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Modeling of reversal flow and pressure fluctuation in rectangular microchannel

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ABSTRACT

Solving the flow instability in microchannel continues to be a topic of current research. In view of this, the current paper presents an analytical model to predict the pressure fluctuation by the analysis of bubble growth in a rectangular microchannel. To facilitate the analysis, bubble growth in the rectangular microchannel is assumed to be composed of three stages, namely, free growth, partially confined growth and fully confined growth. The interfacial velocity of bubble, being used to investigate the relationship between bubble reversal flow and pressure fluctuation, is determined by solving the conservation equations of the momentum of the liquid column coupled with the equations of the force balance at the bubble interface. The model reveals that when the length of fully confined bubble expands to some extent, the tail interface of bubble will reverse resulting in dramatically pressure increase. Additionally, the dependent factors, including Boiling number, nucleation site position, transverse shape and inlet restrictor, of pressure fluctuation are also analyzed based upon the current model, which denote that a smaller aspect ratio corresponds to a premature pressure fluctuation, and the magnitude of pressure fluctuation increases with the increasing Boiling number, decreases as the position of nucleation site moving downstream of the channel. In addition, the magnitude of pressure fluctuation decreases as the increase of pressure drop multiplier parameter, however, accompanied with the penalty of increasing pressure drop.

1. Introduction

With the rapid progress of MEMS and μTAS technology, flow boiling heat transfer in microchannels is widely applied due to their compact sizes and effective heat transfer through its high specific surface area. However, the main disadvantage of this approach to fabricate cooling devices is the flow instability characterized by pressure drop and reversing flow, which can lead to high amplitude temperature oscillations with premature critical heat flux (CHF) and mechanical vibrations. A number of studies provided evidence to the sensitivity of two-phase microchannel systems to flow instabilities. Oscillating pressure fluctuations and visualizations showing cyclical backflow were encountered in many experiments. Qu and Mudawar [1] have investigated hydrodynamic instability and pressure fluctuations in a water cooled two-phase microchannel heat sink containing 21 parallel 231×173 μm microchannels. They have identified two types of two-phase flow instability, namely, severe pressure oscillations and mild parallel channel instability. Wu et al. [2–5] reported two modes of two-phase flow instability in multi-parallel microchannels having a hydraulic diameter of 186 μm, i.e. the liquid/two-phase alternating flow (LTAF) and the liquid/two-phase/vapor alternating flow (LTVAF). Xu et al. [6] measured the dynamic unsteady flow in a compact heat sink which consisting of 26 rectangular microchannels with 300 μm width and 800 μm depth, and three types of oscillations were identified, i.e. large amplitude/long period oscillation superimposed with small amplitude/short period oscillation and small amplitude/short period oscillation. Thermal oscillations were always accompanying the above two oscillations. Wang et al. [7] investigated dynamic instabilities of flow boiling of water in parallel microchannels as well as in a single microchannel, and two types of unstable oscillations were reported, one with long-period oscillations and another with short-period oscillations in temperature and pressure. Bogojevic et al. [8] carried out a series of experiments to investigate pressure and temperature oscillations during the flow boiling instabilities in a microchannel silicon heat sink with 40 parallel rectangular microchannels. Their results revealed that two types of two-phase flow instabilities with appreciable pressure and temperature fluctuations were observed, that depended on the heat to mass flux ratio and inlet water temperature. These were high amplitude/low frequency and low amplitude/high frequency instabilities.

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Nomenclature

A	bubble projected area (m^2)
A^+	dimensionless area given by Eq. (27)
Bo	Boiling number
Ca	Capillary number
c_l	specific heat of liquid (J/kg K)
D_h	equivalent diameter of the channel (m)
f	Fanning friction factor
F_E	evaporation momentum force (N)
F_M	liquid inertia force (N)
F_σ	surface tension force (N)
g	gravitational acceleration ($m\ s^{-2}$)
H	height of microchannel (m)
H''	channel height subtracts liquid film thickness (m)
h_{lv}	latent heat of water (kJ/kg)
Ja	Jacob number
L	channel length (m)
M	pressure drop multiplier parameter
p	pressure (Pa)
p^+	pressure nondimensionalized by $\rho_{l,out}u_0^2$
Δp_f^+	frictional pressure drop nondimensionalized by $\rho_{l,out}u_0^2$
Pr	Prandtl number
q_{in}	heat flux (kW/m^2)
R_1, R_2	principal radii of bubble (m)
R^+	dimensionless radius given by Eq. (28)
Re	Reynold number
t	time (s)
t^+	dimensionless time defined as Eq. (35)
T	temperature (°C)
u	velocity (m/s)
u_0	initial liquid velocity in the channel inlet (m/s)
u^+	dimensionless velocity defined as Eqs. (15)–(17)

