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Enhanced flow boiling in microchannels using auxiliary channels and multiple micronozzles (II): Enhanced CHF and reduced pressure drop

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ABSTRACT

Enhancing critical heat flux (CHF) of flow boiling without escalating pressure drop is highly desirable in thermal management of high power-density electronic devices. Usually, an improved CHF can be achieved by restricting flow or at a higher mass velocity, leading to a higher pressure drop. In this study, compared to the two-nozzle microchannel configuration, the improved microchannel configuration as detailed in the Part (I) of this study can enhance CHF without sacrificing pressure drop. In this part, CHF is experimentally evaluated together with the pressure drop with mass flux ranging from 120 kg/m^2 s to 600 kg/m^2 s. Compared to the two-nozzle configuration, our study shows that CHF can be enhanced up to 32% with a ~53% reduction of pressure drop at a mass flux of 325 kg/m^2 s. The bubble collapse-removal process is significantly improved because more micronozzles are integrated. The enhanced pumping effect, which is created by rapid bubble collapse processes in the entire main channels, enables a more sustainable liquid supply and hence delays the CHF conditions. Moreover, two-phase flow in terms of pressure drop fluctuations is more stable owing to the effective management of bubble confinement in the entire channel.

1. Introduction

Flow boiling in microchannels is one of the most promising cooling techniques for microelectronics [1]. Using latent heat by vaporization can significantly improve heat dissipation of high power density electronic devices. However, the vigorous and rapid generation of vapor through phase change leads to adverse two-phase flows in microchannels due to the well-known bubble confinement effect [2], which can lead to unfavorable two-phase flow instabilities in terms of low frequency and large amplitude of wall temperature and pressure drop/flow fluctuations. These could trigger premature CHF conditions and result in high pressure drop [2]. CHF and pressure drop are two of the most critical factors in evaluating flow boiling performance in two-phase microchannel cooling. Usually, it is highly desirable to enhance CHF without escalating two-phase pressure drop. Nonetheless, it is challenging to achieve this goal that appears conflicting. In last decades, numerous techniques have been developed to improve CHF by regulating bubble slugs [2,3], suppressing flow instabilities [4,5], modifying surface properties [6–11], and promoting liquid rewetting [12–15]. A comparison of experimental CHF data has been reported in our previous study [16]. The microchannels with inlet restrictors (IRs) have been proved to effectively delay CHF conditions by controlling vapor flow reversal, but the frequency of periodic bubbles/vapor slugs growth-collapse process is low [2].

Promotion of bubble collapse/removal can provide a more effective approach to regulate the two-phase flows in microchannels. Enhanced pumping effect, which refers to the high frequency periodic growth-collapse of bubbles/vapor slugs, can facilitate adequate liquid supply and eventually, delay CHF conditions.

In our previous study, a novel concept was developed by rapidly collapsing confined bubbles [17]. With this concept, CHF is enhanced by improving the liquid supply to main channels through rapid bubble-collapse-induced jetting flows and the resulting enhanced pumping effect [17,18]. However, the two nozzles located at the middle of each main channel cannot remove the elongated bubbles effectively in the entire channel, particularly, in the upstream. Thus, persistent vapor slugs were observed near the inlet region during the fully developed boiling. To address this issue, an improved design has been developed to extend the effect of high frequency jetting flows on bubble collapse/removal to the entire channel [19].

It would be highly desirable to enhance CHF without escalating two-phase pressure drop. Numerous techniques have been proposed to address this issue. These include using diverging channels

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Nomenclature

a	channel aspect ratio
A	area, m^2
C_c	parameter for exit effect
C_f	frictional coefficient
D	diameter, m
H	height, m
h_{fg}	latent heat of vaporization, kJ/kg
f	fanning friction factor, m
G	mass flux, kg/m^2 s
k_d	momentum correction factor, W/m K
L	length, m
$\dot{m}$	mass flow rate, kg/s
N	number of pin fins
Δp	pressure drop, Pa
P	power, W
S	slip coefficient
S_T	transverse pitch, m
u	velocity, m/s
$\bar{u}$	average velocity, m/s
W	microchannel width, m
z	coordinate, m

