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Evaluation of Condensation Pressure Drop Correlations for Microfin Tubes

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Abstract

The characteristics of nine existing condensation frictional pressure drop correlations for microfin tubes were evaluated with geometries, vapor quality, mass flux, and refrigerants. The Müller-Steinhagen and Heck [17] smooth tube frictional pressure drop correlation was utilized to evaluate the pressure drop penalty factor (*PF*). Except the Nozu et al. [2], the Kedzierski and Goncalves [3], the Choi et al. [10], and the Cavallini et al. [7], other pressure drop correlations did not consider the effect of tube geometry. The prediction values for R407C by pressure drop correlations show discrepancy with previous researcher's experimental trend. Additional efforts on the development of reliable condensation pressure drop correlation for microfin tubes are still required with the systematic investigation of various effects like geometries and working conditions.

Key words: Microfin tube; Condensation; Pressure drop; Correlations

Nomenclature

D_i	maximum inside tube diameter [m]
dP	pressure drop [N/m^2]
dz	distance along the flow direction [m]
E	dimensionless parameter [-]
e	fin height [m]
F	dimensionless parameter [-]
f	friction factor [-]
Fr	modified Froude number [-]
G	mass flux [kg/m^{2}s]
g	gravitational acceleration [m/s^2]
h_{fg}	specific enthalpy of evaporation [J/kg]
L	test section length [m]
n	number of fins [-]
p	axial fin pitch [m]
PF	pressure drop penalty factor [-]
We	dimensionless parameter [-]
T_c	condensation temperature [^{o}C]
x	vapor quality [-]
X_{tt}	Lockhart-Martinelli parameter [-]

Greek symbols

β	spiral angle [^{o}]
Φ	two-phase frictional multiplier [-]
Γ	dimensionless parameter [-]
γ	apex angle of fins [^{o}]
μ	dynamic viscosity [Pa s]
ρ	density [kg/m2]
ξ	correlation parameter [-]
ζ	dimensionless parameter [-]

Subscript

c	based on fin tip diameter
e	based on equivalent diameter
fr	frictional
go	gas only
ho	homogeneous
i	inside
in	inlet
l	liquid phase
lo	liquid only
o	outlet
r	based on fin root diameter
v	vapor phase

1. Introduction

Among passive heat transfer enhancement techniques, microfin tubes have been used widely because

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they ensure a large heat transfer enhancement with a relatively low pressure drop increase. Typically, microfin tubes are made of copper and have an outside diameter from 4 to 15 mm, a single set of 50-70 spiral fins with spiral angle from 6 to 30°, and a fin height from 0.1 to 0.25 mm. The heat transfer enhancement is caused by surface area increase and the mixing induced by the fins. Even though relatively a lot of correlations for microfin tubes have been introduced, systematic research has not been performed thoroughly. Therefore, the characteristics of each correlation were investigated with the consideration of tube geometries, working conditions (mass flux and vapor quality), and refrigerants (R22, R134a, R407C, and R410A) in this study. This study can be used for the heat exchanger design with microfin tubes.

