Friedel [5]	Zhang and Webb [6]	Muller and Heck [13]
Channel	M-C	Si-C	Si-C
Fluid	Air-water	R134a, R22, R404a	air-oil, air-water, water-steam, refrigerants
MAD	45%	16%	56%

M: multi-port, Si: single channel, C: circular.

Comparisons with existing models and correlations

The frictional pressure drop of FC-14 is investigated experimentally in this paper. The data measured from the test Section II shown in fig. 5 is compared with three correlations listed in tab. 2. The vapor quality is assumed to be constant through the test sections, because the very little bit heat leakage in the vacuum vessel can be omitted. The calculated data is also based on this assumption. The measured frictional pressure drop is converted into frictional pressure gradient by dividing the length of the test sections. The comparative results are provided as an illustration in figs. 6-8, respectively.

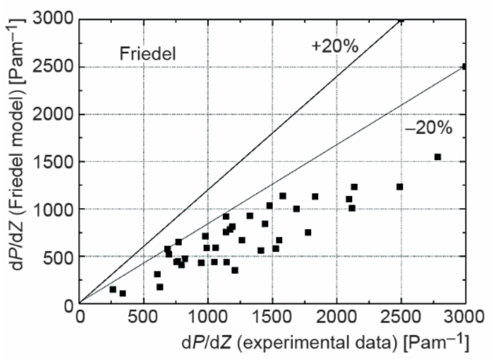

Figure 6. Comparison between the measured pressure gradient and the predicted results by the Friedel [5] model

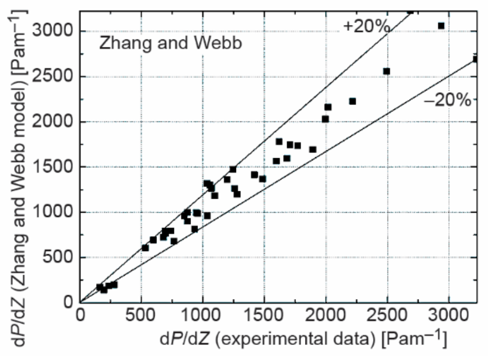

Figure 7. Comparison between the measured pressure gradient and the predicted results by the Zhang and Webb [6] model

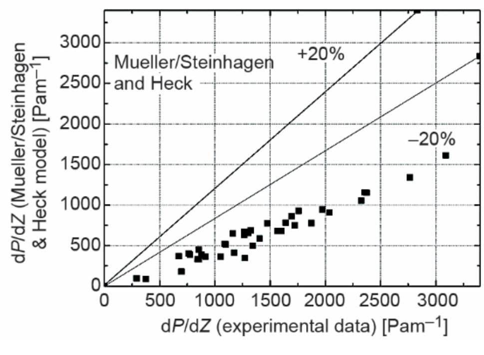

Figure 8. Comparison between the measured pressure gradient and the predicted results by Mueller and Heck's [13] model

Apparently, the results predicted by Friedel, Muller and Heck [13] models is lower than measured ones, which is similar to the situation reported by Hamdar *et al.* [14]. The mean deviations of the two prediction models are much bigger, but the predicted data is convergent. The results predicted by Zhang and Webb's [6] model gives a better agreement.

Conclusions

In this paper, the two-phase flow frictional pressure drop of FC-14 are studied experimentally in horizontal tubes at a pressure of 0.4 MPa. The impact of the mass-flow rate and the inlet vapor quality on the frictional pressure drop are studied. Two-phase flow frictional pressure drop increased with the increasing of the mass-flow rates and the vapor quality. The experimental data are compared with three existing models, among which Zhang and Webb's gives a best agreement with an average deviation of 16%. The mean deviation of Friedel's model is 45% and Müller and Heck's model is 56%, but the predicted results are convergent, which means the models can be modified to fit for the experiment results.

