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Boiling characteristics of water and self-rewetting fluids in packed bed of spherical glass beads

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ABSTRACT

Enhancing the heat transfer of boiling has been extensively investigated by either surface modification technique or alteration of the properties of working fluids. In this paper, an experimental investigation on the nucleate boiling characteristics of deionized water and some typical self-rewetting fluids (aqueous n-butanol, n-pentanol and n-hexanol solutions) in spherical glass beads packed bed porous structures was performed. Unique bubble dynamics was observed in the porous structures for these working fluids under different heat flux conditions. The results show that the heat transfer during nucleate boiling can not only be enhanced by the porous structures, but also be enhanced by increasing the number of carbon atoms of the alcohols. This work provides fundamental data for further development of theoretical models of pool boiling heat transfer in porous structures. Extended investigation can be performed by improving the superheats, to fully understand the effect of interfacial property on the heat transfer characteristics of various working fluids in the glass beads packed porous structures and in related applications.

1. Introduction

In the last few decades, the enhancement of pool boiling heat transfer has been extensively investigated by either surface modification technique or alteration of the properties of working fluid. Modification techniques can be implemented by roughing the surface to provide preferential nucleation sites [1–5] in spite of the ageing effects [6,7], or by the use of external coatings or attachments such as wire meshes [8], pin–fin structures [9,10], metal foams [11–13], and porous particle layers [14–17]. Particularly, boiling heat transfer in a liquid saturated porous bed is important in many industrial applications, such as heat pipe, liquid cooled nuclear reactor and geothermal energy system. The change of local surface morphology has been proven to be an effective means of enhancing the heat transfer coefficient and the critical heat flux in pool boiling [18–20]. The boiling incipience superheat can therefore be drastically reduced due to the presence of corner cavities formed by the particles attached to the heated surface, and thus the nucleate boiling superheats are also reduced. Among these studies, the parametric effects of sintered coating particle size, porosity, and thickness on pool boiling performance have been largely investigated [21,22]. While the existence of an optimum layer thickness can be identified by the performance studies on either sintered/fixed [23–28] or fluidized/free particle bed [26–28] porous coatings. The fluidized/free particle bed technique can provide insight into the expected boiling performance of sintered coatings.

The alteration of the properties of working fluid provides an alternative enhancement technique. In particular, the use of nanoparticles as additives in working fluids for boiling heat transfer enhancement has been widely studied. The improvement of critical heat flux (CHF) was reported in several studies for this novel fluid which is named as nanofluid [29,30]. However, mild improvement [31,32], slight deterioration [33] and negligible variation [34] of the boiling heat transfer coefficient have also been reported. It was believed that the deposition of thin particle layers on the heated surface during the nucleate boiling process contributes to the CHF improvement by changing the wettability with the narrow corner gaps between the particle and the heated surface and thus the local surface topography. While the enhancement mechanism, which is due to the presence of the corner geometry that leads to a decreased incipient superheat compared with a flat surface [35,36], is similar to the conventional fluidized/free particle bed porous coatings.

For common liquid such as water, it has negative surface tension gradient and cannot improve the wettability on a substrate.

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Nomenclature

d	outside diameter (m)
h	heat transfer coefficient (W m^{-2} °C^{-1})
I	current (A)
L	length (m)
q	heat flux (W m^{-2})
Q	heat transfer rate (W)
R	electric resistance (Ω)
t	temperature (°C)
Δt	wall superheat (°C)
U	voltage (V)
W	width (m)
Greek symbols	
δ	thickness (m)
ϕ	inner diameter (mm)
τ	time (s)

