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Influence of heating surface characteristics on flow boiling in a copper microchannel: Experimental investigation and assessment of correlations

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ABSTRACT

Experiments were carried out to investigate the effect of surface characteristics on flow boiling heat transfer and pressure drop in a microchannel using degasified and deionized water as the working fluid. Test section consists of a 40 mm long, 0.5 mm wide and 0.24 mm deep microchannel machined in copper. Experimental results are reported for three different surface characteristics – fresh machined surface (case-1), the same channel surface when aged after repeated experimentation (case-2) and the surface obtained after cleaning the same aged surface with 0.1 M hydrochloric acid (case-3). Parameters considered include inlet temperature 95 °C, mass flux from 1000 to 2220 kg/m^2 s and heat flux from 400 to 1200 kW/m^2. Single-phase experiments have been performed to estimate the heat loss from microchannel and also to validate the experimental setup. The results indicate that the boiling heat transfer performance of case-2 is lower than that of case-1 and the performance of case-3 is higher than that of case-1. The main reason behind the reduction of two-phase heat transfer coefficient for case-2 as compared to case-1 is attributed to the increased wettability due to the thermal oxidation of the heating surface caused by the repeated experimentation. The enhanced boiling performance of case-3 is attributed to the increased nucleation site density. However, the change in the two-phase pressure drop is relatively small. The experimental results were compared with the available correlations in the literature to check the predictability of the correlations for the three cases. The degree of agreement (or disagreement) varies depending on the correlation and the surface characteristic. The reasons for the deviations are discussed.

1. Introduction

High-performance power electronic devices exceed their safe operating temperature limits if the large amount of heat generated by these devices is not effectively dissipated. Thermal management of high heat flux devices such as high-performance computer chips, laser diode etc needs the dedicated cooling technologies to run these devices more efficiently. Sustainability of microelectronic industry depends on the promising innovative and advanced cooling technology that will meet the future requirement of thermal management of these electronic packages. Microchannel heat sinks which make use of flow boiling heat transfer has the potential to remove the heat fluxes in the range 30–100 W/cm^2 with acceptable surface temperatures.

Recent studies by Kuznetsov and Shamirzaev [1], Wang and Sefiane [2], and Karayiannis and Mahmoud [3] are aimed at better understanding of the effects of heat flux, mass flux, vapor quality and channel hydraulic diameter on the flow boiling heat transfer in a microchannel. Heating surface characteristics play an important role in microchannel flow boiling. Many researchers have contributed to the understanding of the effect of surface characteristics on the boiling heat transfer (Mahmoud et al. [4], Wang and Dhir [5], Thome [6], Kandlikar [7], Jone and Garimella [8], Alam et al. [9], and Jafri et al. [10]). Several factors influence the flow boiling heat transfer in a microchannel. Surface roughness and wettability are the two major factors that constitute surface characteristics which affect the performance of the boiling greatly [5]. The first part of the literature presented in this section deals with the influence of surface roughness on the boiling behaviour and the latter part focuses on the influence of surface wettability and oxidation.

It is very well known that the surface roughness has a major influence on nucleate boiling heat transfer in pool boiling system or flow boiling system. A study by Hsu et al. [11] was the earliest one that presented the influence of surface roughness on boiling

