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Rupture of thin liquid film based premature critical heat flux prediction in microchannel

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ABSTRACT

Accurate prediction of critical heat flux (CHF) is vital for the application and safety of compact heat exchanger with flow boiling in microchannel. In view of this, the current paper presents a criterion model to predict the premature CHF caused by upstream compressible volume instability (or flow reversal) in microchannel, i.e. the premature CHF is affirmed when the period of flow reversal is in excess of the maximum duration of the existence of the thin liquid film. Partial differential equation (PDE) for the thin film thickness is developed to analyze the transient characteristic of thin liquid film thickness, and film breakup occurs when the thin liquid film is evaporated to a critically low thickness. Mass-spring model is employed to predict the period of reversed flow with the upstream compressibility volume acting as the spring and the liquid column constituting the mass. Both of the maximum duration of liquid film existence and periodic flow reversal decrease with an increase of CHF, and increase with the increase of heat-to-mass flux ratio (or Boiling number). Premature CHF can be eliminated by increasing flow rate and pressure drop multiplier parameter, and the CHF increases with the increase of mass flux and the pressure drop multiplier parameter respectively. The periodic flow reversal model can satisfactorily predict the experimental oscillation periods with the maximum relative error of ±25%, and the CHF predicted by the current criterion is in possession of accuracies within the relative error of ±22.5%.

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, flow boiling in microchannel is a quite complex process with some limitations on its use. In particular, an upper operational limit on the heat flux is defined as the critical heat flux (CHF) condition, at which a wet-wall, high heat transfer coefficient operating condition transitions to a dry-wall, low heat transfer coefficient situation, resulting in the sudden increase of the heated surface temperature and possible failure of the devices. Therefore, the ability to predict CHF is of vital importance for safe operation.

The last decade has witnessed a very large number of experimental investigations [1–3] on critical heat flux during flow boiling through microchannels covering a wide range of geometry, physical dimensions, working fluids, and operating parameters. It has been observed that some trends (including mass flow rate, channel hydraulic diameter, subcooling, cross sectional aspect ratio of channel, etc.) of the variation of CHF have already emerged according to the expanse of the parametric range and variation, which has encouraged the researchers to try to predict CHF as a function of geometric and operational parameters as well as fluid properties. Such predictions can be made through correlations or modeling. In the endeavor of proposing correlations [1–3], often the researchers restrict themselves to limited data set, and it is found that different correlations give drastically different results for the same data set [1–3], which casts a doubt on the applicability of the correlation over a wider range, although in certain specific cases those correlations can provide more accurate results. Therefore, to extend the CHF correlations or models to different conditions with more confidence, mechanistic models of CHF for microchannel should be developed.

Kandlikar [4] developed a CHF model for pool boiling in microchannel based on the force balance among the evaporation momentum, surface tension, inertia and viscous forces at the contact line at the base of a bubble on the heater surface, which was expanded to flow boiling in microchannel by using the scale analysis [5] in consideration of five scaling parameters. Those scaling parameters should be determined from experimental data, resulting in this model could not be validated until a large number of CHF data in microchannels became available. An analogous

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Nomenclature

A	dispersion constant (J)
A_{cross}	cross-sectional area of channel (m^2)
Bo	Boiling number, Bond number
D_h	equivalent diameter of the channel (m)
f	frequency of pressure fluctuation (s^{-1})
h_{fg}	latent heat of water (kJ/kg)
L_l	liquid column length (m)
$\dot{m}_e$	rate of evaporation (kg/m^2 s)
m_x	mass flow rate of liquid at any section x (kg/m s)
p	pressure (Pa)
p_c	capillary pressure (Pa)
p_d	disjoining pressure (Pa)
q	heat flux (kW/m^2)
R	radius of curvature (m)
t	time (s)
T	temperature (°C)
u	velocity (m/s)
U_b	initial bubble velocity (m/s)
V_c	compressible volume (m^3)

Greek symbols

δ	liquid film thickness (m)
k_l	thermal conductivity, W m^{-1} K^{-1}
λ_c	critical wavelength (m)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ_{dryout}	Eq. (26)
τ_{period}	period of flow reversal (s)

