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Investigation on critical heat flux of flow boiling in parallel microchannels with large aspect ratio: Experimental and theoretical analysis

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ABSTRACT

Critical heat flux (CHF) for microchannel heat sink makes significant sense to industrial applications in preventing thermal safety accidents and avoiding facility burnout. Nevertheless, the fundamentals of CHF in confined microchannels are lack of clear comprehension, and related visualization experimental data about CHF also needs complement. The present work explores flow boiling CHF in parallel shallow microchannel heat sink with visualization experiments, aiming to provide new CHF data for microchannels with large aspect ratio (AR = W/H = 5). Two test configurations (S1: $H = 400$ μm, $W = 2000$ μm, S2: $H = 300$ μm, $W = 1500$ μm) and two kinds of working fluids (ethanol and acetone) are adopted. By capturing bubble behaviors with high speed photography, the characteristics and mechanism of CHF for such shallow microchannels are revealed. It is found out that the boiling curve keeps a linear growth with the wall superheating degree after the local dry-out, where the dominate heat transfer mechanism directly transits to the film boiling without experiencing the transition boiling. Meanwhile, the effect of mass flux, working fluid, and hydraulic diameter of channel on the CHF is also studied respectively. The experimental results illustrate that the CHF in the microchannels with large AR is significantly influenced by flow instability and presents a third order polynomial increasing trend with G. Besides, statistic analysis on the CHF data with some well-known correlations is conducted to find out the suitable theoretical mode for the shallow microchannels. A new CHF correlation that can especially fit for the microchannels with aspect ratio heavily deviated from 1 is proposed, where 116 data points involving 8 different working fluids and 9 types of microchannels are verified with MAE of 7.3%.

1. Introduction

As is well known, critical heat flux (CHF) is the maximum heat flux before the occurring of a boiling crisis, which is triggered by a heavy deterioration in heat transfer. Usually, for the cases where the heat flux is the controlled variable, a sudden increase in the surface temperature can be observed and has been widely adopted as the index to detect the appearance of CHF. To practical industrial applications, such as the nuclear reactors, heat boilers, electronic cooling devices, steam generators, etc., an accurate prediction of CHF makes significant sense to prevent operating hazard and reduce equipment breakdown.

So far, numerous of researches with either experimental method or theoretical analysis have been conducted on the CHF. The experimental investigations about CHF focus on revealing the affecting factors, involving the working fluid [1,2], the inlet subcooling degree [3,4], channel size [5,6], critical pressure [7,8], mass velocity [9,10], surface preparation [11,12], and so on. Besides, since the mechanism behind the flow boiling CHF requires to be further exploited, most of the predictions of CHF still depend on the empirical correlations originated from experimental database.

Li et al. [13] experimentally and theoretically explored the critical heat flux during the flow boiling in silicon parallel microchannels (AR = W/H = 0.8), where the microbubble-excited high frequency two-phase oscillations were considered. They found out that the steady formation of vapor columns in the set auxiliary channels enabled an enhancement in CHF. To accurately reflect the CHF in parallel microchannels under the condition of two-phase oscillations, they established a semi-theoretical CHF model on the ground of energy conservation principles and the Helmholtz instability and Rayleigh instability theories.

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Nomenclature

A	heating area of test section, m^2
AR	aspect ratio, $AR = \frac{W}{H}$
a	nominal error range of a instrument
C	constant term in CHF correlation
Cp	specific heat, $kJ/kg{\cdot}K^{-1}$
D	diameter of microchannel, m
G	mass velocity, $kg/m^2\ s^{-1}$
g	acceleration of gravity, 9.81 m/s^2
H	height of channel, m
h_{fg}	phase transition enthalpy of the working fluid, $kJ/kg{\cdot}K^{-1}$
I	input current regulated byDC power supply, A
K	coverage factor based on the data distribution of a test parameter
k_{copper}	thermal conductivity of copper, $W/m\ K^{-1}$
L	length of channel, m
MAE	mean absolute error
N	amount of channel
n	total number of data points
Q_{input}	input heat load, W
q_{input}	input heat flux, W/m^2
q_{eff}	effective heat flux, W/m^2
q''_{CHF}	critical heat flux related to heating wall, W/m^2
T	temperature, K
U	input voltage regulated byDC power supply, V
V	volume flow rate, m^3/s
W	width of channel, m