2. Condensation frictional pressure drop correlations for microfin tubes

Haraguchi et al. [1] developed a condensation pressure drop correlation for a microfin tube with measured R123, R134a, and R22 friction pressure gradients. Nozu et al. [2] proposed a correlation based on an annular flow model in which the effect of the shear stress at the condensate surface and the fin geometry was taken into account. Their correlation was based on three microfin tubes and four refrigerants: R11, R123, R22, and R134a. Their correlation considered the effect of heat flux on condensation frictional pressure drop. Kedzierski and Goncalves [3] suggested a different approach to calculate the pressure drop during condensation in microfin tubes. Starting from the semiempirical equations developed by Pierre [4] for flow boiling pressure drop in a horizontal tube, they obtain a correlation based on their own data. Their correlation was developed using the hydraulic diameter concept and was a function of the fin height, the spiral angle, and the apex angle of fins. Newell and Shah [5] recommended a method for calculating the pressure drop by multiplying the pressure drop penalty factor (*PF*) by the smooth tube pressure drop correlation proposed by Souza and Pimenta [6]. Their pressure drop penalty factor correlation is the function of the ratio between the liquid and the vapor phase densities. Cavallini et al. [7] suggested frictional pressure correlations for the microfin tube in condensation by modifying the Friedel [8] model. The Friedel model [8] was developed for adiabatic two phase flow. Cavallini et al. [7] accounted for the effects of mass transfer on the interfacial shear stress. Cavallini et al. [7] used Rouhani's void fraction correlation [9] to evaluate the acceleration pressure drop. Cavallini et al. [7] separated the friction factor correlation into turbulent and laminar regions and used the fin height and the spiral angle of fins to calculate the relative roughness of microfin tubes. Choi et al. [10] proposed a pressure drop correlation similar to that of Kedzierski and Goncalves [3]. The Choi et al. correlation [10] was based on the experimental data of a microfin tube for R32, R125, R134a, and R410A. They reported that their correlation could be applicable to condensation in smooth and microfin tubes for lubricant free refrigerants and refrigerant/ lubricant mixtures. Goto et al. [11] developed two correlations using two phase frictional multipliers and friction factors. In this work, the Goto et al. [11] (a) and (b) denotes their vapor and liquid phase correlations, respectively. They did not consider any geometry effects in their correlations. However, they considered the effect of Reynolds number and proposed five different friction factor correlations based on the Reynolds number. Their condensation and evaporation pressure drop data in a helical microfin tube and a herringbone microfin tube with R22 and R410A were used in the development of the correlations. Han and Lee [12] proposed a friction factor and two-phase multiplier correlation for 4 microfin tubes with R134a, R22, and R410A. Their friction factor correlation was derived from their single phase experiments [13]. The summary of the correlations is presented in table 1.

3. Evaluation of pressure drop correlations by previous researchers

Recently, Wang et al. [14] compared existing condensation frictional *dP* correlations for microfin tubes with eight different microfin tubes and seven refrigerants (R11, R123, R134a, R22, R32, R125, R410A). Their collected data composed of the fin height between 0.15 and 0.24 mm, helix angle between 13 and 20°, maximum inside diameter between 6.41 and 8.91 mm, and mass flux from 78 to 459 kg/m^{2}s. They reported that the r.m.s. deviations decreased in the order of the correlations of the Nozu et al. [2], the Newell and Shah [5], the Kedzierski and Goncalves [3], the Cavallini et al. [7], the Goto et al. (b) [11], the Choi et al. [10], the Haraguchi et al. [1], and the Goto et al. (a) [11].

Cavallini et al. [7] compared their own correlation and the Kedzierski and Goncalves [3] with ten different experimental sources. Their collected data covers

Table 1. Summary of the existing condensation pressure drop correlations.

Haraguchi et al. [1] [symbol : ●] $\left(\frac{dP}{dz}\right)_{fr}=\Phi_v^2\frac{2f_v(Gx)^2}{D_e\rho_v}$ $f_{v,e}=0.046\,\mathrm{Re}_{v,e}^{-0.2}$ $\Phi_v^2=1.1+1.3(\mathrm{Fr}_e X_{tt})^{0.35}$	Nozu et al. [2] [symbol : ○] $\left(\frac{dP}{dz}\right)_{fr}=(\xi+\varsigma)\frac{2f_v(G_r x)^2}{D\rho_v}$
Kedzierski and Goncalves [3] [symbol : ▼] $\left(\frac{dP}{L}\right)_{fr}=\frac{f_{tp}G^2}{D_h}\left(\frac{1}{\rho_{ho,in}}+\frac{1}{\rho_{ho,out}}\right)$ $f_{tp}=\left[0.002265+0.00933EXP\left(\frac{-e}{0.003d_e}\right)\right]\mathrm{Re}_{lo,h}^{\frac{-1}{4.16+532e/d_e}}\left[\frac{(x_{in}-x_{out})h_{fg}}{Lg}\right]^{0.211}$	
Cavallini et al. [7] [symbol : ■] $\left(\frac{dP}{dz}\right)_{fr}=\Phi_{lo}^2\frac{2f_{lo}G_c^2}{D_c\rho_l}$ $\Phi_{lo}^2=E+\frac{3.24FH}{\mathrm{Fr}_c^{0.045}\mathrm{We}^{0.035}}$	Choi et al. [10] [symbol : □] $\left(\frac{dP}{L}\right)_{fr}=\frac{f_{tp}G^2}{D_h}\left(\frac{1}{\rho_{ho,in}}+\frac{1}{\rho_{ho,out}}\right)$ $f_{tp}=0.00506\,\mathrm{Re}_{lo,h}^{-0.0951}\left[\frac{(x_{in}-x_{out})h_{fg}}{Lg}\right]^{0.1554}$
Goto et al. (a) [11] [symbol : ◆] $\left(\frac{dP}{dz}\right)_{fr}=\Phi_v^2\frac{2f_{v,Go}(Gx)^2}{D_e\rho_v}$ $\Phi_v^2=1+1.64X_{tt}^{0.79}$	Goto et al. (b) [11] [symbol : ◇] $\left(\frac{dP}{dz}\right)_{fr}=\Phi_l^2\frac{2f_{lv,Go}[G(1-x)]^2}{D_e\rho_l}$ $\Phi_l^2=1+7.61X_{tt}^{0.79}$
Han and Lee [12] [symbol : ▲] $\left(\frac{dP}{dz}\right)_{fr}=\Phi_l^2\frac{f_l[G(1-x)]^2}{D_r\rho_l}$ $f_l=0.193\left[\frac{G(1-x)D_r}{\mu_l}\right]^{-0.024}\left(\frac{p}{e}\right)^{-0.539}$ $\Phi_l^2=2.684X_{tt}^{-1.946}$	Newell and Shah [5] [symbol : △] $\left(\frac{dP}{dz}\right)_{fr}=PF\Phi_{lo}^2\frac{2f_{lo}G^2}{D_e\rho_l}$ $\Phi_{lo}^2=1+(\Gamma^2-1)x^{1.75}(1+0.952\Gamma X_{tt}^{0.4126})$

