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Research Paper

Enhanced flow boiling in an interconnected microchannel net at different inlet subcooling

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HIGHLIGHTS

- IMN yields higher HTC and lower pressure drop at low to medium inlet subcooling.
- IMN significantly suppresses the two-phase instability at low to medium inlet subcooling.
- Reentrant and segmented structures of the IMN lead to superior flow boiling heat transfer.
- HTC changes in line with the transition from nucleate boiling to convective boiling heat transfer.

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ABSTRACT

An interconnected microchannel net (IMN) was developed by using traditional wire electric discharge machining method to explore the feasibility of enhancement and application in confined cooling. It features orthogonally parallel channels on the both sides with the channel depth exceeding half the substrate thickness to ensure the interconnectivity. Two-phase boiling heat transfer performance of the IMN was evaluated and a comparison with conventional rectangular microchannels (RMC) was investigated. Using deionized water as the coolant, flow boiling tests were conducted with variation in the heat flux and inlet subcooling of 10, 40 and 70 K. The results showed the IMN yielded higher heat transfer coefficient and lower pressure drop at subcooling of 10 and 40 K, while the advantage diminished when the subcooling increased to 70 K. A transition of boiling mechanism from the nucleate boiling region to the convective boiling region occurred with increase of vapor quality, which was accompanied with the flow pattern changing from the bubbly flow to annular flow. Further study revealed that the IMN can significantly mitigate the two-phase flow instability due to the unique reentrant and segmented structure characteristics, indicating a highlight for the potential application in the flow boiling enhancement of microchannel heat transfer.

1. Introduction

Efficient heat removal from the compact micro-electronic components has been a major challenging issue to the optimum design of modern micro-electronics industry, which should take consideration of enhanced functionalities, high-power density, high-speed operation, and size miniaturization. Since the early introduction by Tuckerman and Pease in 1980 s [1], microchannels with high surface area to volume ration have attracted wide attention in the heat transfer community, because of the prominent heat dissipation capacity for critical heat flux (CHF) micro-devices. In order to keep pace with the ever growing cooling demand, various kinds of microchannels have been developed to further explore the heat transfer enhancement, such as circular [2], rectangular [3], trapezoidal [4], V-grooved [5], diverging/converging [6], expanding [7] shape ones.

However, there are still many extant problems that limits the further application of the microchannel heat sinks, e.g., the two-phase flow instability [8], the large wall superheat at the onset of nucleate boiling (ONB) [9] and the considerable wall-temperature differences along the channel and between the channels [10], etc. Recent researches claim that the above problems could be addressed in the microchannels with reentrant cavities. Kuo and Peles [11] reported that with the application of reentrant structures, the heat flux at the ONB decreased by 70% while the CHF increased by 50% as a result of the enhanced and more stable bubbly dynamics. A Similar observation was also proposed by Kosar et al. [12], who developed reentrant cavities on the side walls of the microchannels. It was observed that the reentrant structure

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Nomenclature

IMN	interconnected microchannel net
RMC	rectangular microchannels
ONB	onset of nucleate boiling
CHF	critical heat flux, kW/m^2
HTC/h_l	local heat transfer coefficient, $kW\ m^{-2}\ K^{-1}$
$G/\dot{m}$	mass flux, $kg\ m^{-2}\ s^{-1}$
q_n	nominal electric power supplied to test section, kW/m^2
q_a	actual heat flux supplied to test section, kW/m^2
C_l	specific heat of working fluid, J/(kg °C)
T_{wi}	wall temperature, °C
T_{ci}	thermocouple reading, °C
T_{in}	inlet fluid temperature, °C
T_{out}	outlet fluid temperature, °C
$\triangle T_{Sat}$	wall-superheat, °C
$\triangle T_{sub}$	degree of liquid subcooling, K
$T_{Sat,ci}$	local saturation temperature at the location of thermocouple at the local pressure, °C
$\dot{V}$	volumetric flow rate, m^3/s
A_{cl}	total cross section area of the longitudinal channels, m^2
φ	heat transfer ratio of the actual heat flux absorbed by the working fluid to the total nominal power input indicated by the wattmeter, q_a/q_n, –
λ_c	thermal conductivity of pure copper, $W\ m^{-1}\ K^{-1}$
λ_s	thermal conductivity of solder, $W\ m^{-1}\ K^{-1}$
l_c	distance between the upper surface of copper block to the thermocouples
l_s	thickness of the solder layer, m
R_{total}	total thermal conduction resistance, °C/m
R_c	thermal conduction resistance of pure copper, °C/m
R_s	thermal conduction resistance of solder, °C/m
A_p	platform area of the upper surface of copper block, m^2
x	vapor quality, –
h_{fg}	evaporation latent heat of deionized water
L_i	distance from the inlet to thermocouple location in the stream-wise direction, m
L	length of the microchannel, m
P_{in}	pressure in the inlet plenum, kPa
P_{out}	pressure in the out plenum, kPa
$\triangle P$	pressure drop, kPa
t	time, s
ρ	liquid density, kg/m^3

