International Journal of Heat and Mass Transfer 55 (2012) 3522–3532

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental investigation of condensation heat transfer and pressure drop of R22, R410A and R407C in mini-tubes

Hui-Yong Zhang [1], Jun-Ming Li *, Na Liu, Bu-Xuan Wang

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 15 July 2010
Received in revised form 1 March 2012
Accepted 1 March 2012
Available online 14 April 2012

Keywords:
Condensation heat transfer
Pressure drop
Mini-tube
Refrigerants

ABSTRACT

Condensation heat transfer and pressure drop of R22, R410A and R407C were investigated experimentally in two single round stainless steel tubes with inner diameter of 1.088 mm and 1.289 mm. Condensation heat transfer coefficients and two phase pressure drop were measured at the saturation temperatures of 30 °C and 40 °C. The mass flux varies from 300 to 600 kg/m^2 s and the vapor quality 0.1–0.9. The effects of mass flux and vapor quality were investigated and the results indicate that condensation heat transfer coefficients increase with mass flux and vapor quality, increasing faster in the high vapor quality region. The experimental data was compared with the correlations based on experimental data from large diameter tubes (d_h > 3 mm), such as the Shah and Akers correlations et al. Almost all the correlations overestimated the present experimental data, but Wang correlation and Yan and Lin correlation which were developed based on the experimental data from mini-tubes predicted present data reasonably well. Condensation heat transfer coefficients and two phase pressure drop of R22 and R407C are equivalent but both higher than those of R410A. As a substitute for R22, R410A has more advantages than R407C in view of the characteristics of condensation heat transfer and pressure drop.
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1. Introduction

Refrigerators and air-conditioning systems are very common necessities in domestic and industrial application. Because of their many applications, a large amount of refrigerant has been used and inevitably leaked to the atmosphere, leading to ozone depletion and global warming effects. According to the Montreal protocol, CFCs had been prohibited and HCFCs are also being phased out step by step. In fact, some countries have completed the elimination of HCFCs such as Japan and Germany. Thus, new refrigerants are urgently needed to be developed out. HCFC R22 has been used most widely in domestic air conditioners, so the substitutes of R22 also became most important. Up to now many new refrigerants had been developed to replace R22, of which R410A and R407C are of the greatest concern. The aim of the present work is to investigate and compare the characteristics of the condensation heat transfer and two phase pressure drops of R22, R410A and R407C in two mini-tubes.

Early in the 1980s, Tuckerman and Pease [1] had found that the heat transfer coefficient would be enhanced by reducing the tube diameter. From then on, the heat transfer in mini and micro tubes has been one of the hottest topics in this field. As the tube diameter decreases, the ratio of area to volume increases, enhancing the heat transfer. In addition, the effects of gravity, interfacial shear stress and surface tension on condensation heat transfer in mini-tubes obviously differ from those in conventional large diameter (d_h > 3 mm) tubes, because the relative magnitude of them changes. Surface tension will play a more important role in condensation heat transfer due to the increasing interface curvature. In practice, micro-channel heat exchangers have been widely used in vehicle air conditioning systems, but their application in domestic air conditioners has also been being under evaluation [2]. A concise review of condensation heat transfer and pressure drop in mini and micro channels is given below.

Yang and Webb [3,4] measured condensation heat transfer coefficients and two phase friction pressure drops of R12 in flat extruded aluminum tubes with the inner diameter of 2.637 mm (smooth tubes) and 1.564 mm (micro-fin tubes). The results show that condensation heat transfer coefficients increase with heat flux. They also compared their results with the Shah [5] and Akers et al. [6] correlations and found that Akers et al. [6] correlation agreed well with their experimental data at low mass flux, but over-predicted by 10–20% at high mass flux. They also found that the effect of surface tension became more obvious when the vapor quality

* Corresponding author. Address: Department of Thermal Engineering, Tsinghua University, Beijing 100084, PR China. Tel.: +86 10 62771001; fax: +86 10 62770209.
E-mail addresses: zhanghuiyong@cgnpc.com.cn (H.-Y. Zhang), lijm@tsinghua.edu.cn (J.-M. Li).
[1] Huiyong Zhang graduated from the Department of Thermal Engineering, Tsinghua University and now works at China the Nuclear Power Technology Research Institute. Tel.: +86 755 25310953; fax: +86 755 82940692.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.03.012

Nomenclature

G	mass flux (kg/m^2 s)
I	electric current (A)
j	superficial velocity (m/s)
U	electric voltage (V)
h	enthalpy (kJ/kg)
Q	heat transfer (W)
T	temperature (°C)
D	diameter (m)
C	specific heat capacity (kJ/kg K)
l	length (m)
m	mass flow rate (kg/s)
k	heat conductivity (W/m K)
p	pressure (Pa)