the fin height of 0.15-0.2, the helix angle of groove of 15-25°, the diameter of 6.04-11.5 mm, and the mass flux of 69-878 kg/m^{2}s. Their data composed of six different working fluids like R22, R12, R134a, R32, R502, and R410A. According to their comparison, the Cavallini et al. [7] and the Kedzierski and Goncalves [3] showed 20% and 18% mean absolute deviation, respectively.

According to Han and Lee [12], the Newell and Shah [5] showed the best overall predicting performance for their experimental results. However, the best predicting correlation was varied as each tube type and refrigerant. Han and Lee's experimental data based on four different tubes with relative roughness from 1.3 to 3.3%, helix angle from 9 to 25, mass flux from 91 to 1110 kg/m^{2}s.

4. Effects of geometry, working condition, and refrigerants on correlations

Figure 1 shows the effect of geometry (fin height, spiral angle, number of fins) on the condensation frictional dP correlations. Censi et al. [15] observed the R134a condensation flow pattern of a microfin tube and reported that a stratified wavy flow pattern was detected at 100 kg/m^{2}s and a fully developed annular flow pattern was detected for mass flux greater than 400 kg/m^{2}s in a 7.69 mm inside diameter tube with 0.23 mm fin height and a 13° spiral angle. There-fore, the 100 kg/m^{2}s and 500 kg/m^{2}s mass fluxes were selected for the 8.92 mm diameter micro-fin tube to examine the effect of flow regime. All predicted values were for R134a at 40°C condensa-

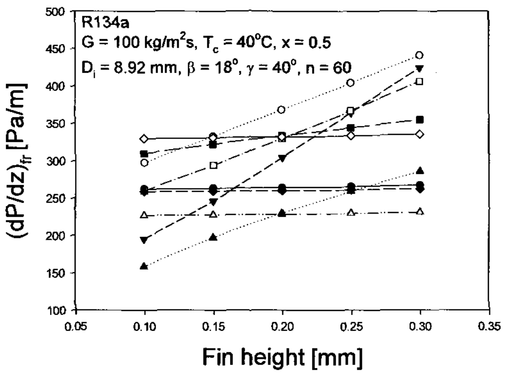

Fig. 1. (a) The effect of fin height on $(dP/dz)_{fr}$.

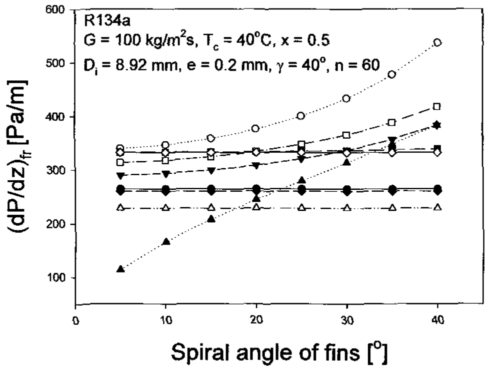

Fig. 1. (b) The effect of spiral angle on $(dP/dz)_{fr}$.

