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Effect of structural parameters on pool boiling heat transfer for porous interconnected microchannel nets

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ABSTRACT

Porous interconnected microchannel nets were developed using microfabrication techniques for pool boiling heat transfer enhancement with both subcooled and saturated deionized water as working fluid at atmospheric pressure. The effects of varying the powder morphology, powder size and channel width on the pool boiling heat transfer were studied. Experimental results showed that these structures exhibited a lower wall-superheat at the onset of nucleate boiling (ONB) and a higher nucleate boiling heat transfer coefficient (HTC) than the solid interconnected microchannel net. The sample of medium size powders (50–75 μm) yielded a maximum heat transfer coefficient while the powder morphology has little influence on the boiling heat transfer performance. At the low heat flux, the HTC was found to increase with decrease of the channel width while at the high heat flux, a reverse trend was observed. High speed visualization (2000 frames/s) revealed that the bubble growth was governed by the heat transfer regime at q_a = 225 kW/m^2 and no waiting phase was observed due to the overlap of the next bubble expulsion in the same vertical channel.

1. Introduction

Microchannel heat sinks have attracted wide attention in the heat transfer community due to their prominent capacity in the heat dissipation for critical heat flux micro-devices. In the past decade, various kinds of microchannels with geometric variations have been developed, such as circular [1], rectangular [2], triangular [3], trapezoidal [4], expanding [5], double-layers stacked [6], interrupted [7] and cross-links shape [8] ones and have been applied to the field of Rankine cycle devices [9], higher-power LEDs [10], densely packed intergrated circuit (ICs) [11], thermal control in PV cells [12], capillary artery evaporators [13–14], outer fin-tube heat exchangers [15] and so on. Besides the aforementioned microstructures, microchannels with reentrant cavities, which serve as vapor trap, have been widely known to promote the boiling nucleation. Since it was introduced by Benjamin et al. [16], the superior performance of reentrant cavities in heat transfer enhancement have been justified repeatedly in extensive studies, both experimentally and numerically [17–21]. An interconnected microchannel net (IMN) is typical of microchannel with reentrant inner structures. The IMN consists of an array of rectangular microchannels aligned orthogonally to the ones at the backside on a flat substrate. Since the channel depth exceeds half the substrate thickness, reentrant square pores are created at the intersections. Besides the reentrant property due to the interconnectivity by the backside channels, the IMN structure provides a large surface area to increase the bubble nucleation probability. Moreover, since the vapor slug is constrained in the backside channels, it spreads throughout the channel once formed, producing the benefits of negating the temperature overshoot at the boiling inception. The solid matrix IMN, with either silicon or copper matrix, has been extensively studied by the research group led by Y.K. Joshi [22–26]. The authors created the aforementioned structure for enhancing the thermal performance of a two-phase thermosyphon loop using wafer dicing, wet-chemical etching and laser milling [22]. The result indicated that the heat dissipation was at least three times better than that of a plain polished silicon surface. Further study focusing on the bubble characteristics, .i.e. the bubbly growth rate, the bubbling frequency and the bubble site density etc., was conducted in the wall superheat range of 4–30 °C with high-speed visualization [23]. A semi-analytical model was also established based on the boiling mode of suction evaporation and menisci evaporation, which showed good agreement with the experimental data [24–26].

In general, most of the previous reports have focused on solid-matrix microchannels, such as silicon [27], aluminum [28], copper [29] and stainless steel [30] ones. Despite their good

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Nomenclature

PIMN	porous interconnected microchannel net
SIMN	solid interconnected microchannel net
ONB	onset of nucleate boiling
CHF	critical heat flux, kW/m^2
HTC	heat transfer coefficient, $kW{\cdot}m^{-2}{\cdot}K^{-1}$
W	channel width, mm
P	channel pitch, mm
L_1	distance between thermocouple T_2 and the lower surface of the solder layer, mm
L_2	solder layer thickness, mm
λ_i	thermal conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$
R_i	thermal resistance, °C/W
q_a	actual heat flux supplied to test section, kW/m^2
T_{avg}	average temperature of T_1, T_2 and T_3, °C
T_w	wall temperature, °C
T_b	bulk liquid temperature, °C
h	heat transfer coefficient, $kW{\cdot}m^{-2}{\cdot}K^{-1}$
η	HTC enhancement factor, –
$\triangle T_{sub}$	degree of subcooling, °C
$\triangle T_{Sat}$	wall-superheat, °C
D	bubble diameter, mm