Greek symbols

α	void fraction
β	kinetic energy correction factor
γ	surface tension, N/m
θ	contact angle
μ	viscosity, kg/(s m)
ρ	density, kg/m^3
χ	vapor quality
σ_i	interfacial stress, N/m^2
τ	flow area contraction ratio

Subscripts

2ϕ	two-phase
acc	accelerational
c	cross section
CHF	critical heat flux
e	exit
eff	effective
exp	experimental
f	frictional
h	hydraulic
i	inlet
l	liquid
m	mixture
o	outlet
sat	saturated
v	vapor

[20,21], stepped fin microchannels [22] and taper channels [5,23]. However, these techniques did not consider rapidly removing the confined bubbles. Since the accelerational and frictional pressure drop would be elevated by the rapid bubble expansion, the management of bubble collapse/removal could be promising to reduce accelerational and frictional pressure drop. In our previous study, the two-nozzle configuration was shown to effectively remove the confined bubbles in microchannels [17], leading a significant reduction of pressure drop compared to the plain wall microchannel with IRs [2]. A further reduction of pressure drops owing to an efficient bubble removal has been demonstrated in our early study of the improved four-nozzle design [19] and will be further studied herein. A low collapse frequency of elongated bubbles and flow reversal due to vigorous vapor generation in conventional microchannels is the key factor resulting in an obvious increase of two-phase pressure drop compared to single phase flow at a specific flow rate [24].

Based on our previous studies in developing the two-nozzle microchannel configuration [16,17], an improved microchannel configuration with an aim at enhancing CHF without elevating pressure drop is developed in this study. The global liquid supply would be significantly improved owing to two more evenly-distributed nozzles in each main channel. Pressure drop would be effectively managed owing to increased bypass flow areas and the enhanced pumping effect induced by high frequency bubble growth-collapse processes.

2. Data reduction

2.1. Two-phase frictional pressure drop

Experimental frictional pressure drop ($\Delta p_{f,\exp}$) is deduced from the following equation [24]:

$$\Delta p_{f,\exp} = \Delta p_{total} - \Delta p_{acc} - \Delta p_i - \Delta p_o - \Delta p_{plenum} - \Delta p_{distributor} \quad (1)$$

where the total pressure drop (Δp_{total}) was measured by two pressure transducers at the pressure-drop measuring ports; $\Delta p_{distributor}$, Δp_{plenum}, Δp_i and Δp_o are the pressure drop of the flow distributor, pressure drop of the plenum chambers, inlet minor losses and exit minor losses, respectively. Accelerational pressure drop (Δp_{acc}) is given by:

$$\Delta p_{acc} = G^2\left(\frac{1}{\rho_i} - \frac{1}{\rho_{2\phi,o}}\right) \quad (2)$$

where mass flux is estimated from $G = \dot{m}/A_c$; and the density of the exit two-phase flow $\rho_{2\phi,o}$ is estimated by

$$\rho_{2\phi,o} = \alpha \cdot \rho_v + (1-\alpha)\cdot \rho_l \quad (3)$$

where ρ_l and ρ_v denote the densities of liquid and vapor, respectively; the density of inlet flow is assumed to be the density of liquid flow ($\rho_l \equiv \rho_i$), and α is the void fraction, which can be estimated by

$$\alpha = 1\bigg/\left(1 + \frac{1-\chi}{\chi}\frac{\rho_v}{\rho_l}S\right) \quad (4)$$

where S is the slip ratio, which is calculated based on Chisholm correlation: $S = \sqrt{1 - \chi\left(1 - \frac{\rho_l}{\rho_v}\right)}$ [25].

The inlet minor losses is estimated from the model developed in [26]:

$$\Delta p_i = \rho_l \frac{\bar{u}_{l,i}}{2}\,\frac{1 - \beta\cdot\tau^2\cdot C_c^2 - 2C_c + 2C_c\cdot K_d}{C_c} \quad (5)$$

The exit minor losses is calculated using an equation developed by Abdelall [26]:

$$\Delta p_o = \rho_v \frac{\bar{u}_{v,o}}{2}\left[\frac{1 - 2C_c\cdot\tau + \tau^2(K_d - 1)}{2} - (1-\tau^2)\right] \quad (6)$$

where the parameter (C_c) is given by Geiger [27]: