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Flow boiling in vertical narrow microchannels of different surface wettability characteristics

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ABSTRACT

An experimental investigation of saturated flow boiling in a high-aspect-ratio, one-sided heating rectangular microchannel was conducted with deionized water as the working fluid. The bare silicon wafer bottom surface of the microchannel was hydrophilic with a contact angle of 65° ± 3°, compared with the super-hydrophilic surface deposited by a thin film of 100-nm-thickness silicon dioxide through PECVD with a contact angle less than 5°. In experimental runs the mass fluxes were in the range of 120–360 kg/m^2 s, the wall heat fluxes were spanned from 4 W/cm^2 to 20 W/cm^2 and the inlet vapor qualities were varied from 0.03 to 0.1. Parametric study and flow visualization on pressure drop, local heat transfer coefficient, and flow pattern for surfaces of different surface wettability characteristics were carried out. Measured total pressure drops in single phase and two phase flow experiments agreed well with predicted values. The experimental data points were almost all located in the annular flow regime, and the local heat transfer coefficients approached a constant value and then increased towards the exit along the flow direction. According to flow visualization, the local dryout phenomenon occurred on the untreated hydrophilic surface at high heat fluxes for low mass fluxes, accompanied with deteriorative heat transfer performance, while it was not observed on the super-hydrophilic surface at the identical condition. Meanwhile severe heat transfer deterioration was obtained on the hydrophilic surface with increased inlet vapor quality, while the heat transfer coefficient of the super-hydrophilic surface was relatively constant which outperformed the untreated silicon wafer surface without increased pressure drop penalty.

1. Introduction

Many industrial applications such as high-power electronic devices, nuclear and conventional power plants, refrigeration and air conditioning systems, aerospace station, to mention a few, rely on boiling to transfer large heat fluxes across system boundaries [1]. Compared against single-phase fluid loops, better heat transfer performance can be attained at lower mass flow rates for heat sinks utilizing flow boiling at cost of increased pressure drop, accompanied with a more uniform distribution of surface temperature due to the constant fluid temperature in the two-phase regime [2].

Ribatski et al. [3] and Qu et al. [4] stated that microchannel heat sinks utilizing flow boiling outperforms conventional macroscale ones for the combination of higher surface area per volume and much higher heat transfer coefficients as well as minimal mass velocity. In recent years, an increasing number of micro-scale heat exchange devices are based on heat transfer through the phase change of liquid coolants in microchannels combined with various geometries and orientations [5]. Micro-channel flow boiling heat sinks which combine the attributes of high surface area to volume ratio, enhanced convective heat transfer performance and small coolant inventory constitute an innovative solution for cooling schemes of the high heat-dissipation requirement from a small area in sophisticated devices [6], which have been involved in a wide range of industrial applications such as the microfluidic system [7] and microelectronic technology [8].

Kandlikar [9] stated the divergences between heat transfer mechanisms of microchannels and classic macroscale in the two phase flow regime. The bubbles generated from boiling incipience of the liquid coolant on the superheated surface are confined between the surrounding walls with decreased channel

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Nomenclature

A	cross-section area [m^2]
C	Martinelli–Chisholm constant [–]
D_h	hydraulic diameter [m]
G	mass flux [kg/m^{2}Hangzhous]
h	heat transfer coefficient [W/m^2 K]
h	specific enthalpy [J/kg]
I	current [A]
J	superficial velocity [m/s]
L	length [m]
q	heat flux [W/m^2]
Q	heat [W]
T	temperature [K or °C]
U	voltage [V]
W	width [m]
x	vapor quality [–]
X	Lockhart-Martinelli parameter [–]
z	axial coordinate [m]

Greek symbols

$\triangle P$	pressure drop between inlet and outlet [Pa]
ρ	density of fluid [kg/m^3]
σ	surface tension [N/m]
ε	void fraction [–]
θ	inclination angle [°]
θ	contact angle [°]
$\emptyset_l^2$	two-phase frictional multiplier based on local liquid flow rate

