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Pool boiling heat transfer of porous structures with reentrant cavities

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ABSTRACT

Porous structures with reentrant cavities (PS–RC) were proposed and developed for pool boiling cooling systems. They were totally constructed by sintered copper powder via a solid-state sintering method. They featured 12 parallel Ω-shaped reentrant channels with large circular cavities inside and narrow exit slots upside. Their pool boiling heat transfer performance was systematically explored using two coolants (deionized water and ethanol) in different liquid subcoolings (3–30 °C) at atmospheric pressure. Solid structures with the same reentrant cavities were prepared and tested for comparison. Experimental results revealed that the porous structures with reentrant cavities presented a significant reduction of wall superheat for the onset of nucleate boiling (ONB), and a maximum 3 and 5.3 folds enhancement in pool boiling heat transfer in water and ethanol tests, respectively. The above enhancement was associated with the merits of PS–RC in the enlargement of heat transfer area, increase in active nucleation sites and improvement of liquid replenishment. Besides, the heat transfer curves together with visualization results showed that three boiling regimes dominated in the PS–RC with the increase in heat fluxes, i.e., isolated bubbles nucleate boiling, fully developed nucleate boiling and bubbles coalescence nucleate boiling. The PS–RC was able to maintain sufficient liquid replenishment and efficient surface rewetting even at high heat fluxes, which help to avoid the fast deterioration of heat transfer at moderate to high heat fluxes.

1. Introduction

Urgent demand for efficient cooling of microelectronic chips, nuclear power plants and laser generators has spurred the development of enhanced boiling techniques [1]. Utilizing latent heat exchange, pool boiling is widely recognized as an effective method to dissipate high heat fluxes from a limited space, and simultaneously maintain relatively uniform surface temperatures. Various boiling enhancement methods have been proposed and implemented in the last few decades [2–3], which address one or more aspects of boiling to improve heat transfer performance. Except the newly emerged nano-related means, e.g., nano structures [4–5] and nanofluids [6], common and stable enhancement methods can be roughly categorized as two directions.

One is to form reentrant cavities or tunnels on the boiling surface using the machining techniques. The reentrant cavities or tunnels have been widely known to act as vapor traps during nucleate boiling, which facilitate the increase of stable bubble nucleation sites and thus enhanced pool boiling heat transfer [7]. Their wide utilization in the outside tubes of commercial heat exchangers, such as Gewa-T tubes [8], Thermoexcle-E tubes [9], and Turbo-B tubes [10], has promoted the third-generation heat transfer technology [11]. The merits of reentrant cavities or tunnels have been demonstrated repeatedly, such as by Chien and Webb [9], Chen et al. [12] and recently, Das et al. [13]. Moreover, Nakayama et al. [14] introduced an enhancement structure consisting of interconnected tunnels with small pores connecting the tunnels and pool liquid. Experimental results demonstrated an 80–90% reduction of wall superheat to transfer the same heat flux compared to a plain surface. A suction-evaporation model was also given to interpret the bubble behaviors inside the enhanced surfaces. Ramaswamy et al. [15] fabricated interconnected microchannels using wafer dicing and wet etching method on either side of silicon substrate and aligned at an angle of 90° to each other. Square pores or tunnels formed at the intersection of channels, which contributed to the bubble nucleation considerably. Honda et al. [16] fabricated micro-pin–fins on a silicon chip using a dry etching technique, and found that the micro-pin–finned chips showed a considerable heat transfer enhancement and 1.9–2.3 times improvement in critical heat flux (CHF) over the smooth chip.

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Nomenclature

c_p	specific heat of fluid, kJ/kg °C
D_h	hydraulic diameter, μm
d	powder size, μm
H	height of sample, mm
H_{fg}	latent heat of vaporization, kJ/kg
h	boiling heat transfer coefficient, kW/m^2 K
k_{Cu}	thermal conductivity of copper block, W/m K
L	length of sample, mm
l	distance between the top three thermocouples and bottom surface of test sample, mm
N	number of reentrant microchannels
ONB	onset of nucleation boiling
q''	heat flux, W/cm^2
T_{ave}	average temperature, °C
T_i	thermocouple reading (i = 1–6), °C
T_w	wall temperature, °C
T_{sat}	Saturation temperature of liquid, °C
ΔT_{sat}	wall superheat, °C
ΔT_{sub}	liquid subcooling, °C
W	width of sample, mm

