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Experimental study on boiling heat transfer of a self-rewetting fluid on copper foams with pore-density gradient structures

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ABSTRACT

Light-weight and high-surface-area metal foams used in phase change heat transfer may suffer flow resistance from the porous matrix and cause boiling deterioration. To alleviate the flow resistance, metal foams with pore-density gradient was proposed and significant enhancement of pool boiling heat transfer was achieved for fluids such as water and refrigerants. In this work, a self-rewetting fluid (aqueous n-butanol solution) was used for boiling on copper foams with pore-density gradient structures formed by using several layers of foam covers. The experimental results show that, comparing with the one-layer foam, the bubble departure phenomenon was substantially attenuated due to the largely increase of pore density and hence the bubble moving resistance when using a two- or three-layer foam structure. However, the increase of pore density can enhance the pool boiling of water when the foam thicknesses are the same due to more active cavity sites being formed in a denser metal foam. While the enhancement for the solution is not obvious especially for that in the foam structure with higher pore density and heat transfer deterioration may emerge at high heat fluxes, the boiling heat transfer of the solution can generally be enhanced by using the 110 ppi foam and its gradient structures as compared to the polished surface. This provides new insight into enhancing the boiling heat transfer utilizing both the surface properties formed in the pore-density gradient structure and the unique interfacial properties of the self-rewetting fluids.

1. Introduction

The past decade has witnessed the use of metal foams became an efficient way to transport heat in applications such as electronic cooling, compact heat exchangers, heat pipe wicks, solar thermal collectors, vapor chambers, etc. [1–10] This can be attributed to the high surface area to volume ratio (up to 8000 m^2/m^3) as well as the enhanced convection due to the tortuosity of metal foams. These light-weight and high-surface-area materials have also been extensively investigated in phase change heat transfer. It was shown that pore density has significant effect on heat transfer performance [11–13]. However, bubbles inside metal foams may suffer flow resistance from the porous matrix and cause boiling deterioration [14,15]. Metallized porous surfaces somewhat resemble the foams and reveal a significant increase in the heat removal rate up to the critical heat flux [16]. However, this requires nanostructured surface such as nanofibers oxidized on the metal surface. Metal foams with pore density gradient was proposed recently for alleviating the flow resistance [17]. Significant enhancement of pool boiling heat transfer was achieved by using the gradient metal foams, and the enhancement was strongly dependent on the pore density gradient, together with the foam thickness.

Besides the technique that can enhance the pool boiling heat transfer of a working fluid through variation of surface properties, e.g., using metal foams, modification of fluid properties can be utilized for this purpose. Among them is the means of using self-rewetting fluids [18]. Dilute aqueous solutions of high carbon alcohols with number of carbon atoms higher than four are conventionally called self-rewetting fluids. These fluids exhibit an increase in surface tension with temperature after a certain value and this allows both the solutocapillarity (or concentration-driven Marangoni effect) and thermo-capillarity (or thermal Marangoni effect) to pull liquid in the same direction back toward the heated surface (self-rewetting effect), thus removing the bubbles and enhancing the heat removal performance. The critical point of temperature may change due to the predominant evaporation of more volatile alcohol at the interface and hence the variation of their composition and self-rewetting properties. However,

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Nomenclature

A	area (m^2)
B	propotional constant
c	specific heat capacity ($J\ kg^{-1}\ {}^\circ C^{-1}$)
d_s	diameter for which n would be one per unit area (m)
D	diameter (m)
f	bubble frequency (s^{-1})
g	gravitational acceleration ($m\ s^{-2}$)
h_{fg}	latent heat of evaporation ($J\ kg^{-1}$)
m	power in Eq. (4)
n	number of active sites per unit area (m^{-2})
N	layer numbers
P	power (W)
ppi	pores per inch (m^{-1})
q	heat flux (W/m^2)
T	temperature (°C)
ΔT	wall superheat (°C)
w	mass fraction (%)

Greek symbols

ε	porosity (%)
δ	thickness (m)
λ	thermal conductivity ($W/m\ {}^\circ C^{-1}$)
θ	contact angle (°)
ρ	density ($kg\ m^{-3}$)
σ	surface tension (N/m)
φ	a complex of fluid properties

