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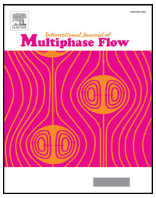

Frictional pressure drop correlation for two-phase flows in mini and micro single-channels

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ABSTRACT

1521 frictional pressure drop data points were collected from 12 literatures. The database included adiabatic and diabatic systems composed of 10 working fluids. The diameter range was from 0.1 to 3 mm, and the pressure drop ranged from 1.26 kPa/m to 2 MPa/m. 17 existing single channel two-phase pressure drop correlations including homogenous flow model and separated flow model were evaluated with the database. The comparison results showed that the correlations of Pamitran et al., Hwang and Kim, Mishima and Hibiki and Zhang et al. gave better predictions than the others. However, the performance evaluation results also showed the mean absolute errors higher than 40%. Based on the relatively large prediction error by the existing correlations, a new correlation was proposed by classifying the flow conditions into four regimes (namely, 1: gas laminar-liquid laminar, 2: gas laminar-liquid turbulent, 3: gas turbulent-liquid laminar, 4: gas turbulent-liquid turbulent). The newly developed correlation is expressed by a function of the two-phase Reynolds number, Re_{tp}, the two-phase viscosity number, $N_{\mu_{tp}}$, and the gas quality, x, and was able to predict the two-phase frictional pressure drop with the mean absolute percentage error of 17.4%. The correlation demonstrated an excellent performance for predicting the two-phase frictional pressure drop in mini/micro single channels.

1. Introduction

In the development of the electronic devices, the power density increases rapidly. The thermal management of the high power electronic devices is the bottleneck problem for the development sustainably. There are two restrictions for the electronic equipment evolving: how to cool down devices efficiently and how to cool down devices in compact spaces. In comparison with conventional air-convective-flow cooling with fins, compact heat exchangers show excellent performances on solving these two problems.

Compact heat exchangers are composed of mini/micro channels. Researchers have proposed the classifications of micro-channel and mini-channel. Mehendale et al. (2000) defined that the micro-channel and meso-channel ranges were from 1 to 100 µm and 100 µm to 1 mm, respectively. The range of the conventional channel diameter was defined as above 6 mm. In view of the single-phase and two-phase flow applications in compact heat exchangers, Kandlikar (2003) recommended that the ranges of micro-channel and mini-channel diameters were from 10 to 200 µm and 200 µm to 3 mm, respectively. This definition was proposed based on the smallest channel dimension in the channels. This simple criterion is used in the present study. Since the channel dimension has a significant effect on the bubble motion in two-phase flow, Cornwell and Kew (1993) proposed a classification method based on the confinement number defined by:

$$Co = \frac{\left[\frac{\sigma}{g(\rho_l-\rho_g)}\right]^{0.5}}{D} \tag{1}$$

where D, σ, ρ_l and ρ_g are, respectively, the hydraulic diameter of the channel, the surface tension, the liquid density and the gas density. Observed heat transfer and flow characteristics suggest that the flow characteristics changed around $Co = 0.5$. Hence, they proposed $Co = 0.5$ as the threshold value between the micro-channel and the conventional channel.

Heat transfer coefficient, pressure drop, flow distributions and other parameters are employed for evaluating the capabilities of the compact heat exchanger. Numerous researchers have studied on the heat transfer characteristics of the compact heat exchanger. For micro-channel and mini-channel heat exchanger, they con-

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Nomenclature

Bo	Bond number
Bl	Boiling number
C	Chisholm parameter
Co	Confinement number
D	Hydraulic diameter
e	Error between experimental value and predicted value
Fr	Froude number
f	Friction factor
G	Mass flow rate
g	Gravity force
La	Laplace number
MAPE	Mean absolute percentage error
ME	Mean error
MPE	Mean percentage error
N_{conf}	Confinement number
N_{μ}	Viscosity number
P	Pressure
PE	Percentage error
Re	Reynolds number
RMSE	Root mean square error
RMSPE	Root mean square percentage error
We	Weber number
x	Vapor quality
X	Martinelli parameter
z	length

