International Journal of Heat and Mass Transfer 112 (2017) 587–596

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A new general correlation for frictional pressure drop during condensation inside horizontal micro-fin tubes

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ARTICLE INFO

Article history:
Received 19 March 2017
Received in revised form 6 May 2017
Accepted 6 May 2017
Available online 12 May 2017

Keywords:
Condensation
Frictional pressure drop
Two-phase flow
Micro-fin tube
Prediction model

ABSTRACT

Experimental pressure drop data of condensation from present study and literature were collected to develop a new frictional pressure drop correlation for horizontal micro-fin tubes. The collected database contained 481 data points, covering nine refrigerants including CO_2 at average saturated condensing temperatures ranging between 14 and 65 °C, with mass velocities ranging from 50 to 800 kg/m^2 s, and average vapor qualities from 0.11 to 0.91. The hydraulic diameter of micro-fin tubes varied from 2.16 to 5.67 mm and was employed in the calculation of Reynolds number. The Fanning frictional factor was calculated by adopting the Churchill model with the empirically fitted relative roughness. Four existing pressure drop correlations developed for micro-fin tubes were evaluated by the database for condensation in micro-fin tubes. The correlation proposed by Cavallini et al. was the best prediction model among them, predicting 85.6% of the collected data points within the 30% error band. In addition, a new correlation based on the Martnelli parameter X_{tt} modified by incorporating the reduced pressure was proposed to predict the present database, which showed a good agreement. Finally, some corresponding experimental work was conducted for evaluating the reliability of the new prediction model.

1. Introduction

Micro-fin tubes have been widely used in the commercial air-conditioning applications since the early 1980s. Their characteristic geometry can significantly improve the heat coefficient with a smaller increasement of the friction penalty. Therefore, the micro-fin tubes belong to the most common heat transfer enhancement method to improve the performance of the heat exchangers for heat pump and refrigeration systems. Typical micro-fin tube geometry has an outside diameter from 4 to 15 mm, 50–70 fins with helix angle (β) from 6° to 30°, fin height (h) from 0.1 to 0.25 mm, fin apex angle (α) from 25° to 70° [1–3]. Fig. 1 shows the characteristic geometrical parameters of typical micro-fin tubes.

Single-phase and adiabatic two-phase flow pressure drop in micro-fin tubes have been extensively investigated. Many researchers have participated actively in improving the surface of the micro-fin tubes by using pure refrigerants as working fluids. The frictional pressure drop of R22 during condensation inside micro-fin tubes with outer diameters larger than 9 mm were reported in Muzzio et al. [4] and Smit and Meyer [5]. Li et al. [6] measured two-phase flow pressure drop for R22 inside five micro-fin tubes with the same outer diameter of 5 mm and helix angle of 18°. The results suggest that the tube has the highest condensation heat transfer coefficient and also has the highest condensation pressure drop penalty. In addition, Nualboonrueng et al. [7] tested the condensation pressure drop of R134a in smooth and micro-fin tubes at high mass fluxes. The experimental results show that the pressure drop increases with increasing average quality and mass flux, and tends to decrease with increasing condensing temperature. Colombo et al. [8] also performed the experiments on condensation for R134a inside two 9.52 mm outer diameter micro-fin tubes.

R410A is a widely used ozone depletion free refrigerant, and is recognized as the important replacement to R22. Flow condensation pressure drop characteristics of pure R410A inside micro-fin tubes have also been reported by many researchers, such as Huang et al. [9], Kim et al. [10], Lee et al. [11] and Kim [12].

Kedzierski and Concalves [13] carried out a large number of studies on local convective condensation for four refrigerants (R125, R134a, R32, R410A) in a micro-fin tube, and developed a pressure drop correlation using the hydraulic diameter, which can predict most of their experimental data points within ±20%.