Subscripts

b	bubble
d	departure
j	measurement point
l	liquid
sat	saturation
v	vapor
w	wall

the surface tension of most dilute butanol solutions at different concentrations, measured using both the maximum bubble pressure method and Wilhelmy's method, increase with increasing temperature starting at the point of approximately 50–60 °C [19,20]. This indicates that even such mixtures might change their composition in time, their self-rewetting properties would not deteriorate too much and it ensure yielding heat removal enhancement. This unique interfacial property has proven to be promising in applications in heat transfer devices such as heat pipes [21–23]. In our recent work, self-rewetting fluid was used to experimentally investigate its bubble dynamics and boiling heat transfer characteristic in porous structures formed by packed glass or copper beads [24]. The results show that the heat transfer during nucleate boiling can not only be enhanced by the structures, but also be enhanced by varying the interfacial properties of fluids. However, the inner structures are different between the metal foams and the packed beads, and hence the mechanism of pool boiling heat transfer characteristics in this gradient structure needs to be clarified.

In this paper, the bubble behavior and heat transfer characteristics of aqueous n-butanol solution boiling in the porous structure of metal foam which have pore-density gradient were characterized, in order to integrate the interfacial effects formed in the structure and the unique interfacial properties of the self-rewetting fluid. The effects of ppi (pores per inch), thickness, number of layers, and heat flux, on the pool boiling heat transfer characteristics were experimentally investigated. It is expected that this may be helpful for further modeling of pool boiling heat transfer of liquid with multi-components in applications using this porous gradient structure.

2. Experimental

Fig. 1 shows the schematic of the experimental setup, the principle of which is similar to that developed by Kim et al. [25]. The heating block was insulated by ceramic fiber fire barrier which has a thermal conductivity $k = 0.035\ W/(m\cdot K)$. Meanwhile, high temperature resistant sealant was applied around the block sides. The copper heating block was a commercial H62 brass, with geometry of 49 mm × 49 mm × 180 mm. Twelve cartridge heaters were embedded in the heating block to form the base of liquid bath. The diameter and length of the cartridge heaters were 6 mm and 40 mm. These heaters, which distribute symmetrically in the block as shown in Fig. 1, supply uniform heat flux to the test surface. Eight T-type thermocouples, with diameter of 1 mm and measurement error of 0.3 °C, were embedded in between the heaters and the block to monitor the block temperature. One T-type thermocouple was used to measure the outer surface temperature, in order to estimate the heat loss from the heating block using the temperature difference between the outer surface and the environment. The measurement has indicated that the heat loss can be neglected, ensuring that the heat flux can be calculated by using the input electrical power. The other T-type thermocouple was used to measure the saturation temperature of the test liquid. The temperature measurements were logged to a data acquisition system (Agilent 34972A). The bubble behavior was recorded by using a digital camera (Canon 700D) with frame rate of 30 fps. The test liquid was degassed before each experiment.

Copper foam blocks (commercial H62 brass) with varying ppi were packed on the copper heating block to perform the test with pore density gradient structure. To ensure small thermal resistance between the copper block and the foam cover, the fusion or the diffusion welding procedure was usually adopted. However, the fusion welding method used in [17] requires that the wafer (tin) surface is sufficiently clean, flat and smooth, otherwise unbonded voids, i.e. interface bubbles, may occur. The diffusion welding procedure used prior to it [26] operates at elevated temperature and pressure, but it cannot ensure that the pores were not damaged and clogged after the welding process. The foams used in our test were bonded using thin copper wires at the cover perimeter, and a copper block with square hollow was used on top of the bonded foams to ensure they were effectively contacted with the heating block.

The test liquid was also degassed over the porous structure before each experiment was conducted and measured in steady wall superheat. The surface tensions of the aqueous n-butanol solutions at different mass fractions measured at 17.8 °C are given in Table 1. Three group of tests were performed for each case study under conditions of different foam structures in order to verify the repeatability of data. The maximum temperature difference between the measured temperatures and the average temperature was taken as the measurement error. Then the average temperature was used to calculate the heat flux and the corresponding wall superheat as described above. To test the boiling heat transfer of liquid over a packed porous structure with pore-density gradient,