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Nomenclature

a	width of the channel, m
b	height of the channel, m
Bd	Bond number, $Bd = g\Delta\rho D^2/\sigma$
Bo	Boiling number, $Bo = q/Gh_{fg}$
C_p	specific heat, J/kg K
C	Chisholm constant
Co	confinement number, $Co = (\sigma/g\Delta\rho)^{0.5}/D_h$
D_h	channel hydraulic diameter, $D_h = 2ab/(a+b)$, m
E	convective boiling enhancement factor
F_{fl}	fluid dependant parameter
f	Fanning friction factor
g	gravitational acceleration, m/s^2
G	mass flux, kg/m^2 s
h	heat transfer coefficient, W/m^2 K
h_{fg}	latent heat of vaporisation, J/kg
I	heater current, A
k	thermal conductivity, W/mK
L	length of the channel, m
$\dot{m}$	mass flow rate, kg/s
M	total number of data point
M_W	molecular weight, kg/kmol
MAE	mean absolute error
Nu	Nusselt number, $Nu = hD_h/k$
N_{co}	convection number, $N_{co} = \left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}$
P	pressure, Pa
P_r	reduced pressure
Pr	Prandtl number
ΔP	pressure drop, Pa
q	heat flux, W/m^2
Q	heat rate, W
R_a	arithmetic mean roughness, µm
R_q	root mean square roughness, µm
R_z	average distance between highest peak and lowest valley, µm
R_t	maximum height of the profile = $R_p + R_v$, µm
R_p	maximum valley depth, µm
R_v	maximum peak height, µm
Re	Reynolds Number
S	nucleate boiling suppression factor
T	temperature, K
ΔT_{sat}	channel wall super heat
V	heater voltage, V
v	specific volume, m^3/kg
We	Weber number, $We = G^2D_h/\rho\sigma$
x	thermodynamic equilibrium quality
X	Martinelli parameter
z	distance, m

Greek symbols

ρ	density, kg/m^3
μ	viscosity, kg/ms
α	channel aspect ratio = b/a
α_o	void fraction
σ	surface tension, N/m
φ	two-phase multiplier

Subscripts

a	ambient
app	apparent
ch	channel
CBD	convective boiling dominant
exp	experimental
f	friction component
fd	fully developed
$fd,3$	fully developed, 3-sided heating
$fd,4$	fully developed, 4-sided heating
g	vapour
g_o	all vapour only
h	hydraulic
i	channel inlet
lo	all liquid only
l	liquid
nb	nucleate boiling
NBD	nucleate boiling dominant
o	channel outlet
$pred$	predicted
p,i	plenum inlet
r	reduced
sat	saturated
sp	single-phase
sub	sub-cooled
tp	two-phase
tw	thermocouple below the channel bottom
vv	laminar–laminar
tt	turbulent–turbulent
vt	laminar–turbulent
tv	turbulent–laminar
w	wall

heat transfer and suggested the model to predict the cavity size required to nucleate bubble on a surface. For the past three decades, the focus has been on understanding the effect of surface roughness and the methods of enhancing the boiling heat transfer. Of late, there have been attempts to enhance the heat transfer in mini/microchannels using augmentation techniques and surface coating techniques. The level of enhancement has increased to 1.5 to 3 times the heat transfer on a bare machined surface [12].

Jone and Garimella [8] carried out flow boiling heat transfer experiments with water in three-different microchannel surfaces, which were fabricated by two different methods, namely saw-cutting and electrical discharge machining (EDM) process. The method of fabrication of the channel influences the surface roughness. The EDM surfaces ($R_a = 3.9$ µm and $R_a = 6.7$ µm) have shown notably higher heat transfer coefficients than the saw-cut surface ($R_a = 1.4$ µm) at a given heat flux. For a fixed heat flux above 1500 kW/m^2, the EDM surfaces have resulted in 20% and 35% higher heat transfer coefficients than the saw-cut surface. Authors have noticed that the two EDM surfaces with different roughness values ($R_a = 3.9$ µm and $R_a = 6.7$ µm) have similar values of the heat transfer coefficients at higher heat fluxes. However, for wall heat fluxes below 700 kW/m^2, only small differences in the saturated boiling heat transfer coefficient due to the change in surface roughness were observed. Roughness did not appear to have a significant impact on the boiling incipience wall temperature, although this is usually not the case [9,10]. Surface roughness was also found to have only a minor influence on the critical heat flux. The microchannel with $R_a = 6.7$ µm surface appeared to have higher-pressure drop compared to the ones with $R_a = 1.4$ µm and $R_a = 3.9$ µm surfaces. The study demonstrates that under certain circumstances, the surface roughness does influence the heat transfer coefficient and pressure drop in microchannel flow boiling.

Alam et al. [9] conducted flow boiling heat transfer experiment over a silicon micro gap heat sink with surface roughness $R_a = 0.6$ - µm, 1.0 µm and 1.6 µm, using deionized water as the working fluid. Three different heat sinks of dimension 1.27 cm width and 1.27 cm