Nomenclature

A – cross-sectional area, [m^2]
C_p – specific heat capacity, [$kJkg^{-1}K^{-1}$]
d – diameter of cavity, [m, mm]
d_i – inner diameter of the tube
dz – infinitesimal length of tube, [m]
Fr – Froude number, [–]
g – acceleration of gravity, [m^2s^{-2}]
L – length of the tube
M – number of data used to calculate MAD
m_{total} – mass flux, [$kgm^{-2}s^{-1}$]
P – local pressure, [Pa]
ΔP – pressure drop, [Pa]
ΔP_{static} – static pressure drop, [Pa]
ΔP_{mom} – momentum pressure drop, [Pa]
p_c – critical pressure, [Pa]
R_{LV} – vaporization latent heat, [$kJkg^{-1}$]
dP/dz – pressure gradient, [Pam^{-1}]
Q – heating power, [W]
T_{sat} – local saturated temperature, [K]
T_i – liquid subcooling temperature, [K]
Re – Reynolds number ($= UD/\nu$), [–]
We – Weber number, [–]
x – vapor quality, [–]

Greek symbols

ε – void fraction, [–]
ν – kinematic viscosity, [m^2s^{-1}]
μ – dynamic viscosity, [Nsm^{-2}]
ρ – density of fluid, [kgm^{-3}]
ρ_h – two-phase density, [kgm^{-3}]
σ – surface tension, [Nm^{-1}]
ϕ – two-phase multiplier, [–]

Subscripts

L – liquid phase
Lo – all liquid phase
G – vapor phase
Go – all vapor phase
f – friction
h – two phase
pred – predicted value
exp – experimental value

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Appendix. More details for the three cited correlations

Friedel's correlation	
M-C, air-water, MAD: 45%	$\Delta p_\mathrm{f} = \Delta p_\mathrm{L} \Phi_\mathrm{Lo}^2, \quad \Delta p_\mathrm{L} = 4 f_\mathrm{L} \left(\frac{L}{d_\mathrm{i}}\right) m_\mathrm{total}^2 \left(\frac{1}{2\rho_\mathrm{L}}\right),$ $\Phi_\mathrm{Lo}^2 = E + \frac{3.24FH}{\mathrm{Fr}_\mathrm{h}^{0.045} \mathrm{We}_\mathrm{L}^{0.035}}, \quad \mathrm{Fr}_h = \frac{m_\mathrm{total}^2}{\mathrm{g} d_\mathrm{i} \rho_\mathrm{h}^2}$ $E = (1-x)^2 + x^2 \frac{\rho_\mathrm{L} f_\mathrm{G}}{\rho_\mathrm{G} f_\mathrm{L}}$ $H = \left(\frac{\rho_\mathrm{L}}{\rho_\mathrm{G}}\right)^{0.91} \left(\frac{\mu_\mathrm{G}}{\mu_\mathrm{L}}\right)^{0.19} \left(1-\frac{\mu_\mathrm{G}}{\mu_\mathrm{L}}\right)^{0.7}$ $\rho_h = \left(\frac{x}{\rho_\mathrm{G}} + \frac{1-x}{\rho_\mathrm{L}}\right)^{-1}, \quad F = x^{0.78}(1-x)^{0.224}$
Zhang and Webb's correlation	
Si–C, R134a,R22,R404a, MAD: 16%	$\Delta p_\mathrm{f} = \Delta p_\mathrm{L} \Phi_\mathrm{Lo}^2, \quad \Delta p_\mathrm{L} = 4 f_\mathrm{L} \left(\frac{L}{d_\mathrm{i}}\right) m_\mathrm{total}^2 \left(\frac{1}{2\rho_\mathrm{L}}\right),$ $\Phi_\mathrm{Lo}^2 = (1-x)^2 + 2.87x^2 \left(\frac{P}{p_c}\right) + 1.68x^{0.8}(1-x)^{0.25} \left(\frac{P}{p_c}\right)^{1.64}$
Mueller-Steinhagen and Heck's correlation	
Si-C, air-oil,air-water, water-steam, refrigerants, MAD: 56%	$\left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_\mathrm{f} = G\sqrt[3]{1-x} + bx^3$ $G = a + 2(b-a)x$ $a = \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_\mathrm{Lo} = f_\mathrm{L} \frac{2m_\mathrm{total}^2}{d_\mathrm{i}\rho_\mathrm{L}}, \quad b = \left(\frac{\mathrm{d}p}{\mathrm{d}z}\right)_\mathrm{Go} = f_\mathrm{G} \frac{2m_\mathrm{total}^2}{d_\mathrm{i}\rho_\mathrm{G}}$

M: multi-port, Si: single channel, C: circular.

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