Greek

ρ	density, kg/m^3
μ	viscosity, Pa·s
φ	heating efficiency
ω	uncertainty
δ	distance between the location of thermocouple and the bottom wall of channel, m
σ	surface tension, N/m
ΔT_{wall}	superheating degree of wall, K

Subscripts

v	vapor
l	liquid
c	characteristic length
h	hydraulic
th	threshold
m	sequence number of temperature
j	sequence number of repeated tests
p	predicted
e	experimental
$w.in$	inner wall
$w.out$	outer wall

Dimensionless numbers

Bo	Boiling number, $Bo = \frac{q}{Gh_{fg}}$
Co	Confinement number, $Co = \frac{\sqrt{\sigma/g(\rho_l-\rho_v)}}{D_h}$
Eo	Eötvös number, $Eo = \frac{g\cdot(\rho_l-\rho_g)L^2}{\sigma}$
Ga	convective confinement number, $Ga = Bo^{0.5}Re_l$
Re	Reynolds number, $Re = \frac{\rho\cdot u\cdot D_h}{\mu}$, u is the liquid velocity, m/s
We	Weber number, $We_L = \frac{G^2L}{\rho\cdot g}$, $We_D = \frac{G^2D_h}{\rho\cdot g}$

Agostini et al. [14] conducted series of CHF experiments for saturated R236fa in a silicon heat sink with 67 parallel microchannels ($AR = 0.328$), and their results illustrated that the raising of the mass velocity resulted in the increasing of the saturated CHF, and the inlet subcooling degree had a negligible impact on the CHF in such parallel microchannels. In addition, according to the comparison with their experimental data, the classic correlations for rectangular channels would over evaluate their CHF data whereas the predictive methods for circular pipes underestimated results.

By reviewing the researches on critical heat flux in microchannels, Bergles and Kandlikar [15] pointed out that the instability caused by the upstream compressible volume (Ledinegg instability) was not considered sufficiently or avoided effectively so that many available CHF data for the parallel multi-channels were possibly acquired under unstable boiling condition. That is to say, the acquired CHF was actually lower than that under the stable boiling condition. Furthermore, Kuan and Kandlikar [16] experimentally studied the effect of the pressure drop element (PDE) on enhancing the CHF by using a manifold at the inlet of each channel. Their experimental results confirmed their conclusion that the decreased CHF is owing to the disadvantage caused by the flow instability.

Previous researchers have made considerable contributions to the identification of micro- scale so as to clarify the distinctive features. For instance, Kew and Cornwell [17] defined confinement number Co and proposed 0.5 as the threshold value. Cheng and Wu [18] used boiling number Bo to divide the channel scales, i.e. Bo for microchannels should be <0.05. Moreover, Ullmann and Brauner [19] put forward that Eötvös number $Eo = 1.6$ could be used as the criterion to divide macro- and micro-channels, while Harirchian and Garimella [20] considered convective confinement number $Ga = 160$ ($Ga = Bo^{0.5}Re_L$) as the key threshold to define the micro-scale. Although there are kinds of classification methods for the microchannels, the consistent opinion is that the threshold for microchannel is closely associated with the bubble confinement as well as the properties of the working liquids, instead of just the hydraulic diameter D_h [21]. Particularly, for the channels with aspect ratio heavily deviated from 1, the geometric size in the width/depth direction might be extremely small that restricts the bubble growth and causes confinement [22]. In this case, researches on the flow boiling in the microchannels with different aspect ratios have become more and more popular since 2012. Nevertheless, among those related investigations, there are only fragmentary studies concerning about CHF, while the others mainly discuss about the bubble behaviors, flow pattern, heat transfer coefficient, two-phase pressure drop, etc.

Choi et al. [23,24] experimentally studied the effect of aspect ratio (AR from 1.09 to 6.25) on the flow pattern, pressure drop, and bubble behaviors in the adiabatic microchannels with water and nitrogen gas as the working fluids. They pointed out that the distribution of liquid film in the rectangular microchannel was not uniform, and the thickness of liquid film in the corner became even thinner along with the increasing of AR from 1.09 to 6.25, which without doubt leaded to obvious differences in bubble dynamics.

Markal and Aydin [25] investigated the saturated flow boiling performance of deionized water in the parallel microchannels with diverse aspect ratios (AR from 0.37 to 5.00), and the results indicated that $AR = 1.22$ was a threshold value for the heat transfer coefficient. Although the phenomena including the quasi-periodical rewetting/drying, bubble elongation, and flow reversal were all observed and discussed in Markal and Aydin's visualization experiments, the research on CHF in the microchannels,