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Correlations of two-phase frictional pressure drop and void fraction in mini-channel

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ABSTRACT

Alternative correlations of two-phase friction pressure drop and void fraction are explored for mini-channels based on the separated flow model and drift-flux model. By applying the artificial neural network, dominant parameters to correlate the two-phase friction multiplier and void fraction are picked out. It is found that in mini-channels the non-dimensional Laplace constant is a main parameter to correlate the Chisholm parameter as well as the distribution parameter. Both previous correlations and the newly developed correlations are extensively evaluated with a variety of data sets collected from the literature.

1. Introduction

In relation to many cutting-edge electronic chips, avionics, compact heat exchangers and bioengineering devices, mini-channel cooling technologies have attracted considerable attention in recent years. In comparison with single-phase flow, flow boiling is deemed as an optimum option to be applied in mini-channels in view of its extremely high heat transfer efficiency at the cost of small wall temperature rises. However, a penalty of flow boiling is the increased pressure drop and pressure fluctuation, which limit the applicable range of flow boiling in such devices. Therefore, a comprehensive understanding of pressure drop and void fraction during two-phase flow in mini-channel is of considerable practical importance for the design and performance evaluation of such cooling devices.

Starting from studies on adiabatic two-phase flow, extensive experimental and analytical efforts have been accumulated on characteristics of two-phase flow and/or flow boiling pressure drop in mini-channel. However, in regard to the applicability of existing correlations to mini-channel, there exist some discrepancies in the literature. Mishima and co-workers [1,2] extensively studied air/water two-phase flow pressure drop in rectangular and circular mini-channels with diameters ranging from 1 to 5 mm, and found that the separated flow model could well predict their data and the Chisholm's parameter C [3] was successfully correlated by the hydraulic diameter of channel. However, Triplett et al. [4] reported that for bubbly and slug flows at high Reynolds numbers the experimental two-phase frictional pressure drop data agreed reasonably well with the predictions of a homogeneous model with a mixture viscosity, whereas at low Reynolds numbers or for annular flow, both the homogeneous mixture model and Friedel's correlation [5] predicted the data poorly. In addition, Tran [6] measured two-phase flow pressure drop during a phase-change heat transfer process with three refrigerants (R-134a, R-12, and R-113) under pressures ranging from 138 to 856 kPa, and in two round tubes (i.d.: 2.46, 2.92 mm) as well as a rectangular channel (i.d.: 4.06 mm). They reported that correlations for conventional channels failed to predict their experimental data. In contrast, Kawahara et al. [7] investigated nitrogen/water two-phase flow in a quartz capillary with the inner diameter of 100 μm. They showed that the two-phase friction multiplier data were in good agreement with existing correlations for conventional channels.

To date, studies on void fraction in mini-channels are still limited. Experimental investigations on void fraction in mini-channel with diameters in the order of 1 mm, or smaller than that, were addressed in the literature [1,2,4,8–11]. Among them, Kariyasaki et al. [8] correlated their data in terms of the gas volumetric quality (or homogeneous void fraction), β. Moriyama et al. [9] measured void fractions during N_2–R113 adiabatic gas–liquid two-phase flow in extremely narrow channels with a clearance of 5–100 μm between

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Nomenclature

C	Chisholm parameter
C_0	distribution parameter
D_h	hydraulic equivalent diameter of flow channel
dp/dz	friction pressure gradient along channel axis
G	mass flux
j	superficial velocity
j_T	mixture volumetric flux, $j_g + j_f$
Lo^*	non-dimensional Laplace constant, $\{\sigma/[g(\rho_f - \rho_g)]\}^{0.5}/D_h$
p	pressure
p_{cr}	critical pressure
Re	Reynolds number, GD_h/μ_f
Re_f	liquid Reynolds number, $G(1 - x_{eq})D_h/\mu_f$
Re_{fo}	all-liquid Reynolds number, GD_h/μ_f
Re_g	gas Reynolds number, $G{\cdot}x_{eq}D_h/\mu_g$
v	velocity
V_{gj}	drift velocity
We_{fo}	Weber number, $G^2D_h/(\sigma\rho_f)$
X	Martinelli parameter
x_{eq}	thermodynamic equilibrium quality

Greek symbols

α	void fraction
ρ	density
σ	surface tension
ϕ^2	two-phase friction multiplier

Subscripts

cal	calculational value
exp	experimental value
F	friction
f	saturated liquid or liquid
fo	all flow taken as liquid
g	saturated vapor or gas
tp	two-phase

Mathematical symbol

exp	exponential function

horizontal parallel plates, and proposed a drift-flux type correlation to correlate their data. Later, Mishima and Hibiki [2], and Hazuku et al. [11] also reported that the measured void fractions could be successfully reproduced by the drift-flux type correlations. In contrast to this, Triplett et al. [4] claimed that homogeneous models provided the best predictions for their data in bubbly as well as slug flow regimes, and existing correlations significantly over-predicted void fractions in annular flow regimes.

