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Flow boiling characteristics in microchannels with half-corrugated bottom plates

Zhenping Wan [a], Yongnan Wang [a], Xiaowu Wang [b,*], Yong Tang [a]

[a] School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China
[b] Department of Physics, School of Science, South China University of Technology, Guangzhou 510640, China

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ABSTRACT

This study investigates the two-phase heat transfer performance of half-corrugated micro-channels with bottom sinusoidal structured surfaces. The boiling curves, heat transfer coefficients, flow morphologies and temperature and pressure oscillation have been obtained over a range of effective heat fluxes (350 KW–950 KW/m^2) and mass flux of 400 kg s^{-1} m^{-2}. The half-corrugated micro-channels can achieve higher heat transfer coefficients and lower superheat temperatures for the same effective heat flux than plain bottom micro-channels during the boiling process. The flow in saturated boiling regions begins with bubbly flow. The bubbly flow evolves to slug flow, churn flow and annular flow with the increase in effective heat flux. The churn flow and annular flow are observed together with bubbly flow at higher effective heat flux. Bubbly flow can contribute to relieve dry-out and enhance film–styled boiling. Bubbly flow may also result in fluid going forward and backward rapidly. The upstream flow reduces energy output. A sinusoidal half-corrugated structure is a help in not only storing more liquid for evaporation and nucleating bubbles, but also impeding the upstream flow of liquid in a round movement. Thermal-hydraulic performance of micro-channels is influenced by the geometric characteristics of corrugation. Different from conventional micro-channels with sinusoidal structures on both the upper and bottom plate, all half-corrugated micro-channels except micro-channels with wave length of 1 mm and wave amplitude 0.3 mm have a smaller pressure drop than plain bottom micro-channels. The experiments show that the sinusoidal half-corrugated micro-channels with wave length 3 mm and wave amplitude 0.2 mm or with wave length 5 mm and wave amplitude 0.3 mm have better heat transfer performance and smaller pressure drop.

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* Corresponding author.
E-mail address: jouney5@163.com (X. Wang).

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Nomenclature

a	depth of channel, m
A	area, m^2
A_{ch}	heat transfer area including the fin, m^2
b	width of channel, m
c_w	specific heat of the working liquid, J/kg
d	hydraulic diameter, m
D	wave length, m
G	mass flux, kg/(s m^2)
h	heat transfer coefficient, W/(K m^2)
h_{fg}	latent heat, J/kg
H	wave amplitude, m
k	thermal conductivity, W/(km)
l_{tin}	thickness of the solder, m
l_{cu1}	distance between the thermocouple and the top of the copper block, m
l_{cu2}	distance between the bottom of the sample and the bottom of the channels, m
L	length of micro-channel, m
N	amount of micro-channels of the sample
P	pressure, Pa
q	heat flux, W/m^2
Q	power, W
Q_{in}	input power, W
R	thermal resistance, (k m^2)/W
T	temperature, °C
T_{iw}	wall temperature corresponding to ith thermocouple, °C
v	flow speed, m/s
X	mass quality

Greeks

ρ	density, kg/m^3
η	efficiency of fin

Subscripts

c	cross section of a single channel
Cu	copper
eff	effective
i	position corresponding to ith thermocouple
in	inlet
loss	heat loss
out	outlet
sat	saturated boiling
sp	two phase between liquid and gas
t	bottom plate
tin	tin lead solder

1. Introduction

Micro-channels are being considered in many advanced heat transfer applications including automotive and stationary fuel cells and electronics cooling [1]. In recent years, there has been rapid development of heat transfer enhancement of micro-channels and many technologies have been proposed. Corrugated structure is a promising heat transfer enhancement technique that has been extensively investigated. Kosar et al. [2] fabricated a silicon micro-channel device consisting of five parallel micro-channels encompassed by reentrant cavities in each sidewall and investigated flow boiling of water in the micro-channels. Average two-phase heat transfer coefficients and critical heat flux conditions were obtained over a range of effective heat fluxes and mass velocities. Kuo and Peles [3] presented the flow boiling patterns, heat transfer coefficients and critical heat fluxes of water in micro-channels with reentrant cavities on the sidewalls. Xu et al. [4] experimentally studied the heat transfer performance in ten parallel silicon micro-channels using acetone as the working fluid. A full cycle can be subdivided into three sub stages: liquid refilling stage; bubble nucleation, growth and coalescence stage; and transient annular flow stage. Four flow patterns are identified. Lee et al. [5] investigated the flowing boiling heat transfer and pressure drop characteristics of water in a plate heat exchanger with corrugated channels. They reported that the effect of heat flux on the flow boiling heat transfer coefficient was almost negligible. Maryam et al. [6] presented a large eddy simulation of turbulent flow and convective heat transfer of a half-corrugated channel with AM (the ratio of wave amplitude to wave length) from 0 to 0.15 at Reynolds number 10,000. Yin et al. [7] studied the influence on performance of various phase shifts between the upper and bottom corrugated sinusoidal wavy plates with uniform wall temperature and Reynolds number from 2000 to 10,000. The effect of phase shift was more pronounced in higher Reynolds numbers; the optimal performance was obtained at 0° phase shift in lower Reynolds numbers. Pehlivan et al. [8] experimentally investigated heat transfer rates for three different types of sharp corrugated peak fins and a plain surface at varied Reynolds numbers from 1500 to 8000. Heat transfer performance and flow characteristics of corrugated micro-channels with different channel profiles, such as rectangle [1], triangle [9] or trapezoid [10] were investigated. The combination of corrugated structures and other methods proved to be a positive approach to enhance the heat transfer performance of micro-channels. Chang and Huang [11] proposed compound rolling and pitching oscillations to change the thermal performance of a narrow wavy channel with swings about two orthogonal axes. They detected full-field Nusselt number images over the wavy channel wall at static and swinging conditions by the infrared thermography method and found that the influence of rolling and pitching oscillations on heat transfer performance was profound. Khoshvaght-Aliabadi [12] used a parametric study method to analyze the heat transfer and flow characteristics of the sinusoidal-corrugated channel in practical applications such as plate-fin compact heat exchangers. Al_2O_3–water nanofluid was chosen as the working fluid. It was found that the nanofluid had higher values of Nusselt number compared with base fluid. Ahmed et al. [13] presented a numerical study on the laminar forced convection heat transfer performance of copper–water nanofluid with nanoparticle volume fraction 0–5% in a trapezoidal-corrugated channel. The average Nusselt number and pressure drop all increased with the