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Effects of heat flux, mass flux and two-phase inlet quality on flow boiling in a vertical superhydrophilic microchannel

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ABSTRACT

Saturated flow boiling experiments were conducted to investigate the influence of surface wettability on the hydraulic and thermal transport performance in a large width-to-height aspect ratio, one-sided heated rectangular microchannel with deionized water as the working fluid. The contact angles of the bare silicon wafer surface and superhydrophilic surface after deposited by a thin film of 100-nm-thickness silicon dioxide were 65° ± 3° and less than 5° respectively, both of which were utilized as heated surfaces of the microchannel. Parametric experimental studies were carried out with the inlet vapor quality varied from 0.03 to 0.1 and the wall heat fluxes spanned from 4 W/cm^2 to 20 W/cm^2, at various mass fluxes ranging from 120 to 360 kg/m^2 s. High speed flow visualizations were conducted coupled with instrumental measurements to illustrate the effects of heat flux, mass flux and two phase inlet quality on the local heat transfer coefficient, averaged heat transfer performance, two phase flow structure and pressure drop characteristics for surfaces with distinct surface wettability characteristics in the microchannel. Experimental results showed that the local heat transfer coefficient decreased first until approaching a minimum value and then increased towards the exit along the flow direction. Severe heat transfer deterioration was obtained for the bared silicon wafer surface with increased inlet vapor quality and heat flux, resulting from the local dryout phenomenon as can be verified by the flow visualization. While the heat transfer performance of the superhydrophilic surface was relatively constant due to continuous and uniform distribution of the thin liquid film on the heated surface during annular flow dominance and subsequent delay to partial dryout occurrence, which outperformed the untreated hydrophilic surface without additional pressure drop penalty.

1. Introduction

Over the last few decades, for improving the functionality and signal speed of electronic devices, electronic components have been miniaturized and an increasing number of elements have been packaged in the device. As a result there has been a steady rise in the amount of heat necessitated to be dissipated from the electronic device [1]. Nevertheless, conventional air cooling and liquid coiling are proved to have limited capability to dissipate such high power densities meanwhile protect the device from burnout [2]. Faced with these challenges, recently high performance cooling schemes, such as jet impingement, spray and microchannel heat sink have emerged as phenomenal thermal management solutions for next generation high power electronic devices.

Investigations on microchannel heat sinks utilizing flow boiling have been intensively performed for the past decade, mainly focused on extensive aspects including two phase flow instability, heat transfer, pressure drop, critical heat flux and flow structure combined with various channel geometries and orientations [3,4]. The primary merits of two-phase microchannel heat sinks are attributed to minimal coolant inventory and occupied volume, extremely high heat transfer coefficient and better stream-wise temperature uniformity compared against single-phase loop cooling schemes [5,6], which are closely associated with rapid fluid acceleration along the flow channel and close proximity of the liquid-vapor interface to the heated surface [1]. These advantages render the two-phase microchannel heat sink very suitable to constitute an innovative solution as cooling schemes for heat dissipation requirement involved in a wide range of industrial

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Nomenclature

A	cross-section area [m^2]
D_h	hydraulic diameter [m]
G	mass flux [kg/m^2 s]
h	heat transfer coefficient [W/m^2 K]
h	specific enthalpy [J/kg]
I	current [A]
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 [–]
z	axial coordinate [m]

Greek symbols

ΔP	pressure drop between inlet and outlet [Pa]
θ	contact angle [°]

Subscripts

l	liquid
i	local
in	inlet
mea	measurement
out	outlet
sat	saturation
v	vapor
w	wall
z	axial coordinate

applications such as the high-performance microprocessors, Micro-Electro-Mechanical Systems (MEMS), microfluidic system and compact heat exchangers [7,8].