W	width of microchannel (m)
W''	channel width subtracts liquid film thickness (m)
We	Weber number
X_1	length of liquid column (m)
Z	bubble length (m)

Greek symbols

α	thermal diffusivity (m^2/s)
γ	aspect ratio of the channel
δ	liquid film thickness (m)
δ^+	dimensionless liquid film thickness defined as Eq. (31)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
ρ^+	dimensionless density defined as Eqs. (13) and (14)
σ	surface tension (N/m)

Subscripts

b	bubble
exp	channel expansion
f	friction
i	interface, initial
in	inlet
l	liquid
1	tail interface of bubble
2	nose interface of bubble
out	outlet
orf	orifice
s	saturation
v	vapor
w	wall

A number of researchers confirmed that the high amplitude/low frequency oscillation is attributed to the presence of flow reversal. Because of which reverse vapor flow in parallel microchannels will cause the flow mal-distribution, as vapor–liquid interface in each channel may temporally extend into different directions, either forward or backward [9]. Hetsroni et al. [10] observed periodic wetting and rewetting boiling in triangular microchannel heat sink, and the pressure oscillations coincided with the reversed flow. Chang and Pan [11] found that the magnitude of pressure oscillations may be used as an index for the appearance of reversed flow. Barber et al. [12,13] emphasized that the confined bubble growth can cause pressure fluctuations due to the reversed flow. Tuo and Hrnjak [14] revealed that reversed flow due to confined bubble longitudinal expansion caused periodic oscillations of the evaporator inlet pressure and the pressure drop based on simultaneous flow visualization and pressure measurements. Hence, preventing the reversed flow was crucial for the application of the flow boiling heat transfer in microchannels. Gedupudi et al. [15] concluded that the reversed flow can occur only if there exists upstream compressibility, i.e. a volume of trapped condensable or non-condensable gas or an expanding component such as a bellows. Generally, inlet header served as a buffer tank, providing significant compressible volume upstream of the heated microchannel tubes. Such volume may be able to intermittently retain and discharge the backflow vapor [16].

The two-phase flow stability is generally influenced by the boundary conditions. Preliminary experiments conducted by Brutin and Tadrist [17] indicated a strong dependence of the boundary conditions on the thermo-hydraulic behavior in the microchannel. Wang et al. [18] showed that the resistance associated with the configuration of the connections between the external circuit and the inlet and outlet plena influenced flow reversal as well as flow instability characterized by pressure fluctuation. In pursuit of the solutions to eliminate or mitigate the pressure fluctuation caused by the bubble reversal flow, many references have devoted the researches to this matter so far. Qu and Mudawar [19] placed a throttling valve upstream of the test module and increased the overall pressure drop to eliminate upstream compressible flow instability. Kosar et al. [20] fabricated 20 μm wide 400 μm long restrictors in the inlet of 200 μm wide microchannels to successfully eradicate flow oscillations. Subsequently, Kosar et al. [21] proposed a dimensionless parameter, M, accounting for the pressure drop increase imposed by the inlet restrictors, to correlate the extent of flow instability suppression, and revealed that the onset of unstable boiling in the microchannels asymptotically increased with M and upstream compressible volume instabilities were completely eradicated at sufficiently high M values.

Bergles and Kandlikar [22] were perhaps the first researcher to comprehensively discuss apparent flow instabilities in microchannels and suggested various means for suppression. In a latter study, Kandlikar et al. [23] experimentally investigated several methods to reduce the occurrence of flow instabilities in channels having hydraulic diameter of 333 μm by throttling valves and artificially drilled nucleation sites. It should be noted that, as mentioned by Kandlikar [24], the nucleation characteristics in the microchannel were crucial for bubble dynamics, pressure drop and etc. Because the microchannel interior surfaces were generally smooth due to the micro fabrication processes [25], resulting in the increase of nucleation wall superheat due to the absence of cavities of all sizes. Once boiling was triggered, the superheated liquid would readily change phase causing an explosive vapor growth and subsequently reversal flow. Therefore, in addition to placing the inlet restrictors,