Therefore, it is evident that although existing experimental works have revealed some unique phenomena in mini-channels, there is still no general theory or correlation available, and some discrepancies existing among the experimental results are not clarified yet. In view of this, as an extension of efforts by Mishima and co-workers [1,2] and a part of study dedicating to the development of a series of correlations for flow boiling in mini-channel [12,13], the purpose of this study is to summarize the previous studies on two-phase frictional pressure drop and void fraction in mini-channels, evaluate their applicability, and then propose alternative correlations for mini-channels.

2. Correlation development

2.1. Application of neural network

The artificial neural network (ANN) is an advance information processing techniques. The ANN is composed of elements analogous to the elementary functions of biological neurons [14,15]. One of the most important characteristics of the ANN is its capability to learn from trained data and to predict for new data. The back-propagation neural network (BPN) is one of the simple but powerful ANNs. Owing to its objectivity of judgment, the BPN is regarded as a powerful alternative to current techniques for the prediction of CHF [16] and the classification of flow regimes [17]. Since any functional relationship can be approximated by a BPN if the sigmoid layer has enough neurons [14], an architecture-fixed BPN (layer and neuron numbers fixed) can be utilized to carry out the input sensitivity (trial and error) analysis in order to select a set of non-dimensional numbers which could well correlate the two-phase frictional multiplier or void fraction. The BPN was trained under MATLAB environment. The TRAINCGP algorithm in the NEURAL NETWORK TOOLBOX of MATLAB was employed to train the network in this study.

2.2. Frictional pressure drop

In order to correlate the data for two-phase friction pressure drop, it is necessary to find out dominant experimental parameters related to two-phase friction pressure drop. The hydraulic diameter of channel, D_h, mass flux, G, pressure, p, and thermal equilibrium quality, x_{eq} (or their alternatives) are often considered as the related correlating parameters of local two-phase friction pressure drop (or its equivalence, the two-phase frictional multiplier). By combining physical properties with these experimental parameters, two-phase friction pressure gradient can be expressed in many non-dimensional forms. For instance, the correlations of Lockhart and Martinelli [18], Friedel et al. [5], and Zhang and Webb [19] employed different non-dimensional numbers. However, as demonstrated by numerous studies on two-phase friction pressure drop since the pioneering work by Lockhart and Martinelli in 1940s, the separated flow model is the most commonly used method [20]. The success of this model to correlate the existing data has demonstrated the usefulness of the Martinelli parameter, X, which is a combination of the inertial and viscous forces of both phases. Therefore, it may be deemed as one of the most dominant parameters to correlate two-phase friction pressure gradient for mini-channels. A widely used correlation to calculate the two-phase frictional multiplier is that proposed by Chisholm and Laird [21],

$$\phi_f^2 \equiv \frac{-(dp/dz)_{tp}}{-(dp/dz)_f} = 1 + \frac{C}{X} + \frac{1}{X^2}, \quad (1)$$

where Chisholm parameter C ranges in value from 5 to 20 for conventional channels, depending on whether the liquid and gas flows are laminar or turbulent. This successful performance of Eq. (1) has been shown in the literature [1,7,22,23]. However, the functional form of Chisholm parameter C needs to be clarified for mini/micro-channels. The dependence of the Chisholm parameter C on experimental parameters was made clear by the application of the BNP to the collected database. The output of the BNP is set to be the two-phase frictional multiplier, ϕ_f^2. The Martinelli parameter is set as one of inputs to the BNP. The mean deviation is used as a measure of predictive accuracy, defined as

$$\text{Mean deviation} = \frac{1}{N}\sum |(\phi_{exp} - \phi_{cal})/\phi_{exp}| \times 100\%, \quad (2)$$

where N is the data number. Based on the analysis of input sensitivity (trial and error method), it was found that the introduction of