Greek symbols

ε	porosity
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

Cu	copper
g	gas
l	liquid
sat	saturation
sub	subcooling

The other means is to introduce porous coating on the heated surface, which normally employs sintering, painting, spraying or electrodeposition techniques. The porous coatings, such as metal particles [17], wire meshes [18] and metal foams [19], induce a significant increase in surface area and nucleation sites, which is desirable for the high rates of evaporation and wall superheat reduction at boiling incipience. As such, they show great promise in the enhancement of both heat transfer coefficient and critical heat flux. Among these porous coatings, the porous metal particles have been extensively recognized to be ideal enhanced boiling surfaces due to its relative simplicity in manufacturing process since the introduction and commercialization of the High-Flux surface by O'Neill et al. [20]. The research groups of You et al. [21–22] developed several enhanced boiling layers (ABM, CBM, DBM, DOA and SOA) by painting or spraying a mixture of metal powder particles, binder and carrier on heater surface. Pool boiling test results indicated that these porous enhanced surfaces introduced about an 80–90% reduction of incipience superheat, about 30% enhancement in nucleate boiling heat transfer coefficient and about 100% enhancement in CHF over an unenhanced surface. They attributed such enhancement to the significant increase in the active nucleation sites of porous coatings. Weibel et al. [23] assessed the capabilities of monoporous sintered copper powders to support local heat fluxes of greater than 500 W/cm^2 without the occurrence of dryout under the condition of water boiling. The copper powder layer ranged from 600 to 1200 μm thick and the particle sizes were from 45 to 355 μm. Thiagarajan et al. [24] developed microporous copper powder surfaces by fusing the copper particles of the size between 5μm and 20 μm on copper heated surface. Such copper coatings, with the thicknesses of 100–700 μm, porosity of 55–60%, and cavity sizes in the range of 0.5–5 μm, were found to present a significantly lower boiling incipience temperature, and enhance the heat transfer coefficient by 50–270% and the CHF by 33–60% compared to a plain surface.

Despite the above advantages of uniform porous coatings, the tortuous flow paths inside porous coatings may hinder the liquid replenishment from the pool, and vapor blankets may emerge near the heating surface at high heat flux input. The degradation of heat transfer and occurrence of CHF are thus induced. To address this issue, modulated porous surfaces with channels or valleys inside the porous layer were proposed to generate alterative regions for vapor escape with low resistance and high capillary liquid draw. Separated flow paths of liquid and vapor phases were maintained and the counterflow resistance of liquid–vapor was thus decreased. Since this concept is proposed by Malyshenko [25] and Stubos and Buchlin [26], lots of attentions [27–32] have been paid to modulated porous surfaces to enhance boiling heat transfer and CHF. Liter and Kaviany [27] theoretically and experimentally demonstrated that the 3-D modulated porous surfaces made by sintering copper powders enhanced the CHF up to 3 times in pentane compared to a plain surface. The 2-D modulated porous surfaces with parallel V-shaped grooves in the later studies of Kaviany's group [28] also presented a notable enhancement of pool boiling. Following this direction, Ji et al. [29] comprehensively explored the enhancement feasibilities to prepare parallel or cross-linked V-shaped channels in uniform sintered copper powder surfaces in acetone. Moreover, Wu et al. [30] assessed the enhancement in heat transfer coefficients and CHF by the porous coatings with rectangular channels. Li et al. [31] shed lights on the importance of horizontal liquid replenishing for pool boiling heat transfer enhancement and CHF improvement by introducing a hybrid modulated porous structures with porous base and circular porous pillars. Besides of the porous powder coatings, the metal foam layers with single-directional and crossing V-shaped channels inside were also showed to be able to enhance the pool boiling heat transfer by Qu et al. [32].

From the above literature review, it is clear to see that reentrant cavities and porous coatings incur a significant contribution to the pool boiling enhancement, while adding grooves or channels inside uniform porous coatings is even more helpful for the vapor release and liquid replenishment. Motivated by this, we in this study develop enhanced porous structures with reentrant cavities (PS–RC), differing from the open V-shaped or rectangular channels significantly. Pool boiling tests were conducted in subcooled deionized water and ethanol in different subcooling levels at atmospheric pressure. The boiling heat transfer performance of these porous coatings with reentrant cavities was examined compared to the solid counterpart to explore the heat transfer enhancement feasibility.

2. Fabrication of porous structures with reentrant cavities

The porous structures with reentrant cavities, which are designed to be of a reentrant configuration as shown in Fig. 1(a), are fabricated via a solid-state sintering method under the