Subscript

in	inlet
out	outlet
c	thermocouple reading
w	wall
a	actual
n	nominal
cl	cross section
ci	thermocouple location in stream-wise direction
wi	location on the wall surface in line with the thermocouple
s	solder
p	platform of on the upper surface of the copper block
sat	saturated
sub	subcooled

yielded an augmentation of ~30% in the HTC when compared with the plain wall. A novel kind of Ω-shaped reentrant structure was developed by Deng et al. [13,14]. The experimental results indicated that besides enhancing the two-phase heat transfer, the novel structure can suppress the two-phase flow instability significantly.

Another type of enhanced structure that is promising to relieve the problem of heat transfer deterioration due to the thickened thermal and hydraulic boundary layer on the channel wall [15] and bubble clogging is the segmented fin structures. A number of segmented structures have been proposed recently, including square fin [16,17], pin–fin [18] and oblique fin [19,20]. Cheng et al. [10] attributed the enhancement in two-phase heat transfer of the segmented structures to the induced secondary flow in the channels, which improves the chaotic motion in the near-surface region, thus reducing the thickness of the boundary layer. Such phenomenon was justified in the visualization study conducted by Law et al. [19]. It was observed that the boundary layer collapsed and redeveloped periodically along the channel and more importantly, the large bubble slug broke apart at the sharp corners of the fin, which avoids the agglomeration of large slug. A similar finding was also reported by Far et al. [21], who applied the nano-encapsulated phase change material (NEPCM) as the working fluid to investigate the benefit of the segmented microchannels. The authors asserted that the strong disturbance led to a thin boundary layer on the walls of the segmented microchannels, resulting in a high heat transferal rate.

The above literatures indicate that both the reentrant and segmented structures are able to address the issues of temperature overshoot at the ONB, two-phase flow instability and heat transfer uniformity along the channel. In order to combine both merits of the reentrant and segmented structures, an interconnected microchannel net (IMN) is developed in this study. It features an array of rectangular microchannels on both sides of the substrate with the channel depth exceeding half of the substrate. Therefore, segmented fin structures are created at the intersections of the channels. Due to the interconnectivity between the frontside and backside channels, the IMN also takes the advantages of the reentrant cavity characteristics. The IMN structure provides a large surface area to increase the nucleation probability. Besides, the vapor-slug constraint due to the confinement of the backside channel produces the benefits of negating the temperature overshoot at the boiling incipience. Ramaswamy et al. [22–26] have investigated the benefit of the IMN in enhanced pool boiling heat transfer both experimentally and numerically. Our previous works [27,28] also focused on the pool boiling heat transfer augmentation by combining the IMN and sintered porous material. Despite the abundant data in pool boiling heat transfer for the IMN, there is still a lack of experiment on its enhanced flow boiling heat transfer characteristics, i.e. the convective heat transfer coefficient, pressure drop, flow pattern and flow instabilities. Therefore, in this study, flow boiling experiments were conducted using the deionized water as the working fluid to investigate the two-phase convective heat transfer enhancement, pressure drop characteristics and mitigation of two-phase instabilities for the IMN with variation in heat flux and inlet subcooling. The performance of the IMN is assessed by comparing with the conventional straight microchannels.

2. Fabrication and characterization of test samples

An optical photograph and a scanning electron microscope (SEM) micrograph of the IMN created in this study are shown in Fig. 1. With dimensions of 45 mm × 20 mm × 2 mm, both sides