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Experimental study on the flow boiling pressure drop characteristics in parallel multiple microchannels

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ABSTRACT

In this paper, the characteristics of flow boiling pressure drop had been experimentally investigated in a microchannel heat sink which contains 14 parallel 0.15 × 0.25 mm rectangular microchannels with hydraulic diameter of $D_h = 187.5\ \mu m$ by using deionized water as working fluid. The experiments were performed over a heat flux ranges from 5.38 to 116.89 kW/m^2 and mass flux ranges from 47.49 to 1267.80 kg/m^2 s. The inlet temperature was maintained constant and the outlet pressure of microchannels was about $p = 1.07$ bar. The experimental results revealed that the pressure drop exhibited a trend of slight decrease and then sharp increase with the increase of heat flux under constant inlet temperature and mass flux. Moreover, the mass flux, heat flux, and inlet temperature were of paramount important parameters for the variation of pressure drop. Because the ratio of heat to mass flux can approximately indicate the variation of outlet thermodynamic equilibrium quality, the effects of the heat to mass flux ratio and the outlet thermodynamic equilibrium quality on pressure drop were analyzed. It was found that the phenomena of the bubble growth, confinement, reversal flow and clearing away phenomena lead to the system instability. The pressure drop shows a trend of increasing oscillation intensity with the increasing vapor quality. The pressure drop correlations, which are available in open literatures for mini/microchannels, were evaluated on basis of the current experimental results. However, large deviations exist among them in terms of quantitative analysis of the pressure drop under the same working conditions. A new pressure drop correlation was modified from the Friedel correlation by combining both the ratio of liquid to vapor phase Fanning friction factor and the Weber number. The predicted results show good agreement with the experimental pressure drop. The MRE of the new correlation is 12.23%.

1. Introduction

With the increasing wide application of microchannels which demand for dissipating increasingly higher heat fluxes from electronic, power, and laser devices etc., flow boiling heat transfer through microchannels is one of the research hotspots in recent years due to their compact sizes and effective heat transfer. As a result of large specific surface area of the electronic devices nowadays, a higher heat transfer performance is expected comparing to the conventional ones [1]. It is anticipated that the surface tension of liquid will gradually be a vital factor with the decreasing channel scale. The bubble dynamics and pressure drop characteristics of this type of channel will be different from those of the conventional ones. Li and Wu [2] considered that the surface tension will gradually rise as the dominant role with the channel scale decreases. When the Bond number ($Bo \equiv g(\rho_l - \rho_g)d_h^2/\sigma$) within the range of $1.5 < Bo < 11$, surface tension, inertia force and viscous force are the equal important forces. When the Bond number is lesser than 1.5, the surface tension will be the dominant force and the inertia force and viscous force can be neglected at this situation, while the effect of surface tension can be ignored when the Bond number is higher than 11.

With the channel dimension decreases, the dominant mass force in conventional channel flow decreases, and the surface tension effects which can be neglected in conventional channel will gradually increase to a dominant force. Therefore, due to the increase of friction, a substantial increase of the total pressure drop in microchannel as well as a greater pump driving effort are required [1]. Currently, many researchers have studied the two-phase pressure drop of microchannels. Basically, the main method is based on modifying the parameter C in the Chisholm/Lockhart - Martinelli correlation by introducing some influencing factors or dimensionless parameters which can be applied to their specific

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Nomenclature

A	area, m^2
Bo	bond number, $g(\rho_l - \rho_g)D_h^2/\sigma$
C	Chisholm parameter
$c_{p,f}$	specific heat capacity of saturated liquid, J/(kg K)
D_h	hydraulic diameter, m
f	fanning friction factor
F	force, N
Fr	Froude number
G	mass flux, kg/m^2 s
I	heating electrical current, A
L	length, m
N_{conf}	confinement number, $\sqrt{\sigma/g(\rho_l - \rho_g)}/D_h \equiv Bo^{-0.5}$
p	pressure, kPa
Δp	pressure drop, kPa
P	power, kW
q	heat flux, kW/m^2
Re	Reynolds number
Su	Suratman number, $Su_{vo} = \rho_v \sigma D_h/\mu_v^2 = Re_{vo}^2/We$
t	time, ms
T	temperature, °C
U	heating voltage, V
We	Weber number
x	thermodynamic equilibrium quality
X^2	Lockhart-Martinelli parameter
σ	surface tension, N/m
η	heat supply efficiency
ρ	density, kg/m^3
Γ^2	physical property coefficient
ϕ^2	two-phase flow friction multiplier
μ	dynamic viscosity, N s/m^2