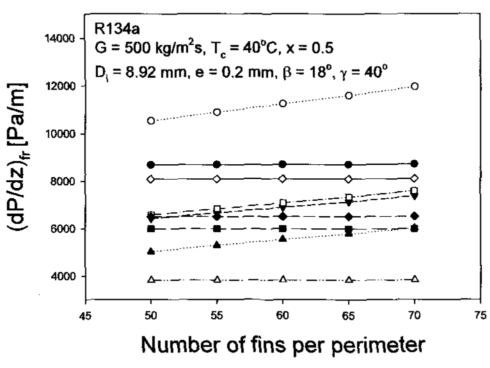

Fig. 1. (c) The effect of number of fins on $(dP/dz)_{fr}$.

tion temperature and 0.5 vapor quality. The Haraguchi et al. [1], the Newell and Shah [5], and the Goto et al. [11] correlations did not consider the geometry effect. Therefore, these correlations do not predict variation with geometry.

The effect of fin height on dP is shown in figure 1(a) at 100 kg/m^{2}s. The Kedzierski and Goncalves [3] correlation is the most sensitive to the fin height. The pressure drop that is predicted by their correlation at 0.3 mm fin height is over twice of that of 0.1 mm fin height. The sensitivity of the Kedzierksi and Goncalves [3] and the Cavallini et al. [7] correlations with respect to fin height increases at higher mass flux (500 kg/m^{2}s). This means that the effect of fin height varies with mass flux for these two correlations. The effect of spiral angle is demonstrated in Fig. 1(b). The Nozu et al. [2], the Choi et al. [10], the Kedzierski and Goncalves [3] correlations produce exponential pattern with spiral angle but the Han and Lee [12] show a linear tendency. The effect of number of fins per perimeter is shown in Fig. 1(c). The Nozu et al. [2], the Kedzierski and Goncalves [3], the Cavallini et al. [7], the Choi et al. [10], and the Han and Lee [12] correlations show linear increasing tendency with number of fins. There is no remarkable change of sensitivity as mass flux for the number of fins. Newell and Shah [16] reviewed the two-phase characteristics of microfin tubes and reported that fin height and spiral angle have a significant impact on the pressure drop in microfin tubes. According to their review, microfin tubes with 0.16 mm fin height had the same pressure drop as smooth tubes, while microfin tubes with 0.24 mm fin height increased pressure drop 1.6 times over that of a smooth tube. And there was no significant difference between 0 to 18° spiral angle. The Kedzierski and Goncalves [3] and the Choi et al. [10] correlations agree with the report by Newell and Shah [16] for the effect of spiral angle on ΔP. However, the effect of spiral angle is somewhat different from investigators. Newell and Shah [16] found no evidence for the effect of number of fins over common range (40 to 70 fins for 4 and 12 mm diameter microfin tubes). The apex angle may have a significant effect on surface tension, however, systematic research on apex angle has not been reported either. Therefore, the effect of apex angle is not shown in this study.

The effect of mass flux and vapor quality on the pressure drop penalty factor (*PF*) is shown in Fig. 2 (a) and Fig. 2(b). The *PF* is defined as the ratio of the dP between the microfin tube and the smooth tube at the same working condition (mass flux, condensation temperature, vapor quality) and the same maximum inside diameter. To evaluate the *PF*, the Müller-Steinhagen and Heck correlation for smooth tube [17] was used. Ould et al. [18] recommended the Müller-Steinhagen and Heck correlation [17] by comparing their collected smooth tube experimental data.

In Fig. 2 (a), the effect of mass flux on *PF* is shown.

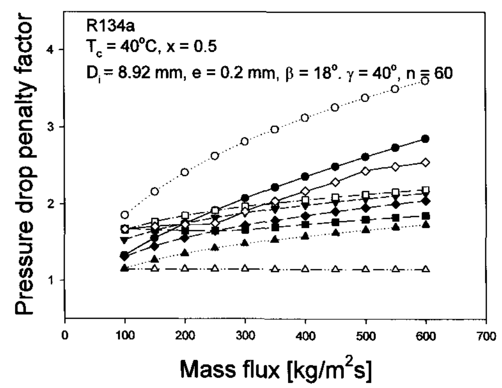

Fig. 2. (a) *PF* vs. *G*.