Greek symbols

α	heat transfer coefficient (W/m^2 K)
Δ	delta
ρ	density (kg/m^3)
γ	A tube/A header
φ	void fraction
Ψ	Form factor

Subscripts

in	inlet
out	outlet
r	refrigerant
s	Saturation, separate flow model
cool	cooling water
w	water
o	outside
H	homogenous flow model
i	inside
s	solid
c	condensation
exp	experimental
f	friction
de	deceleration
contraction	contraction
Expansion	expansion
l	liquid
v	vapor

was less than 0.5 and that the two phase friction pressure drop was larger than that predicted by the classical Blasius equation by 14%. They finally found that the Lockhart–Martinelli multiplier model could not accurately predict their experimental data. Moser and Webb [7] developed an equivalent Re_{eq} model based on the analogy of heat and momentum using experimental data collected from 18 databases including R12, R22 et al. Their model was equivalent to the Shah [5] model in predicting the condensation heat transfer coefficients. Yan and Lin [8] measured the condensation heat transfer coefficients and pressure drops of R134a in small circular minitubes with inner diameters of 2 mm and found that the average condensation heat transfer coefficients over the entire quality range tested was about 10% higher than the results reported in Dobson and Chato [9] for large diameter tubes ($d_h > 3$ mm). Then they developed two empirical correlations for the condensation heat transfer and pressure drop. Kim et al. [10] investigated the condensation heat transfer of R134a in flat aluminum multi-port tubes with hydraulic diameters of 1.41 mm (smooth tube) and 1.56 mm (micro-fin tubes) at saturation temperature of 45 °C and found no effects of heat flux. This is opposite to Yang and Webb's [3,4] results. They also found that Shah [5] and Akers et al. [6] correlations agreed well with their experimental data at low mass flux, but over-predicted at high mass flux region. They attributed the reason to the increasing effects of surface tension and pointed out that the surface tension should be added into the correlation but they did not develop a new model. Wang [11] investigated the condensation heat transfer of R134a in a horizontal rectangular multi-port aluminum tube with inner hydraulic diameter of 1.46 mm. Based their flow regime map, they also found that existing correlations over-predicted their experimental data. The results indicated that liquid is drawn into the corner, which will alter the phase distribution in the annular flow regime and stabilize the annular flow regime at low vapor velocities. They developed a correlation by weighting the regime-specific correlations with the annular flow length fraction from their flow regime visualization. Koyama et al. [12] investigated the condensation heat transfer and pressure drop of R134a in four kinds of multi-port extruded aluminum tubes with hydraulic diameter of about 1.0 mm. They argued that the effect of tube diameter, surface tension and free convection on the pressure drop and heat transfer coefficient should be taken into account and then developed a correlation which included the effects of surface tension and tube diameter which had good agreement with their experimental data. Baird et al. [13] used controllable thermoelectric coolers for cooling to investigate the condensation heat transfer of R123 and R11 in passages with inner hydraulic diameters of 0.92 mm and 1.95 mm and discussed the effects of mass flux, quality, tube diameter and saturate temperature. The results indicated that the effects of heat flux could not be ignored, especially at high vapor qualities region and that condensation heat transfer coefficients decreased with the saturation temperature. They also found that the Shah [5] correlation over-predicted their experimental data and the Lockhart–Martinelli [14] model agreed well with their pressure drop data. Thome et al. [15,16] developed a novel void fraction model from Homogeneous model and Rouhani–Axelsson model, proposed a new flow pattern map for condensation heat transfer by modifying the flow pattern map by Thome [17], and developed a condensation heat transfer model based on the modified flow pattern map. The model had been well verified against a wide range of refrigerants for condensation in conventional large diameter tubes.

Recently, Shin and Kim [18] used a new measurement technique to study the condensation heat transfer of R134a in a horizontal single round tube with an inner diameter of 0.691 mm and did not find the obvious effect of heat flux on the condensation heat transfer and pressure drop. The Shah [5] and Akers et al. [6] correlations also failed in predicting their experimental data. But Friedel [19] correlation gave good agreement with their experimental pressure drop data in the high mass flux region, but failed at low mass flux. Shin and Kim [20] found that the condensation heat transfer coefficients in rectangular channels are higher than those in circular channels for similar diameter tubes at low mass flux. Large pressure drop fluctuations were confirmed except in the high vapor quality region. Garimella and his co-authors [21,22] presented a flow regime map for condensation of R134a in various hydraulic diameter tubes (4.91 mm round and 1–4 mm rectangular tubes) and found that the range of intermittent flow increased while the range of wavy flow decreased with tube diameter. For the 1 × 1 mm rectangular channels, the wavy flow pattern even disappeared. They developed various special models of the pressure drop for different flow patterns based their research

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