Olivier et al. [14] presented a study of flow regimes, pressure drops, and heat transfer coefficients during refrigerant condensation inside a plain, an 18° helical micro-fin, and a herringbone tubes. Experiments were performed for refrigerants (R134a, R22

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.05.022
0017-9310/

Nomenclature

A_{ai}	actual inner surface heat transfer area of the micro-fin tube [m^2]
A_c	inner tube cross sectional area [m^2]
A_{fr}	inside surface area based on fin tip diameter [m^2]
d	diameter [m]
d_e	equivalent diameter of the tube [m]
d_h	hydraulic diameter of the tube [m]
d_i	fin root diameter of the tube [m]
d_t	fin tip diameter of the tube [m]
e_A	mean absolute deviation [%]
e_R	mean relative deviation [%]
f	friction factor [–]
Fr	$G^2/[(\rho_l-\rho_g)^2gd]$, Froude number [–]
g	gravitational acceleration [m/s^2]
G	mass velocity [kg/m^2s]
h	fin height [m]
h_{lg}	latent heat of vaporization [J/kg]
L	tube length [m]
n_s	number of starts [–]
N	number of data points [–]
P	pressure [Pa]
P_f	axial pitch [m]
P_{red}	reduced pressure [–]
Re	Gd/μ, Reynolds number [–]
Rx	empirically fitted relative roughness [–]
s	perimeter of a fin and channel taken perpendicular to the axis of the fin [m]
T	temperature [K]
We	$G^2d/\sigma\rho$, Weber number [–]
x	vapor quality [–]
Xtt	Lockhart–Martinelli parameter [–]

Greek symbols

α	apex angle of the fin [°]
β	helix angle [°]
ε	void fraction [–]
μ	dynamic viscosity [kg/(m·s)]
ρ	density [kg/m^3]
σ	surface tension [N/m]
σ	mean square error [%]
Φ^2	frictional two-phase multiplier [–]

Subscripts

a	acceleration
A	absolute
cal	calculated
e	equivalent
exp	experimental
f	frictional
g	gas phase
GO	gas phase with total flow rate
h	hydraulic
i	inside
i-a	intermittent-annular
l	liquid phase
lg	liquid-gas
LO	liquid phase with total flow rate
Red	reduced
R	relative
s	saturation
tp	two-phase
v	vapor

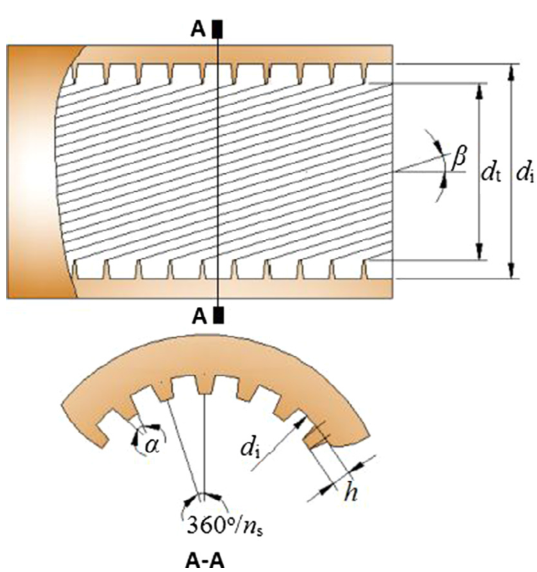

Fig. 1. Characteristic geometrical parameters of micro-fin tubes.

and R407C) at an average saturation temperature of 40 °C, and the results show that the fins can redistribute the liquid layer around the circumference of the tube, forcing the flow to become annular rather than intermittent or stratified.

The hydrofluoro-olefins R1234ze(E) and R1234ze(Z) are environmentally friendly working fluids for industrial heat pump systems and refrigeration applications. Kondou et al. [15] tested condensation and evaporation of R134a, R1234ze(E) and R1234ze (Z) in horizontal micro-fin tubes at higher experimental temperatures. The experimental results for R1234ze(E) and R134a are similar. However, the pressure drop of R1234ze(Z) is higher than that of R1234ze(E), mainly because of the higher vapor velocity due to the lower vapor density and higher latent heat.

Some special applications need a low temperature level, harmless, and odorless working fluid. As a natural refrigerant, CO_2 could be a perfect solution for these applications. Koyama et al. [16] carried out an experimental study on condensation of almost pure CO_2 in a horizontal micro-fin copper tube with an equivalent diameter of 5.67 mm. The effect of heat flux was negligible, hence pressure drop slightly increased in accordance with a decrease in saturation pressure. On the contrary, the increase in mass flux caused a significant increase in pressure drop.

Table 1 lists the collected data of condensation pressure drop in horizontal micro-fin tubes with different geometrical parameters, covering nine working fluids (R125, R1234ze(E), R1234ze(Z), R134a, R22, R32, R407C, R410A and CO_2) at various reduced pressure and operating conditions [6–16].

2. Data base description

The entire database contains 481 experimental data points from 11 different papers, covering 9 different working fluids. Fig. 2