Subscripts

crit	Critical condition
exp	Experimental
f	Fluid
g	Gas
l	Liquid
pre	Predicted
tp	Two-phase flow

Greek alphabet

β	Homogeneous void fraction
ε	Roughness
μ	Viscosity
ρ	Density
σ	Surface tension coefficient
$\emptyset^2$	Two-phase multiplier

ducted a lot of experiments, and developed numerous correlations for predicting the heat transfer coefficient in mini/micro channel heat exchangers. Qu and Mudawar (2003a, 2003b) studied the saturated flow boiling in micro-channel heat sink, and predicted the heat transfer coefficient. In their study, the heat transfer coefficient was predicted based on the annular flow pattern model. Their model captured the decreasing trend of the heat transfer coefficient at the low vapor quality range. Zhang et al. (2002) found that the region of the liquid-laminar and gas-turbulent was the general two-phase flow condition in the mini-channels. By considering the flow conditions with the factor, F, and the single-phase heat transfer coefficient, h_{sp}, they developed a new correlation which showed a good agreement with their database. Lee and Mudawar (2005) investigated the heat transfer characteristics of R134a flow boiling in the micro-channel heat sink. They found that the heat transfer alteration was associated with the flow mechanisms at different vapor quality ranges. A heat transfer correlation was developed based on their experimental results.

In practical applications, micro-channel heat exchanger is usually used with mini pumps. Pressure drop in the micro-channel may also cause hydrodynamic instabilities which would deteriorate the heat exchanger performance. Therefore, it is important to predict the pressure drop in compact heat exchangers. In order to predict the frictional pressure drop in the compact heat exchangers, the frictional pressure drop prediction in single channels is the fundamental procedure. In the present study, existing frictional pressure drop correlations of two-phase flow in single channels are first reviewed. These correlations include the homogenous flow model and the separated flow model. A frictional pressure drop database of two-phase flow in mini/micro single channels is established with 1521 data points. The data points are collected from 12 literatures, including the adiabatic and diabatic systems. The working fluids include R22, R134a, R410A, R290, R744, ammonia, nitrogen, water, R245fa and propane. The diameter range is from 0.1 to 3 mm, and pressure drop ranges from 1.26 kPa/m to 2 MPa/m. 17 frictional pressure drop correlations for single channels including the homogenous flow model and the separated flow model are evaluated with the database. Comparing the correlations with the database, the existing two-phase frictional pressure drop correlations do not show satisfactory performances. A new correlation is developed in the present study. The newly developed correlation is expressed by a function of the two-phase Reynolds number, Re_{tp}, the two-phase viscosity number, $N_{\mu_{tp}}$, and the gas quality, x, and was able to predict the two-phase frictional pressure drop with the mean absolute percentage error of 17.4%. The correlation demonstrates an excellent performance for predicting frictional pressure drop in mini/micro single channels.

2. Existing correlations

2.1. Homogenous flow model

The homogeneous flow model assumes the gas and liquid phases as two-phase mixture with no velocity difference (slip ratio is 1). The properties of the two-phase mixture are calculated with the gas quality and the properties of liquid and gas fluids. The two-phase frictional pressure drop based on the homogenous flow model is expressed by:

$$\left(\frac{dp}{dz}\right)_{tp} = f_{tp}\frac{2G^2}{D\rho_{tp}} \tag{2}$$

G is the mass flow rate, D is the hydraulic diameter, ρ_{tp} is the density of the two-phase mixture, and f_{tp} is the two-phase frictional factor. In the present study, the two-phase frictional pressure drop is calculated by the Churchill (1977) correlation with the two-phase flow Reynolds number as:

$$f_{tp} = 8\left[\left(\frac{8}{Re_{tp}}\right)^{12} + \frac{1}{(A+B)^{3/2}}\right]^{1/12} \tag{3}$$

where

$$A = \left\{2.457\ln\left[\frac{1}{\left(\frac{7}{Re_{tp}}\right)^{0.9} + 0.27\frac{\varepsilon}{D}}\right]\right\}^{16} \tag{4}$$

$$B = \left(\frac{37530}{Re_{tp}}\right)^{16} \tag{5}$$