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Research Paper

Enhanced boiling heat transfer by gradient porous metals in saturated pure water and surfactant solutions

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HIGHLIGHTS

- Pool boiling heat transfer of gradient metal foams was investigated experimentally.
- The main influencing factors are layer number and foam material gradient.
- Departure bubble becomes smaller when it is colliding with the nickel foam skeleton.
- Surfactant effect is dependent on concentrations and nanoparticle deposition condition.

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ABSTRACT

Pool boiling heat transfer of gradient metal foams has been investigated in saturated pure deionized water and surfactant solutions at atmospheric pressure. Pore density gradients are from 5 PPI to 100 PPI, while the porosity remains at the fixed value of 0.98. The parametric study is performed by varying foam layer number and material. Alumina nanoparticle and surfactant (SDS and Triton X-100) effects on pool boiling heat transfer of gradient metal foams are also investigated. Images of nanoparticle-deposited foam fiber are captured by SEM. Bubble growth inside the gradient metal foams is captured by a high-speed camera. For no-nanoparticle-deposited gradient metal foams, pool boiling heat transfer in deionized water is heavily dependent on foam layer number and material gradient. For nanoparticle-deposited gradient metal foams, pool boiling heat transfer in surfactant solutions is dependent on surfactant concentrations and nanoparticle deposition condition on the metal skeletons. The visualization results show that departure bubble size first increases and then decreases in the gradient copper–nickel foam.

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1. Introduction

With rapid development in electronics industry, heat flux on electronic components increases sharply in recent years. Heat flux on integrated circuits (IC) was about 10 W·cm^{-2} in the 1980s [1], and it will increase up to 1000 W·cm^{-2} in the near future [2]. Removing large quantities of heat from electronic components has been a key point for the electronics industry. Pool boiling transfer is an ideal cooling method with less noise and additional equipment. It is well known that special surface development is a critical issue for pool boiling heat transfer. Plasma coating [3,4], micro-electro-mechanical system (MEMS) fabrication [5–7] and mechanical surface machining [8–11] can create appropriate surface structures. In essence, the created boiling enhancement surfaces have a number of small cavities increasing vapor/gas entrapment and active nucleation site density. The structures by the techniques [3–11] reduce incipient and nucleate boiling wall superheats and increase pool boiling heat transfer coefficients [12]. However, high production cost of these creating techniques prohibits the widespread use in industry. Therefore, the new low-cost structures for improving pool boiling heat transfer performance are needed to be developed.

Compared with traditional boiling structures such as fins, porous structures have more surface area and nucleation sites. Furthermore, capillary forces of porous structures supply fresh liquid to vaporize. Generally speaking, porous materials can improve boiling heat transfer coefficient and delay boiling crisis. Porous surface morphology has the significant effect on pool boiling heat transfer. Penley and Wirtz [13] performed saturated pool-boiling experiments to assess the utility of fine-filament screen-laminate enhanced surfaces as effective bubble nucleation sites. The experimental results indicated that boiling performance is a strong function of screen-laminate geometry. Enhancement of up to 27 times that of an unenhanced surface was obtained. Zhang et al. [14] demonstrated that a significantly enhanced pool boiling heat transfer is observed in a submicron regime through three dimensionally interconnected hybrid pores of alumina sponge-like nano-porous structure (ASNPS). The unique structure of ASNPS results in an enlarged surface area, increases active nucleation site density, and

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improves vapor–liquid menisci through the reentrant pore. Dai et al. [15] found that, compared with mono-porous evaporating surfaces, such as microchannels and copper-woven mesh laminates, of the same thickness under similar working conditions, CHF was substantially increased by 83% and 198%, respectively, because of the separation of capillary pressure generation and fluid transport enabled by the micromembrane. More recently, Mori et al. [16] experimentally investigated the effects of a honeycomb porous plate and/or nanoparticle deposited heat transfer surface on the CHF and found that CHF was enhanced greatly by the attachment of a honeycomb porous plate to the modified heated surface by nanoparticle deposition. Kim et al. [17] found that the CHF phenomenon is governed by the frequency of the coalesced bubble departure and the liquid furnishing capability into a thin liquid–vapor layer. The microstructures on the surface change the evaporative mass flow rate owing to the liquid–vapor interface deformation near the triple contact line of the macrolayer, leading to a change in the coalesced bubble departure frequency.

