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Flow boiling characteristics in porous heat sink with reentrant microchannels

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ABSTRACT

A novel porous heat sink with reentrant microchannels has been developed by traditional sintering fabrication method. It features 14 parallel Ω-shaped reentrant microchannels with a hydraulic diameter of 786 μm. Two-phase boiling heat transfer performance of the reentrant porous microchannels (RPM) was evaluated to explore the feasibility of the enhancement and application in heat sink cooling. Using deionized water as coolant, flow boiling tests were conducted at the inlet temperature of 33, 60 and 90 °C, mass flux of 125–300 kg/m^2 s. Comparisons with solid copper microchannels of the same reentrant configuration were performed, and the test results show that the reentrant porous microchannels presented a significant decrease of the wall superheat for the boiling incipience, delay and mitigation of two-phase flow instabilities, and 2–5 folds enhancement in two-phase heat transfer coefficient at low to moderate heat fluxes. It was also found that during the flow boiling of the reentrant porous microchannels, nucleation boiling governed the heat transfer mechanism at low heat fluxes and vapor quality, while forced convective boiling associated with thin film evaporation dominated at moderate to high heat fluxes. Furthermore, the two-phase flow instabilities characteristics were also accessed for the reentrant porous microchannels.

1. Introduction

With high heat dissipation capacity for electric and aerospace systems, microchannels has been widely utilized in two-phase heat transfer devices such as heat sinks, micro heat exchangers, heat pipes and jet impingement cooling systems [1]. Classic microchannels are of circular (micro tubes) or rectangular shapes, which have been intensively investigated in the last three decades [2,3]. Other kinds of microchannels have been seen in the literatures with triangular [4,5], trapezoidal [6], diverging [7], and fractal tree-like [8] shape. Though there are still many challenges for the studies within the current types of microchannels, researchers in the heat transfer community are ready to develop more sophisticated ones. Microchannels with micro-pin fins [9,10], carbon nanotube coating [11], drilling holes on the bottom surface as artificial nucleation sites [12] has been developed, and enhanced two-phase heat transfer [9,11] or moderation of wo-phase flow instability [12] were reached.

Besides of the aforementioned means, microchannel with reentrant cavities is another good choice. As a matter of fact, reentrant cavities has been widely used in the outside finned tubes of heat exchangers, such as the Gewa-T tubes [13] and Thermoexcle-E tubes [14], since Benjamin and Westwater [15] in 1961 demonstrated their superior performance as a vapor trap during nucleate boiling. It was widely accepted that the reentrant cavities enhanced pool boiling heat transfer with the decrease of wall superheat and the increase of stable nucleation sites, which were demonstrated repeatedly by Ayub and Bergles [13], Chien and Webb [14], Chen et al. [16] and recently, Das et al. [17]. Moreover, reentrant channels exhibit a prominent performance in high capacity Ω-shaped grooved heat pipes [18,19], which combines a high capillary pumping pressure with a low axial pressure drop, and minimize the retardation of liquid flow induced by the countercurrent vapor flow. The superior performance of reentrant cavities can be also extended to microchannel heat sinks. Goyal et al. [20] investigated a silicon reentrant cavity heat sink by etching and bonding process for enhanced liquid cooling of silicon multichip substances. Boiling tests indicated that reentrant cavities suppress the temperature overshoot of transition between free convective to nucleate boiling. Boer et al. [21] fabricated parallel reentrant microchannels in silicon wafers by buried channel technology, which employs complicated MEMS procedures. The reentrant microchannel heat sink can be easily integrated with electronic