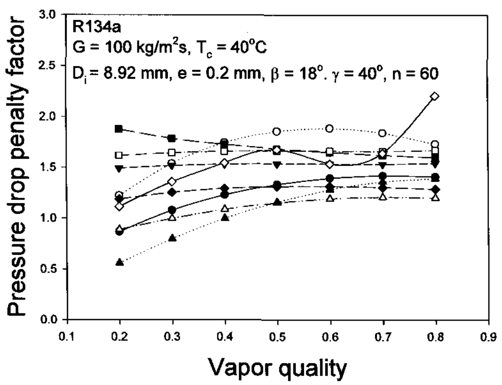

Fig. 2. (b) *PF* vs. vapor quality.

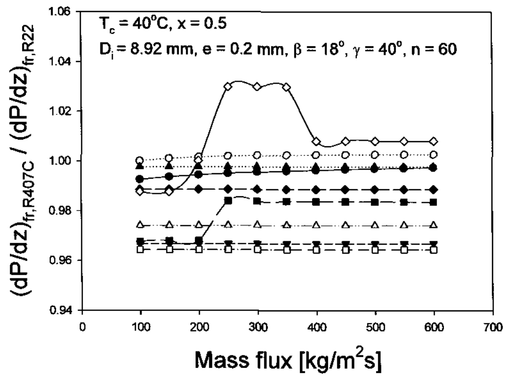

Fig. 3. The comparison of $(dP/dz)_{fr}$ between R407C and R22.

Cavallini et al. [19] and Eckels and Tesene [20] reported that the *PF* decreased with mass flux. However, all correlations except the Newell and Shah [5] correlation show an increasing tendency with mass flux. Figure 2 (b) shows the effect of vapor quality on the *PF* at 100 kg/m^{2}s. Eckels and Tesene [28] reported that the *PF* reduced with vapor quality. Cavallini et al. [19] reported that the *PF* increased with vapor quality at lower mass flux (100 kg/m^{2}s) but it decreased with vapor quality at higher mass flux (800 kg/m^{2}s). However, the Cavallini et al. [7] correlation shows a decreasing tendency at lower mass flux (100 kg/m^{2}s). The Kedzierski and Goncalves [3] and Choi et al. [10], and Goto et al. (a) [11] models show relatively small change with vapor quality. On the other hand, the Haraguchi et al. [2], the Han and Lee [12] and the Newell and Shah [5] correlations show increasing tendency with vapor quality at both mass fluxes (100 and 500 kg/m^{2}s). The Goto et al. (b) [11] correlation varies with fluctuations with vapor quality because the friction factor correlation varies with Reynolds number. Nozu et al. [2] correlation has the maximum *PF* at vapor quality is 0.5.

Figure 3 shows the comparison result between R22 and R407C. Eckels and Tesene [28] reported that R134a, R410A, and R407C had a 20-30% larger, 40% lower, and 10-20% lower pressure drop than that of R22, respectively. For R134a, all correlations except the Goto et al. (b) [11] predict over 20% larger pressure drop than those obtained for R22. For R410A, all correlations except the Goto et al. (b) [11] predict 25-35% lower values than those of R22. The predictions by Kedzierski and Goncalves [3], the Choi et al. [10], the Newell and Shah [5] correlations agree with the measurement trend of Eckels and Tesene [20] for R410A. For 407C, all correlations predict 0 to 4% lower values than those of R22.

5. Conclusions

The characteristics of the existing condensation pressure drop correlations for microfin tubes were investigated with vapor quality, mass flux, geometries, and refrigerants. Because of the physical flow complexity inside of microfin tubes, most pressure drop models show some incongruities with the previous measurements tendency. The Goto et al. [11], the Haraguchi et al. [1], and the Newell and Shah [5] pressure drop correlations did not consider the tube geometry effects like fin height, spiral angle, and number of fins. The effect of spiral angle was embodied well in the Kedzierski and Goncalves [3] and Choi et al. [10] correlations according to the report by Newell and Shah [16]. Except the Newell and Shah [5] correlation, pressure drop penalty factors of the other correlations increase with mass flux. This trend is conflicted to the measurements of Cavallini et al. [27] and Eckels and Tesene [28]. Pressure drop penalty factors that are predicted by the Goto et al. (b)

[11] correlation shows fluctuation with vapor quality. For R407C, all correlations produce 0 to 4% lower pressure drop than those of R22.

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