Saturated flow boiling in microchannels are not as well understood as the hydraulic and thermal transport characteristics of those in macroscale channels [9], the complex nature of which has impeded the practical implementation of the microchannel heat sink utilizing phase change [10]. In the experimental work of Markal et al. [10,11], effects of the aspect ratio and hydraulic diameter on the saturated flow boiling characteristics in parallel microchannels were investigated, where simultaneous flow visualizations were also conducted, recovering the quasi-periodical rewetting and dryout process during the rapid growth and elongation of bubbles confined in microchannels [11]. Their study was followed up by a comparison with various existing macro and mini/micro channel correlations and a new correlation based on thermos-physical parameters, related dimensionless parameters and aspect ratio was proposed [12]. In the review of Kandlikar on research progress for heat transfer in microchannels [13], it was concluded that divergences between heat transfer mechanisms of microchannels and that of conventional macroscale channels were mainly located in the two phase flow regime. Once boiling incipience is initiated, the bubbles nucleated on the superheated surface are confined and elongated between the surrounding walls with decreased channel dimensions, thus giving distinctly different regularities of the flow pattern, heat transfer, pressure drop, flow instability and critical heat flux from those of conventional channels. The author's group performed an in-depth investigation on the heat transfer characteristics of evaporation in micro/mini-channels and presented a general criterion, $Bo * Re_l^{0.5} = 200$ and $Bo = 4$ to classify flow boiling between the microchannel and conventional channel [14]. Based on the criterion, they further developed general correlations to predict the heat transfer performance of saturated flow boiling and CHF in micro/mini-channels [15,16]. As for flow instability, flow boiling instabilities play a crucial role in the deterioration of microchannel heat transfer performance [11] and surface non-uniformities [17]. It was summarized that possible reasons causing flow stability were rapid bubble growth and expansion, inlet compressibility effect and channel surface characteristics [18,19]. Nevertheless, some techniques has been reported to reduce/eliminate flow instabilities, such as inserting flow restrictors at the channel inlet, using channels with a diverging/expanding cross sectional area [18,20] or introducing artificial nucleation sites [19].

Meanwhile, the vast majority of studies on microchannels conducted in the literature were of channel geometries like circular tube, multiport parallel trapezoidal, square or low width-to-depth aspect ratio rectangular microchannels [21]. Researches regarding the micro-gap or single micro-channel with high width-to-depth aspect ratio have been very scarce. More attention to flow boiling in such channels should be paid in view of the potential of larger heat transfer surface to cross sectional area ratio and moderate pressure drop. Tamanna et al. [22] carried out experiments to investigate effects of the flow velocity and heat flux on the heat transfer performance and pressure drop characteristics of flow boiling in a silicon based microgap heat sink with various gap depths. From experimental results it was found that as the gap depth decreased, augmented heat transfer coefficient was obtained and once the nucleate boiling was initiated, the heat transfer mechanism in the microgap channel was dominated by confined slug and annular flow boiling. Thin film evaporation occurred throughout the liquid-vapor interface with increased heat fluxes, which improved the local heat transfer process significantly as a result of confined annular flow.

By now, heat exchange surfaces engineered for boiling heat transfer enhancement are fabricated to explore various boiling heat transfer mechanisms. Although remarkable boiling heat transfer improvement has been reached, the existing physical understanding of bubble dynamics and liquid-vapor interface movement is not adequate to explain the achieved enhanced heat transfer performance during vigorous boiling [23]. While buoyancy and inertia forces have crucial influence on the flow structure and corresponding hydraulic and thermal transport process for conventional channels, the surface tension and surface characteristic parameters such as surface wettability, porosity and roughness are just as important in microscale channels. Among the large quantities of surface modification methods, attention has been paid to study the effect of micro/nano-scale fabricated surface on heat transfer enhancement to pursue low initial superheat of nucleate boiling, high heat transfer coefficient under practically applied heat fluxes, and high critical heat flux [24]. The combination of microscale channels with micro/nano-structured surfaces may promise a much better heat transfer performance at cost of minimal pressure drop increment compared against untreated ones, without changing the surface topography apparently.

The surface wettability effect on the heat transfer and pressure drop performance of various modified surfaces fabricated for boiling enhancement has been investigated for some prior researches [24–28]. It was speculated that the discrepancy of flow patterns observed in various channels was caused by different surface wettability, resulting in distinct boiling flow phenomena [25]. In the experimental work of Choi et al. [26], water flow boiling in