Subscripts

eff	effective
l	liquid
i	local
in	inlet
mea	measurement
out	outlet
sat	saturation
tot	total
tp	two phase
v	vapor
w	wall
z	axial coordinate

dimensions, thus giving distinctly different regularities of the flow patterns, heat transfer, pressure drop, instability and critical heat flux from those in the macroscale channels. Li and Wu studied the heat transfer characteristics of evaporation in micro/mini-channels and presented a criterion, $Bo * Re_l^{0.5} = 200$ and $Bo = 4$ as transitions of flow boiling between the microscale and macroscale [10]. Based on the criterion, correlations for pressure drop, heat transfer, and critical heat flux in the microscale were developed [11]. Thome et al. [12,13] investigated the influence of confinement number on the two-phase flow regimes and liquid film distribution in a single circular horizontal channel. They proposed a new macro–microscale transition flow pattern map, which postulated the lower threshold of macroscale flow is Co = 0.3–0.4 while the upper threshold of symmetric microscale flow is Co $\geqslant$ 1 while the transition (or mesoscale) region locates in-between [12]. Furthermore, a new CHF (critical heat flux) correlation was also developed which accounted for the macro-microscale confinement and the viscous interfacial shear effects on CHF [13]. At the same time attention has been paid to study the influence of micro/nano-scale fabricated surface on heat transfer enhancement. The Buongiorno group at MIT investigated the separate effects of surface characteristics such as hydrophilicity, porosity and roughness on CHF, and found that large CHF enhancement can be obtained with textured surfaces that produce strong wicking of liquid to the surface [14]. They also observed that CHF maxima can be obtained depending on the geometric characteristics of the surface structures, such as thickness of the porous layer and size of the pores which determined the competition between conduction heat transfer within the porous layer, as well as capillary wicking, viscous pressure drop and evaporation [15], or spacing and size of the micro-pillars which influenced characteristic dry spot heating and rewetting timescales during boiling crisis [16]. Mechanistic models were also developed to explain those CHF maxima capturing the geometrical parameters while provided guidelines for further optima [15,16].

While in macroscale channels inertia and buoyancy forces have determined effect on the flow structures and hydraulic and thermal transport process, the surface tension and surface characteristic parameters such as surface porosity, roughness, and wettability are just of the same importance in the microchannel. In the meantime micro/nano-scale surface modification techniques which structure the heat transfer surface with higher surface area to volume ratio and nucleation sites, can effectively change all the surface characteristic parameters including surface roughness, wettability and porosity simultaneously. Design and optimization of the microchannel heat sinks and surface modification methods have been emerging in recent years, both of which intend to pursue low boiling incipience superheat, high heat transfer coefficient under practically applied heat fluxes, and high critical heat flux [14–17]. Thus the combination of surface micro/nano-structures and microchannel heat sinks may promise a much better heat transfer performance at cost of minimal pressure drop increment compared to untreated surfaces without apparent changes in the surface topography.

Most experimental investigations presented in the literature so far, concern micro/nano-scale structured surfaces focusing on microscale structures such as micro-roughness, micro-cavities and micro-porosity for heat transfer enhancement [18–21]. However, the underlying physical mechanisms as for how micro/nano-scale structures enhance HTC (heat transfer efficient) and CHF are still not well understood. Meanwhile, the effect of surface wettability on the aforementioned performance of the various modified boiling surfaces has been studied in part of prior work [17,22–28].

Generally speaking, a latish ONB (onset of nucleate boiling) and suppressed heat transfer performance at low heat fluxes coupled with high CHF values can be attained on homogeneously hydrophilic-wettability boiling surfaces [17], which are featured by contact angle $\theta < 90°$. On the contrary, earlier establishment of boiling incipience results in higher heat transfer coefficients at low heat fluxes for uniformly hydrophobic-wettability surfaces with a contact angle $\theta > 90°$, while pronounced bubble coalescence accompanied with formation of a blocking vapor film surrounding the superheated surface can cause lower CHF values.

In the experimental work of Rioboo et al. [22], the heated surfaces were partially chemically grafted with alkylsilane SAMs (self-assembled monolayers) by micro-contact printing, forming SAM patterned hydrophobic zone against the rest hydrophilic part. It was observed that the density of nano-bubbles nucleated on the