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Experimental investigation on pool boiling mechanism of two-level gradient metal foams in deionized water, aqueous surfactant solutions and polymeric additive solutions

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ABSTRACT

In the present study, metal skeleton temperature, bubble growth, pool boiling curves, and the solid-liquid static contact angle of two-level gradient foams have been experimentally investigated in deionized water, aqueous surfactant solutions and polymeric additive solutions under atmospheric pressure. The surfactant is Triton X-100 and the polymeric additive is polyvinyl pyrrolidone. A two-level gradient foam sample is made by a uniform copper foam layer, a uniform nickel foam layer and a copper plate with the thickness of 2 mm. The pore densities of uniform foams are 5 PPI, 20 PPI and 40 PPI. The foam porosity is fixed as 0.98. The experimental results show that, foam layer position reversal has a great effect on pool boiling heat transfer of the gradient foam. The pool boiling heat transfer rate of the gradient nickel-copper foam increases with increasing bottom foam pore density. The temperature of corner skeleton on the upper surface of the gradient foam is higher than that of inner skeleton because of the heat flow from escaping bubbles by collision, cutting, stagnation, etc. The metal skeleton temperature is heavily affected by the additives of Triton X-100 and polyvinyl pyrrolidone due to the variations of the solid-liquid contact angles.

1. Introduction

The decreasing size of electronic devices and increasing packing density of transistors make the heat generation rate rise tremendously. However, the cooling device must be smaller to meet the demand of miniaturization and lightweight. Therefore, highly-efficient heat dissipation must be developed to reduce the electronic device temperature to ensure the working life. During pool boiling, liquid-vapor phase change process happens and the heat transfer coefficient is high. Pool boiling heat transfer is very important for industrial applications. Thus, it is a hot research area in the field of pool boiling heat transfer [1]. Various enhanced structures have been developed to improve heat transfer coefficient and critical heat flux by increasing nucleation sites and surface area [2,3]. Porous structures have been proved that they can considerably enhance pool boiling heat transfer. Liu and Yang [4] performed an experimental study to examine the effect of aluminum porous coated layer on a copper plate and confinement space on boiling heat transfer of methanol. Heat transfer coefficient enhancement ratio of micro porous surfaces to plain surfaces increased with space confinement at low and moderate heat fluxes. However, this enhancement becomes weakened for high heat fluxes. Sarangi et al. [5] experimentally investigated pool boiling heat transfer of copper-particle surface coatings and found that the best-performing sintered coating has the same 90–106 μm particle range as the free particles, and provides a 95% decrease in wall superheat, albeit at a critical heat flux that is 33% lower than that for the polished surface. Jun et al. [6] investigated pool boiling heat transfer of durable high-temperature thermally-conductive microporous coating in saturated water and found that the critical heat flux and a maximum nucleate boiling heat transfer coefficient of the microporous surface are 2 and 8 times higher than those of a plain copper surface, respectively, at the upward horizontal inclination angle. Bai et al. [7] proposed an innovative artery porous structure to enhance the critical heat flux based on the concept of 'phase separation and modulation' by forming individual flow paths for liquid supply and vapor venting while keeping the liquid/vapor interface located in the porous structure, and a maximum heat flux of 416 $W\,cm^{-2}$ on a heating area of 0.78 cm^2 was achieved without the occurrence of any dryout. More recently, Gheitaghy et al. [8] experimentally investigated pool boiling heat transfer performance of electrodeposited porous surfaces that fabricated in various electrolyte temperatures. All microporous surfaces showed lower boiling incipience temperature than the plain surface due to the presence of large

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Nomenclature

Cu	copper
D_b	bubble departure diameter, m
f	bubble frequency, s^{-1}
g	gravitational acceleration, $m \cdot s^{-2}$
GMF	gradient metal foam
h	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
k	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
Ni	nickel
n	nucleate site density
PPI	pores per inch
ppm	parts per million
PVP	polyvinyl pyrrolidone
q	heat flux, $W \cdot m^{-2}$
T	temperature, K
TX-100	Triton X-100
UMF	uniform metal foam
wt	weight
z	position along vertical direction on the heating surface, m

Greek symbols

ε	porosity
ω	pore density, PPI
θ	static contact angles for droplets on copper or nickel surfaces
ρ	mass density, $kg \cdot m^{-3}$
σ	surface tension of liquid–vapor interface, $N \cdot m^{-1}$

Subscripts

a	active
l	liquid
s	solid
v	vapor
w	wall

number cavities on the microporous surface. The porous surface electrodeposited in room electrolyte temperature reached the maximum critical heat flux of 140 W cm^{-2} and the best heat transfer coefficient of 19 W cm^{-2} K^{-1} that was over 1.6 and 3 times that of the plain surface, respectively. Seo et al. [9] found that the pool boiling critical heat flux is improved for all the nanostructured thin films on a substrate by layer-by-layer deposition technique. The maximum enhancement was 94% compared to the bare heater. Mori et al. [10] experimentally investigated critical heat flux enhancement during saturated pool boiling of water by using a two-layer honeycomb porous plate attached to a heated surface and found that critical heat flux can be enhanced more than twice that for a plain surface. Pastuszko [11] found that boiling heat transfer coefficients obtained from the micro-finned structure without a covering and micro-fins covered with a copper wire mesh were even 6.5 times higher than those for the smooth surface.

