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Local heat transfer in subcooled flow boiling in a vertical mini-gap channel

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ABSTRACT

An experimental study of subcooled flow boiling in a high-aspect-ratio, one-sided heating rectangular mini-gap channel was conducted using deionized water. The local heat transfer coefficient, onset of nucleate boiling (ONB), and flow pattern of subcooled boiling were investigated. The influence of heat flux and mass flux were studied with the aid of a high-speed camera. The bubbles were generated more quickly at higher heat flux and the diameters of departing bubbles decreased with increased flow mass flux. Partial dry-out and rewetting process caused by elongated bubble was also observed at lower mass flux. With the increase of heat flux, the surface near exit started boiling firstly, with more sharply increased heat transfer coefficient compared to the surface near entrance. The experimental heat transfer coefficients were analyzed using four existing correlations. The four correlations are all in an error band of −20% to +25%, and Chen correlation tends to have better performance at higher heat transfer coefficient.

1. Introduction

Highly efficient heat-dissipation system is of great importance to the operation, duration, and performance of high power components such as IGBT (Insulated-Gate Bipolar Transistor) chips. The conventional air cooled and water cooled heat exchangers are unable to meet the need of high heat-flux dissipation density due to the increased power consumption and decreased size of these devices [1]. Tuckerman and Pease found that the microchannel heat sink was a very promising solution for highly efficient heat dissipation in 1981 [2]. Higher heat transfer coefficient, better uniformity of temperature distribution, and lower mass flux as well as lower pump power required can be realized by utilizing phase change in the evaporators. Meanwhile, there is a variety of complicated problems in the microchannel, such as the instability of flow boiling, which imposes limitations on the application of two phase heat transfer in microchannels.

A comprehensive review about the research progress of the microchannel in recent two decades was given by Kandlikar [3]. He concluded that there is no distinct difference between the single-phase heat transfer in the microchannel and that in the classic macroscale channel. The divergences in the literature mainly existed in the two phase flow boiling. The bubbles generated by liquid boiling are confined in microchannels when the channel size is too small, which gives distinctly difference in the flow patterns, heat transfer, pressure drop, instability and critical heat flux compared with the macroscale channels. An author in this study [4,5] studied the heat transfer characteristics of evaporation in micro/mini-channels and presented a criterion, $Bo * Re_l^{0.5} = 200$ and $Bo = 4$ to define microscale flow boiling and macroscale flow boiling. This study's $Bo * Re_l^{0.5} < 200$ and $Bo < 4$ which is in microscale flow boiling region. Based on the criterion, correlations on pressure drop, heat transfer, and critical heat flux were developed [6–10] and adopted in Two-Phase Flow, Chapter 5 of "2012-2016 ASHRAE Handbook - Fundamentals".

There have been many experimental studies for the flow boiling in parallel microchannels, whose primary drawbacks are the flow instability and relatively high pressure drop. The bubbles generated in the narrow microchannel can expand in both axial and crosswise direction in the growth period compared to the parallel microchannels, which greatly improves the flow instability and reduces pressure drop penalties [11–13].

Meanwhile, the vast majority of the micro-channels studied in previous researches were geometries like circular tubes, trapezoidal, square and low aspect ratio rectangular micro-channels.

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Nomenclature

Bo	Boiling number, –
c_p	specific heat capacity, J kg^{-1} K^{-1}
f	friction factor, –
G	mass flux, kg m^{-2} s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
h_{lv}	latent heat of vaporization, J kg^{-1}
I	electric current, A
k	thermal conductivity, W m^{-1} K^{-1}
m	mass flux, kg s^{-1}
Nu	Nusselt number, –
p	pressure, Pa
Pr	Prandtl number, –
q	heat flux, W m^{-2}
Q	heat transferred, W
Re	Reynolds number, –
T	temperature, K
U	electric voltage, V
x	vapor quality, –

Greek letters

μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}

Subscripts

eff	effective
f	fluid
in	flow in
l	liquid phase
loss	loss
nb	nucleate boiling
out	flow out
sat	saturation status
sp	single phase
sub	subcooled status
v	vapor phase
w	wall
z	local

Investigations concerning micro-gaps or micro-channels with high aspect ratio have been very scarce. Closer attention to flow boiling in high aspect ratio micro-channels or micro-gaps should be paid in light of the potential of larger heat transfer surface and moderate pressure drop penalty.