Subscripts

b	bubble
C	critical
CHF	critical heat flux
i	initial
in	inlet
l	liquid
out	outlet
w	wall

situation was encountered in the model constructed by Kuan and Kandlikar [6], who used those underlying forces to represent CHF mechanism in microchannel. Revellin and Thome [7] proposed a theoretical model for the prediction of the critical heat flux under saturated stable conditions in uniformly heated, round micro-scale channels, on the basis of solving the conservation of mass and momentum equations along with the Young-Laplace equation and including the effect of the interfacial waves (i.e. the occurrence of Kelvin-Helmholtz type instability) during annular flow, and dry-out occurred when the film thickness became equal to the interfacial wave height during evaporation. When the parametric sensitivities of the model were studied, it was found that the CHF increases with an increase in diameter of the tube, which was contradictory to some other studies that have been conducted to study CHF in microchannels. Kosar [8] presented a simple model of CHF for saturated flow boiling based on simple algebraic relationships of mass and energy balance, in which complete evaporation of the liquid film gave rise to dry-out. The model was compared for a range of mini and microchannels (0.223 mm < D_h < 3.1 mm), of both round and rectangular cross section, for fluids like water and refrigerants (R123, R113, R134a, and R245fa), 151 experimental data covering a range of mass velocities from 50 to 1600 kg/m^2 s and pressure of 101–888 kPa. An overall mean absolute error of 25.8% was noted. Better prediction was obtained for channels with thin walls and, however, for flow without instability. In fact, the flow instability is very sensitive to be triggered-out for boiling in microchannels, and it is possible for a system to experience this low thermal performance region during its practical operation process, such as a starting and transient condition. However, influence of instability on CHF has not been emphasized in the above mentioned models.

Fortunately, in case of microchannel boiling, a huge number of the phenomena observations respected to flow instability [9] in general and CHF in particular has been generated within a small period of time, which can provide the impetus for the CHF mechanistic model development in microchannels. One of the earliest efforts to consolidate the nature of CHF in microchannels is due to Bergles and Kandlikar [10]. Based on the literature available at that point of time they have made a number of interesting observations, in which premature CHF [11] is prevailing in microchannel boiling flow due to the upstream compressible volume instability. The upstream compressible volume instability that accompanied with the presence of flow reversal [12] occurs when there is a significant compressible volume upstream of the heated section. This compressibility could be due to a volume of trapped condensable or non-condensable gas, an expanding component such as a bellows, or the presence of a large volume of degassed liquid upstream of the small microchannel [13]. As alleged by Bergles and Kandlikar [10], most of the available CHF data in the literature on microchannels suffered from this type of instability, and many research interests [14] are put on the premature CHF. Because the premature CHF values are lower than they would be if the channel flow were kept stable by an inlet restriction at the inlet of each channel [15]. Therefore, it is essential to construct a mechanistic CHF model that can take into account the influence of flow instability, and based on which one may deduce the relationship between the instability and premature CHF in microchannel and pursue the methods that can mitigate flow instability and improve CHF.

However, in the current status of this subject, a reliable mechanistic model specifically tailored to the premature CHF has not been developed yet. For this purpose, a mechanistic model, which is based on the rupture of thin liquid film (i.e. inception of dryout), has been proposed to predict the premature CHF arisen from the flow instability (or reversed flow) in microchannel.

2. Development of CHF model

As delineated in our previous study [16], general characteristics of bubble dynamics in the microchannel with high aspect ratio are divided into three stages subsequently, i.e. free growth, partially confined growth, fully confined growth. Once a nucleated bubble is developed, the growth period from the nucleation to the fully confined vapor bubble filling the microchannel cross-section is very short, and the appearance of flow reversal is at the stage of bubble fully confined growth. When bubble is at the stage of fully confined growth in the microchannel, it grows along axial direction resulting in the formation of elongated bubble. The growth of elongated bubble is mainly governed by the evaporation of thin liquid film around the bubble as asserted by Li et al. [17] who modeled the time rate of elongated bubble length by assuming that heat flux transferred by conduction from the wall was only used to phase change, and found that there was a good agreement between