Open-celled uniform metal foam (UMF) has the potential in phase-change heat transfer enhancement [12] due to the large specific surface area and the strong ability of disturbing liquid by tortuous metallic skeletons. Xu et al. [13] found that, the pool boiling heat transfer performance of the 30 PPI uniform copper foam is better at the low wall superheat while the 90 PPI uniform copper foam is better at high wall superheat. Ji et al. [14] found that, boiling heat transfer performance of horizontal tubes sintered with copper foams significantly outstrips smooth tubes at relatively low heat flux. The experimental results of Zhu et al. [15] showed that, copper foam increases boiling heat transfer coefficient by 4.5 times compared with smooth surfaces in the refrigerant/oil mixture. More recently, Liu et al. [16] carried out experiments to study the influences of working fluid filling ratio, cut and non-cut copper foam blocks on boiling and condensation co-existing heat transfer inside a small and closed space. The results showed that if the space is filled with the cut copper foam block, there is an optimum filling ratio at which both boiling and condensation heat transfer coefficient acquire their maximum values. The present authors [17–18] found that, bubbles generating inside the UMFs meet dual resistance by both the fresh liquid flowing inside and metal skeleton during pool boiling process. Especially when the UMF is thick or dense, the resistance is particularly evident, which slows down the bubble escaping velocity and then deteriorates boiling heat transfer. Even worse, boiling heat transfer performance of some UMFs is lower than that of the smooth plate. Cutting grooves in UMFs improves boiling heat transfer, but destroys original structures of UMFs. To reduce bubble escaping resistance, the present authors have developed gradient metal foams (GMFs) [19,20] which have great potential in boiling heat transfer enhancement. They not only have the advantages of large surface area and the strong ability of disturbing liquid by tortuous metallic skeletons owned by UMF, but also provide reasonable space for the escaping bubbles because of extended interconnected pores. The present authors [19,20] have investigated macroscopic pool boiling performance of GMFs and found that GMFs can considerably enhance boing heat transfer compared to UMFs. Pool boiling heat transfer of GMFs in deionized water is heavily dependent on foam layer number, material gradient, thickness and pore density. Pool boiling heat transfer of GMFs in surfactant solutions is dependent on surfactant concentrations. Adding alumina particle into boiling water worsens pool boiling heat transfer of the gradient copper foams. However, boiling mechanism of GMFs has not been studied due to the visual difficulty caused by the optical opacity of metal skeleton. In the present study, to further understand pool boiling process of GMFs, the metal skeleton temperature, bubble growth, pool boiling curves of the two-level gradient foams are experimentally investigated in deionized water, aqueous surfactant solutions and polymeric additive solutions by considering solid-liquid contact angles.

2. Experimental setup and procedures

The experimental setup (Fig. 1a) includes a heating system, a cooling system, and a data acquisition system. The heating system consists of the copper block heater with maximum power of 5 kW, two auxiliary heaters with maximum power of 1 kW and three corresponding voltage regulators. Two single-phase heating rods are sealed in the main copper block to provide the heating power. The upper heating surface size of the main copper block heater is 25 mm (length) × 25 mm (width). Other surfaces of the main heater and the walls of the liquid bath are wrapped by glass fiber with very good thermal insulation performance to prevent heat loss to the surroundings.

Two UMFs are sintered together by Ag-Cu alloy sheets in a high-temperature muffle furnace to form a GMF (Fig. 2). In the present study, the two gradient copper & nickel foams with the copper plate of 25 mm (length) × 25 mm (width), GMF 20PPI-4 mm-Cu & 5PPI-4 mm-Ni and GMF 20PPI-4 mm-Ni & 5PPI-4 mm-Cu are selected as the investigation objects. To reduce contact thermal resistance, GMF samples are welded on the main heater upper surface. Before welding, the surfaces of copper plate and main heater are roughened by sandpapers. Lead-free solder is melt by a soldering iron and cooled down to be solidified on a GMF sample copper substrate. Lead-free solder is placed on the heating surface and the main heater is switched on to increase surface temperature up to the melting point 180 °C. Then the GMF sample is