Subscript

a	actual
c	copper
s	solder
avg	average
w	wall
b	bulk liquid
sub	subcooled
sat	saturated

thermal conductivities, the large wall-superheat demand to induce the onset of nucleate boiling [31], the severe two-phase flow instability [32] and the heat transfer deterioration at the high heat flux [33] on a smooth solid surface may be problematic for the safe operation of microchannel heat sink cooling. Therefore, various kinds of surface modification method have been introduced in order to address the aforementioned issues, such as adding sprayed ABM coatings [34], carbon nano-tube coating [35], dealloyed surface [36] and electro-deposited porous surface [37] on the channel wall. However, it should be noted that the fabrication of the surface coating is technically difficult and costly because MEMS procedures have to be employed. Worst still, the heat transfer may deteriorate drastically if the coating peels off [38] or transforms in morphology due to the chemical reaction between the surface and the fluid [39] after being tested for several times. Therefore, porous material based microchannels, other than just adding a porous layer on the solid microchannel wall, have been recently proposed to further explore the merits above. Cora et al. [40] fabricated porous copper powder-based V-shape microchannels by hot powder compaction. Pool boiling tests results showed that these porous microchannels enhanced the critical heat flux (CHF) significantly. Similar approach was employed by Min et al. [41] to developed copper powder based V-shape and micro pin–fin structures. The maximum critical heat flux of the modulated surface was 2 to 3.3 times that of a plain surface. Deng et al. [42–44] developed a novel kind of reentrant porous matrix microchannel with a Ω-shape cross section. A drastic decrease of wall-superheat at the ONB, a significant enhancement of the heat transfer and a mitigation of two-phase flow instabilities were observed in the flow boiling tests.

In order to combine the both merits of the IMN structure and the porous matrix, porous interconnected microchannel nets (PIMN) are fabricated using a process of loose copper powder sintering and wire electrical discharge machining (WEDM). In the present work, the performance of the PIMN is assessed by comparing the boiling heat transfer from a solid IMN surface (SIMN) with deionized water as working fluid at atmospheric pressure. A number of PIMNs have been developed with variation in the powder morphology, the powder size and the channel width to investigate the effect of structural parameters on the heat transfer of the PIMN due to their impacts on the internal two-phase mode [45–47]. The test result clearly brings out the effect of different structural features on the augmentation of heat transfer. From the insight gained from the experimental results one can yield an optimum surface design to provide high augmentation without sacrificing simplicity or incurring a higher cost.

2. Fabrication and characterization of the PIMN

The PIMN is fabricated by employing the WEDM method on a copper powder based porous matrix prepared by loose powder sintering, and the detailed fabrication procedure is shown in Fig. 1. Commercial copper powders (supplied by Xinrongyuan Powder Tech Co., China) are of spherical shape and irregular shape in the powder morphology and the purity is 99.5%. The powders are sieved into 3 size ranges, including 25–50 μm, 50–75 μm and 100–125 μm before the sintering process. And then the graphite mold is filled with copper powders of a certain size range and put into a furnace. The copper powders are sintered at 900 °C in 0.3 MPa hydrogen atmospheres for 30 min, which is detailed by Bai et al. [48] (Fig. 1a). The porous matrix is removed as it cools to the ambient temperature and arrays of rectangular channels are fabricated on both sides of the matrix by employing the WEDM method (Fig. 1b). The channels are distributed orthogonally to their counterparts on the backside and their depths are over half the thickness of the matrix so that reentrant square pores are created at the intersections.

A schematic diagram and SEM micrographs of the PIMN are presented in Figs. 2 and 3. The PIMN has an overall size of 20 × 20 mm and is 2 mm in thickness. The channel pitch (P) is fixed at 1.2 mm. The effects of channel width (W), powder morphology and powder size are investigated in this study because of their significant influence on the boiling phenomena. Therefore, seven types of PIMN with different structural parameters as well as the SIMN are fabricated, and their structural characteristics are presented in Table 1.

The porosity of samples sintered with irregular/spherical powders are measured using the mercury intrusion porosimetry method performed on the AutoPore 9510 by Micromeritics Co. USA (with the capacity of measuring and the porosity and the distribution of pore diameters ranging from 0.003 to 1100 μm precisely). It is noted that the powder size hardly affects the porosity due to the fact that porosities for samples of spherical powders are approximately 38% regardless of the powder size. However, sample of irregular powders exhibits higher porosity. The porosity of the PIMN-1 (50–75 μm irregular powders) is 58.04%, about 1.5 times that of the rest samples, which results in a larger nucleate site density but possibly a substantial decrease in the effective thermal conductivity [52] in the meantime.