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Nomenclature

A_{ch}	total heat transfer area of microchannels, m^2
A_t	platform area of copper block, m^2
CHF	critical heat flux, kW/m^2
c_p	specific heat of fluid, kJ/kg k
d	powder particle diameter, um
D_h	hydraulic diameter, mm
H_{cell}	height of unit cell, mm
H_{hs}	height of microchannels heat sink, mm
H_{slot}	height of slot, mm
H_{w1}	thickness of plastic cover plate, mm
h_{fg}	latent heat of vaporization, kJ/kg
h_{tp}	local two-phase heat transfer coefficient, kW/m^2 K
K	permeability of sintered porous powder, mm^2
k	thermal conductivity, W/m K
k_{Cu}	thermal conductivity of copper block, W/m K
k_f	thermal conductivity of fluid, W/m K
k_{por}	thermal conductivity of reentrant porous microchannels, W/m K
k_s	thermal conductivity of solder paste, W/m K
L	length of heat sink, mm
L_i	distance from the inlet to thermocouple location in the stream-wise direction, m
l_{Cu}	distance between the thermocouple and the top surface of copper block, m
l_{hs}	distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m
m	fin parameter
$\dot{m}$	mass flow rate, (kg/s)
N	number of reentrant microchannels
ONB	onset of nucleation boiling
P_{cir}	perimeter of circular portion of reentrant microchannel, m
q_{eff}	effective heat power, W
q_{in}	total power input, W
q_{loss}	heat loss, W
q''_{eff}	effective heat flux, kW/m^2
Ra	surface roughness, um
RPM	reentrant porous microchannels
RCM	reentrant copper microchannels
R_{Cu}	conductive thermal resistance in copper block, (°C/W)
R_s	thermal resistance of solder layer, (°C/W)
R_{hs}	conductive thermal resistance in heat sink, °C/W
R_{por}	conductive thermal resistance of reentrant porous microchannels, °C/W
R_{total}	total thermal resistance along the heat conduction direction, °C/W
T_{tci}	thermocouple reading (i = 1~5), °C
T_{in}	inlet fluid temperature, °C
T_{out}	outlet fluid temperature, °C
$T_{w,tci}$	channel bottom wall temperature, °C
$\Delta T_{sat,tci}$	wall superheat, °C
$T_{sat,tci}$	local saturation temperature, °C
t_s	thickness of solder paste, m
u	flow velocity of fluid, m/s
W	width of heat sink, mm
W_{cell}	width of heat sink unit cell, mm
W_{fin}	width of fin between two reentrant microchannels, mm
W_{slot}	width of slot, mm
x	thermodynamic quality

Greek symbols

ε	porosity
μ	dynamic viscosity of fluid, N s/m^2
ρ	density of fluid, kg/m^3
η	fin efficiency
ρ	density of fluid, kg/m^3

Subscripts

cell	unit cell
cir	circular portion
Cu	copper
hs	heat sink
fin	fin
i	thermocouple location
in	inlet
out	outlet
por	porous
s	solder
sat	saturation
slot	slot
total	total
tp	two-phase

circuits for forced cooling. Also utilizing MEMS fabrication methods, Peles et al. [22–24] conducted several consecutive researches on flow boiling in rectangular silicon microchannels with interconnected and nonconnected reentrant cavities on the side wall. Compared to the plain-wall microchannels, the microchannels with nonconnected reentrant cavities [23] exhibited significant reduction in the wall superheat of boiling incipience and more consistent and reproducible bubble formation. The flow instabilities were also suppressed [24]. The critical heat flux was enhanced significantly to 643 W/cm^2 in the mass velocities of 303 kg/m^2 with deionized water as coolants.

Similarly as aforementioned reentrant cavities in metal or silicon substrates, sintered porous channels have been also found to be promising for the application in heat sink cooling. For porous heat sink, the enhancement of single-phase convective heat transfer was demonstrated repeatedly, such as Jiang et al. [25], Tzeng and Ma [26], Hetsroni et al. [27]. It also enhanced two-phase boiling heat transfer thanks to the significant increase of the solid–fluid contact area, which was early demonstrated by Peterson and Chang [28]. The flow boiling experiments of Ammerman and You [29] shows that, for a small rectangular channel with diamond powder porous coating, boiling initiated at lower wall superheats; both heat transfer coefficients and CHF level increased compared to the uncoated channels. The enhancement of porous coating was attributed to the considerable increase of nucleation sites and bubble departure frequency. Recent works by Sun et al. [30] revealed that by using sintered porous surface in a rectangular minichannel, the heat transfer coefficients can be up to 2.7 times of the smooth surface value in subcooled flow boiling and 3 times in saturated flow boiling.

It is worth to mention that the regular packed and porous channels for heat sink need more pump power, and sometimes introduce worse heat transfer performance at high heat flux, which has been pointed out by Rainey et al. [31]. Since the counterflow of liquid and vapor happens in the same pores of porous matrix, it give rise to higher pressure losses, hinders the download of liquid towards the heated surface and results in earlier transition from nucleate boiling to film boiling. Existence of some open small paths in sintered porous channel is helpful for the separate flow of two phases in porous structures, which is analyzed and experimentally studied in pool boiling conditions by Stubos and Buchlin [32], Liter and Kaviany [33]. These merits of porous channels with open paths