In the work of Alam et al. [14], experiments were conducted to investigate the effects of mass flux and heat flux on flow boiling heat transfer performance and pressure drop characteristics in a silicon based micro-gap heat sink of different gap depths, 190 μm, 285 μm and 381 μm, using deionized water as the working fluid. The results indicated that higher heat transfer coefficient was achieved for micro-gap of smaller size and once the nucleate boiling began, confined slug and annular boiling dominated the heat transfer mechanisms in the micro-gap channel. For high heat fluxes, thin film evaporation occurred throughout the liquid-vapor interface which enhanced local heat transfer coefficients significantly due to confined annular flow.

In the work of Wang et al. [15,16], flow boiling heat transfer characteristics in rectangular microchannels with high width-to-depth aspect ratios of 10 or 20 were experimentally investigated using FC-72 and ethanol as the working fluids. Flow pattern visualizations and thermography measurements were conducted with channel hydraulic diameters of 571 μm, 762 μm and 1454 μm. Flow regimes comprised of onset of nucleation boiling, confined bubbly flow which rapidly developed to slug-annular flow followed by annular flow and wispy-annular flow accompanied with cyclical flow reversal and rewetting process were successively observed and analyzed for FC-72 and then extended to ethanol.

In the present study, experimental measurements and visualizations were carried out for the onset of nucleate boiling (ONB) and local heat transfer coefficient of subcooled flow boiling in the narrow mini-gap channel with deionized water as the working fluid.

2. Experimental method

2.1. Experimental apparatus

Fig. 1 shows the schematic of the flow boiling experimental setup. Before the boiling test, deionized water was fully degassed by long-time boiling. At the end of degassing, dissolved oxygen

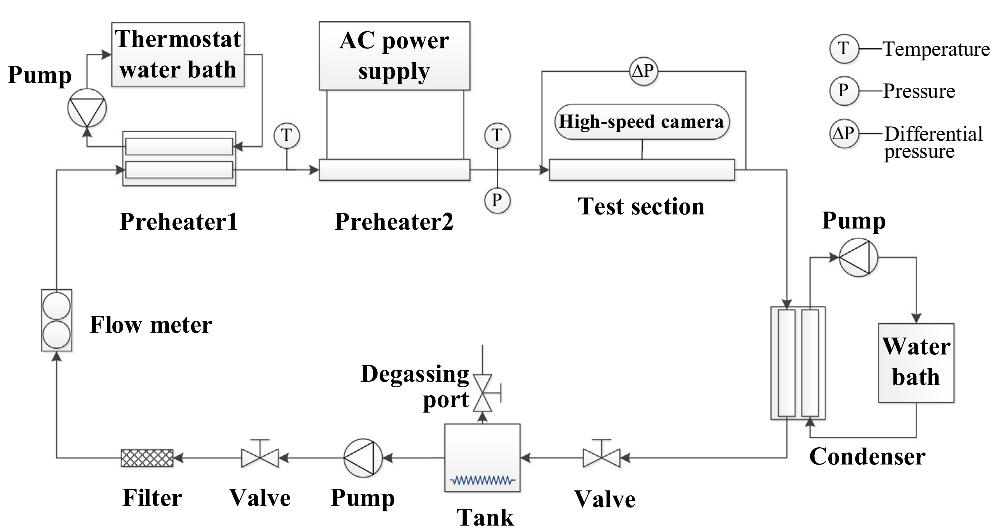

Fig. 1. Schematic of setup for flow boiling in mini-gap channel.