Subscripts

a	acceleration
back	back direction
c	cross section
cont	contractions
crit	critical parameters
eff	effective
exp	experimental
expa	expansions
f	frictional
forward	forward direction
g	gravity
in	inlet
l	liquid-phase
lo	full liquid phase
out	outlet
pred	prediction
sat	saturation
sp	single-phase
sub	subcooled
t	top platform
tp	two-phase
v	vapor-phase
vo	full vapor phase
w	upper-wall section

research conditions [3–11]. Since the surface tension and channel scale have great influence on the pressure drop characteristics in the micro/mini-channel, Li and Wu [2] have studied the pressure drop characteristics which covering 12 different fluids in single microchannel and multi microchannel. The surface tension gradually rise to a dominant role with the channel dimension decrease. Considering the effect of the surface tension and the channel scale, i.e. delimited by the Bond number, they developed a pressure drop correlation by modifying the Chisholm parameter C.

$$\begin{cases} C = 11.9Bo^{0.45}, & Bo \leqslant 1.5 \\ C = 109.4(Bo\ Re_l^{0.5})^{-0.56}, & 1.5 \leqslant Bo \leqslant 11 \end{cases} \tag{1}$$

They alleged that their correlation could effectively predict pressure drop under the condition of $Bo \leq 11$. When the Bo is higher than 11, the pressure drop could be effectively predicted by the method of Beattie and Whalley [12]. In addition, Li and Wu [13] further studied the pressure drop characteristic under the condition of $Bo \cdot Re_l^{0.5} \leq 200$. Two kinds of different pressure drop correlations which were demarcated by $Bo = 0.1$ were proposed. When $Bo < 0.1$, the Chisholm parameter C was modified as,

$$C = 5.60Bo^{0.28} \tag{2}$$

Although the Friedel [14] correlation had considered the effects of surface tension (Weber number, We) and gravity (Froude number, Fr) when $Bo \geq 0.1$ and $Bo \times Re_l^{0.5} \leqslant 200$, the indexes of the Weber number and the Froude number are very small. Therefore, it is difficult to express the dominated effects of the surface tension in microchannel. Whereas the Zhang and Webb [15] correlation was obtained by replacing the dimensionless parameter (density to viscosity ratio) of the Friedel [14] correlation to pressure ratio.

Meanwhile, the pressure drop not only reflects the change of flow resistance characteristics, but also dominates the occurrence of static and dynamic flow instability. Wu and Cheng [16] observed the phenomenon of large amplitude oscillation of inlet pressure in microchannel flow boiling experiment, while the outlet pressure basically remained stable. Similarly, Wang and Cheng [17] studied the variation of the static flow instability starting point (OFI) with the outlet thermodynamic equilibrium quality (x_{out}) in their parallel multi microchannel flow boiling experiments. There are other many similar researches on oscillation characteristics of pressure drop [18–21]. In addition, Lee et al. [22] reported that the flow instability, in the form of flow fluctuations, in an evaporative microchannel originates from the fact that a growing bubble in the narrow channel is severely confined and it expands both upstream and downstream simultaneously. After a very short moment, the liquid film in the elongated bubble may dry out and the bubble growth stops and lost the force to prevent fluid entering the channel as a consequence. Then, fresh liquid rushes into the microchannel and washes out the elongated bubble. When this process occurs repeatedly, the flow oscillation occurred. He et al. [23] also studied the pressure oscillation characteristics at the front and rear of the bubble in the process of bubble confinement. Because the occurrence of flow instabilities can cause pressure drop oscillations, it is possible to study the flow instability through the characteristics of pressure drop.

Firstly, in light of above literature reviewing, this paper analyzed the time averaged total pressure drop characteristics at different operation parameters. Then the bubble dynamics in channels has been analyzed through visual images. Moreover, the time domain and frequency domain characteristics analysis have been used to analyze the mechanism of pressure drop variation. Neglecting the effects of gravity (Froude number, Fr), the Friedel correlation [14] was modified by introducing other factors which can affect the two phase frictional pressure drop [3] (such as hydraulic diameter D_h, mass flux G, pressure p, thermodynamic