International Journal of Heat and Mass Transfer 98 (2016) 150–163

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

An experimental study of flow boiling frictional pressure drop of R134a and evaluation of existing correlations

Yu Xu [a], Xiande Fang [a,*], Dingkun Li [b], Guohua Li [a], Yuliang Yuan [a], Anyi Xu [a]

[a] Institute of Air Conditioning and Refrigeration, Nanjing University of Aeronautics and Astronautics, 29 Yudao St., Nanjing 210016, China
[b] R&D Center, AVIC Aircraft Co., Ltd., Yanliang, Xian 710089, China

A R T I C L E   I N F O

Article history:
Received 15 October 2015
Received in revised form 3 March 2016
Accepted 4 March 2016

Keywords:
R134a
Flow boiling
Frictional pressure drop
Two-phase flow
Evaluation

A B S T R A C T

A series of experiments on flow boiling frictional pressure drop of R134a in three horizontal circular smooth copper tubes with inner diameters of 1.002, 2.168, and 4.065 mm were conducted. A total of 397 experimental data points are obtained for a mass flux range of 185–935 kg/m^2 s, a heat flux range of 18.0–35.5 kW/m^2, a saturation pressure range of 0.578–0.82 MPa, and a vapor quality range of 0.03–1.0. The effects of mass flux, heat flux, vapor quality, saturation pressure, and diameter on the frictional pressure drop are analyzed and the results indicate that the frictional pressure drop increases with increasing mass flux, increases with vapor quality until a peak and then drops, decreases with increasing saturation pressure and hydraulic diameter, and almost keep constant with heat flux. Thirty-two existing correlations of two-phase frictional pressure drop are compared with the experimental data. The best correlation has the mean absolute deviation of 15.0%. Besides, an experimental database of flow boiling frictional pressure drop is complied, which contains 3244 data points, including 397 from the current experiments and 2847 from 27 published papers. The 32 existing correlations are evaluated with the database. The best correlation has the mean absolute deviation of 24.5%. The work provides a guide for selecting a suitable correlation for specific applications of flow boiling frictional pressure drop.

1. Introduction

Flow boiling heat transfer of refrigerants is important in lots of fields, such as refrigeration, air conditioning, and thermal control systems. Since R134a is a widely used environmental friendly refrigerant, flow boiling frictional pressure drop of R134a has been a research hot spot in the last 20 years.

Yan and Lin [1] investigated the characteristics of the flow boiling pressure drop of R134a in a horizontal circular pipe having inner diameter (ID) of 2.0 mm with mass flux of 50–200 kg/m^2 s, heat flux of 5–20 kW/m^2, and saturation temperature of 5–31 °C. It was found that the frictional pressure drop increased with vapor quality and mass flux, increased mildly with heat flux at $x < 0.7$, and decreased observably with saturation temperature at $x > 0.65$. Based on the experimental data, a new correlation of flow boiling frictional pressure drop having an average deviation of 17% was developed.

Ould Didi et al. [2] conducted experiments on flow boiling pressure drop of R134a, R123, R402A, R404A, and R502 in 10.92 and 12.00 mm ID horizontal tubes with mass flux of 100–500 kg/m^2 s and vapor quality of 0.04–1.0. The experimental data were compared with the correlations of Lockhart and Martinelli [3], Bankoff [4], Chawla [5], Chisholm [6], Friedel [7], Grönnerud [8], and Müller-Steinhagen and Heck [9], and the comparison results indicated that the correlations of Müller-Steinhagen and Heck [9] and Grönnerud [7] could provide the most accurate predictions, followed by that of Friedel [7]. The experimental data were also classified as per the flow pattern map of Kattan et al. [10]. The best correlation for annular flow was that of Müller-Steinhagen and Heck [9], and the best for intermittent flow and stratified-wavy flow was that of Grönnerud [7].

Lee and Mudawar [11] measured the flow boiling pressure drop of R134a in a micro-channel (231 × 713 μm) heat sink with inlet pressure of 1.44–6.60 bar, mass flux of 127–654 kg/m^2 s, inlet quality of 0.001–0.25, outlet quality of 0.49-superheat, and heat flux of 316–938 kW/m^2. Homogeneous flow correlations of McAdams [12], Akers et al. [13], Cicchitti et al. [14], Dukler [15], Beattie and Whalley [16], and Lin et al. [17] and separated flow correlations of Lockhart and Martinelli [3], Friedel [7], Mishima and Hibiki [18], Lee and Lee [19], and Zhang and Webb [20] were compared with the experimental data, and the results indicated that all correlations yielded relatively poor predictions. A new correlation was

* Corresponding author. Tel./fax: +86 25 8489 6381.
E-mail address: xd_fang@nuaa.edu.cn (X. Fang).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.018
0017-9310/

Nomenclature

D	inner diameter (m)
D_h	hydraulic diameter (m)
Fr	Froude number
G	mass flux (kg/m^2 s)
g	gravitational acceleration (m/s^2)
L	channel length (m)
p	saturation pressure (Pa)
p_r	reduced pressure
q	heat flux (W/m^2)
Re	Reynolds number
x	vapor quality
Δp	pressure drop (Pa)

Greek symbols

ε	void fraction
ρ	density (kg/m^3)

Subscripts

g	gas
in	inlet
l	liquid
out	outlet

developed and agreed well with the R134a data and the previous micro-channel water data.