Recently, phase-change heat transfer performance of open-celled metal foams has been investigated because of the high surface area and mixing fluctuation and turbulence of the fluid [18–21]. The main factors influencing pool boiling heat transfer performance of open-celled metal foam are pore density, porosity and boiling liquid property, etc. Xu et al. [22] and Yang et al. [23] experimented on the pool boiling heat transfer of water in ultra-light copper foam welded on the heating surface and performed high-speed visualizations. The porosity ranges from 0.88 to 0.95, pore density from 30 PPI to 90 PPI, and foam thickness from 1 mm to 6 mm. The results showed that pore density has a more significant effect on heat transfer performance than porosity. The activated nucleation sites depend heavily on pore density and its distribution. The 30 and 60 PPI foam covers displayed periodic single-bubble generation and departure pattern at low surface superheats; a periodic bubble coalescence or re-coalescence pattern with a cage-shaped bubble was observed. Zhu et al. [24] experimentally studied the pool boiling heat transfer performance of refrigerant R113/oil VG68 mixtures on copper foam covers and found that the presence of oil reduced nucleate pool boiling heat transfer on copper foam covers by 15% (maximum) for VG68. The present authors [25,26] speculated that moving bubbles in uniform metal foams suffer resistances by metal skeleton and the fresh liquid flowing into vaporization zone during boiling. Especially for the thick or dense metal foams, the resistance slowing down departure bubbles is particularly obvious, resulting in boiling deterioration. Cutting grooves in the metal foam or adding surfactant into boiling water can improve boiling heat transfer of the metal foam. However, the enhancement results are unsatisfactory. Moreover, cutting grooves will destroy original structures of metal foams. Gradient metal foams not only have the advantages of high surface area and disturbing liquid capacity but also provide reasonable space for the departure growing bubbles due to enlarging pores vertical to a heating surface. Recently, Li et al. [27,28] experimentally studied the critical heat flux and heat transfer coefficient of de-ionized water pool boiling on gradient porous structures sintered by small particles. The structures of gradient metal foams are very different from the stacked particles [27,28], and thus their boiling heat transfer performance and mechanisms are different. Taking into account the urgency of heat transfer enhancement, it is necessary to investigate boiling heat transfer performance of gradient metal foams. More recently, foam thickness, nanoparticle and surfactant effects on pool boiling curves of gradient foams have been studied by the present authors [29]. However, the pool boiling involves complicated and dynamic processes such as hydrodynamics, heat and mass transfer, nucleation, bubble coalescence and collapse [30]. Pool boiling in gradient foams is more complicated because of the existence of metal skeletons. To understand the boiling mechanism, growing bubble inside the gradient foam is captured by a high-speed camera for the first time in the present study. Furthermore, to fully understand pool boiling heat transfer performance of the gradient foams, material and pore density gradient effects on pool boiling heat transfer of gradient metal foams in saturated pure water are studied. SDS and Triton X-100 effects on pure and nanoparticle-deposited gradient metal foams are investigated using deionized water as the base liquid under saturation condition.

2. Experimental facility and procedure

The whole experimental facility consists of a heating system, a cooling system, a data acquisition system and a chamber (Fig. 1a). The data acquisition system comprises nine thermocouples (Fig. 1b), Keithley data acquisition unit, a NXA7-S1 high-speed camera with the speed of 1000 frames per second and a personal computer. The details of the experimental set-up, data processing and experimental uncertainties have been described in the authors' previous study [31].

3. Gradient and single-layer metal foam parameters

In the present study, there are 7 gradient metal foam samples and 4 single-layer metal foam samples. Foam porosity is fixed as 0.98. The gradient foam (GF) thickness is from 10 mm to 20 mm and the single-layer foam (SF) thickness is from 4 mm to 8 mm. Foam materials are copper and nickel. Different foam layers were sintered together in a high-temperature muffle furnace to form gradient metal foams. The pictures of gradient metal foams are shown in Fig. 2. Single-layer metal foams are considered as the reference samples for comparison purposes. The specifications of metal foams used in the present study are shown in Table 1. Images of foam fibers deposited by nanoparticles were captured by SEM (VEGA3 TESCAN, Instrument Analysis Center of SJTU).

4. Results and discussion

4.1. Foam material gradient effect

Fig. 3(a) and (b) shows the pool boiling curves of a gradient copper–nickel foam and a gradient nickel–nickel foam which have the same thickness. It can be found that, when the heat flux is less than a certain value, the former's pool boiling heat transfer performance is better than the latter because the copper thermal conductivity is far higher than the nickel. However, when heat flux increases further, the latter's boiling performance becomes better. Higher thermal conductivity means higher bubble growing frequency. The limited space in the gradient foam may result in bubble crowding. More growing and departure bubbles mean more serious bubble crowding phenomena, which worsen boiling heat transfer. Compared the results in Fig. 3(a) with those in Fig. 3(b), it can also be found that the heat fluxes at the intersection points between the boiling curves of the gradient copper–nickel foams and those of the gradient nickel–nickel foams decrease from 1.06×10^6 W·m^{-2} to 9.2×10^5 W·m^{-2}. The pool boiling heat transfer difference between the gradient copper–nickel foam and the gradient nickel–nickel foam increases with increasing pore density gradient. The essential factors influencing boiling heat transfer of gradient foams are surface area (number of nucleation sites) and effective thermal conductivity. Fig. 3(a) and (b) also shows that a higher pore density foam layer sintered under a low pore density foam layer can more efficiently improve the latter's boiling heat transfer at the low heat fluxes due to the surface area increment.

In the authors' previous study [25], we found that, when the morphology parameters for the copper and nickel foam samples are identical, although the thermal conductivity of copper (398 W·m^{-1}·K^{-1}) far exceeds nickel (82.8 W·m^{-1}·K^{-1}), the pool boiling heat transfer coefficient of the copper foam is lower than that of

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