Greco and Vanoli [21] conducted an experimental study on flow boiling pressure drop of R134a, R22, R507, R404A, R407C and R410A in a 6 mm ID smooth horizontal stainless steel tube with mass flux of 280–1080 kg/m^2 s, heat flux of 11.7–36.8 kW/m^2, and saturation pressure of 7.0 bar. It was found that the frictional pressure drop increased with vapor quality and mass flux. The correlations of Lockhart and Martinelli [3], Chawla [5], Chisholm [6], Friedel [7], Grönnerud [8], Müller-Steinhagen and Heck [9], Martinelli and Nelson [22], Lombardi and Pedrocchi [23], and Theissing [24] were compared with the experimental data, and the comparison results showed that the best-fitting correlation was Chawla [5].

Lie et al. [25] investigated the characteristics of frictional pressure drop of R134a and R407C flow boiling in 0.83 and 2.0 mm horizontal tubes. For 2.0 mm tube, the parameter ranges were mass flux of 200–400 kg/m^2 s, heat flux of 5–15 kW/m^2, inlet vapor quality of 0.2–0.8, and saturation temperature of 5–15 °C. For 0.83 mm tube, the mass flux was of 800–1500 kg/m^2 s, and the heat flux and inlet vapor quality had the same ranges as those for the 2.0 mm tube. It was found that the frictional pressure drop increased with the inlet vapor quality except at low mass flux and high heat flux, decreased with the rising saturation temperature, increased with mass flux, increased with a reduction in the tube size from 2.0 to 0.83 mm, and was weakly affected by heat flux. Based on the experimental data, a new correlation having a mean deviation of 19.4% was proposed.

Ali et al. [26] conducted experiments on flow boiling pressure drop of R134a in a 0.781 mm ID fused silica tube with mass flux of 100–650 kg/m^2 s, heat flux of 7–60 kW/m^2, saturation temperature of 25 and 30 °C, and vapor quality of 0.1–0.86. The experimental data were compared with the five macro-scale correlations of Lockhart and Martinelli [3], Friedel [7], Grönnerud [8], Müller-Steinhagen and Heck [9], and Cicchitti et al. [14], and four micro-scale correlations of Lee and Mudawar [11], Mishima and Hibiki [18], Zhang and Webb [20], and Tran et al. [27]. It was found that the best macro-scale correlation was that of Müller-Steinhagen and Heck [9] with a mean absolute deviation of 18%, and the best micro-scale correlation was that of Tran et al. [27] with a mean absolute deviation of 17%.

Copetti et al. [28] conducted an experimental study of R134a flow boiling in a 2.6 mm ID horizontal tube with mass flux of 240–930 kg/m^2 s, heat flux of 10–100 kW/m^2, and saturation temperature of 12 and 22 °C. It was found that the frictional pressure drop increased with the increase in vapor quality and mass velocity, was slightly higher at lower saturation temperature, and was influenced by heat flux at higher mass flux. The experimental data were compared with three two-phase frictional pressure drop correlations of Friedel [7], Müller-Steinhagen and Heck [9], and Tran et al. [27]. It was found that the Tran et al. [27] correlation was the best while the Friedel [7] and Müller-Steinhagen and Heck [9] correlations showed larger errors.

Tibiriçá et al. [29] investigated the flow boiling pressure drop of R134a in a 2.32 mm ID horizontal tube with mass flux of 100–600 kg/m^2 s, heat flux of 10–55 kW/m^2, exit vapor quality of 0.20–0.99, and a saturation temperature of 31 °C. It was found that the frictional pressure drop increased with increasing mass flux, seemed to pass through a peak at high vapor quality with increasing vapor quality from 0, and was affected by heat flux negligibly. The experimental data were compared with the correlations of Lockhart and Martinelli [3], Müller-Steinhagen and Heck [9], McAdams et al. [12], Cicchitti et al. [14], Dukler et al. [15], Beattie and Whalley [16], Mishima and Hibiki [18], Davidson et al. [30], Owens [31], García et al. [32], Cioncolini et al. [33], and Sun and Mishima [34]. It was found that the Cioncolini et al. [33] correlation for microscale tube predicted best with a mean absolute deviation (MAD) of 14%, followed by the Lockhart and Martinelli [3] correlation with an MAD of 20%.

Kaew-On et al. [35] investigated the pressure drop characteristics of R134a flow boiling in multiport minichannels made from aluminum with hydraulic diameters of 1.1 mm for 14 channels and 1.2 mm for 8 channels. The experimental conditions were the mass flux of 350–980 kg/m^2 s, heat flux of 18–80 kW/m^2, saturation pressure of 4, 5, and 6 bar, and inlet quality of 0.05. It was found that the frictional pressure drop increased with increasing mass flux, decreased with increasing saturation pressure, slightly increased with increasing heat flux, and decreased with increasing aspect ratio. The correlations of Lockhart and Martinelli [3], Friedel [7], Müller-Steinhagen and Heck [9], Lee and Mudawar [11], Mishima and Hibiki [18], Zhang and Webb [20], Saisorn and Wongwises [36], Kaew-On and Wongwises [37], and Zhang et al. [38] were compared with the experimental data. It was found that the Friedel [7] correlation predicted best, followed by that of Zhang and Webb [20].

The above literature survey clearly indicates that studies on the flow boiling pressure drop of R134a have been gradually tending to small channels. For evaluating existing correlations, most of works were based on the authors own experimental database with limited data points, and the number of the correlations evaluated was around 12 at most. Consequently, remarkable differences exist among the evaluation results.

In this paper, experiments on the flow boiling frictional pressure drop of R134a flowing in 3 horizontal circular smooth copper tubes having IDs of 1.002, 2.168 and 4.065 mm are conducted to provide more data for small tubes. The effects of mass flux, heat