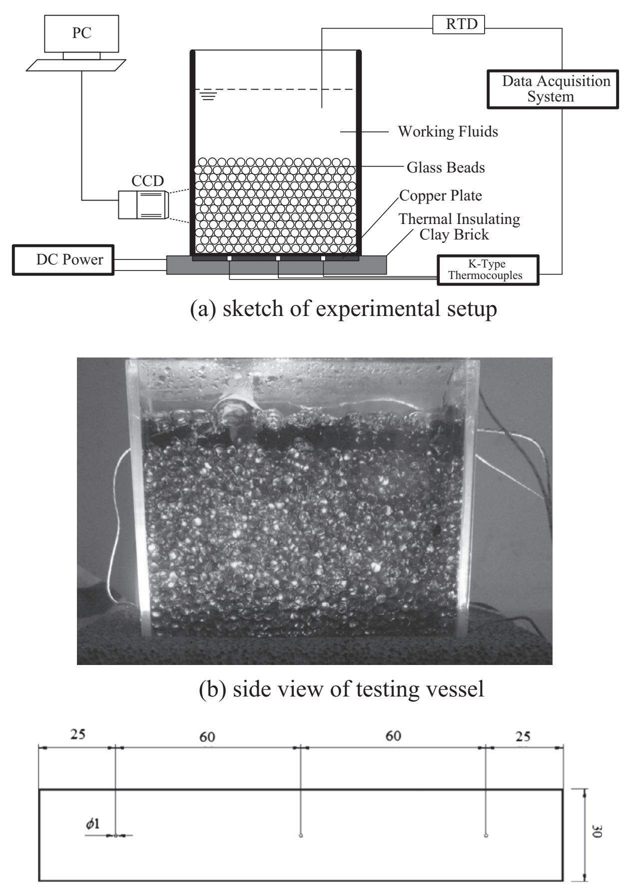
Liquids, especially self-rewetting fluids or dilute aqueous solutions of high carbon alcohols (carbon atom numbers $\geqslant 4$), that exhibit positive surface tension gradient from a certain temperature onward can improve the wettability on a substrate, since the liquid film flow from the colder regions to the hot spots due to the Marangoni or thermocapillary effect, which always induces liquid flow from lower to higher surface tension regions. Therefore, a different method of enhancing the boiling heat transfer by altering the fluid properties is to use self-rewetting fluids. The properties of self-rewetting fluids create unique interfacial phenomena, such as small bubble circling at a larger bubble interface [37]. This improves the wettability, lowers the temperatures, and enhances the boiling heat transfer and especially the CHF [38–42], and it indicates promising applications in pool boiling and heat pipes with the use of self-rewetting fluids [43–47].

The unique interfacial effects formed in the characteristic geometry of a porous structure is associated with the basic boiling process involving the performance of heat transfer and fluid flow in, e.g., a capillary-driven evaporator, since the bubble dynamics is significantly affected by the porous structure and fluid properties during boiling. In this paper, an experimental study on the boiling characteristics of water and self-rewetting fluids is conducted to investigate the influence of interfacial properties on bubble dynamics and boiling performance in the porous structure formed by packed bed of spherical glass beads, from which it is also expected to provide fundamental data for further development of theoretical models of pool boiling heat transfer in heat pipes and related applications.

2. Experiment set-up and procedures

The sketch of the experimental setup is shown in Fig. 1(a). The testing apparatus consists of a sintered silica vessel with a 210 × 30 mm^2 copper plate heating surface at the bottom. The bottom view distribution of the thermocouples and the geometrical dimensions are shown in Fig. 1(b). The copper plate is mounted at a thermal insulating clay brick, the bottom of which is heated by a 35 Ω electric resistance heater. The heat flux is conducted through the copper plate to the heating surface of the vessel, and the heat loss can be neglected since the outer surface temperature of the brick and the environment temperature are measured to be nearly the same. The electric heating power employs a DC Power supply (Dahua DH1720A-3) with the ranges of the voltage U and the current I are 200 V and 5 A, respectively. The instrumental errors for the voltage and the electric current are 1.0 V and 0.05 A, respectively. The heat flux can be calculated by $q = UI/(LW)$, where L and W are the length and the width of heating plate, respectively. Thus, the error for heat flux can be determined by the error transfer formula, or $\Delta q/q = \Delta U/U + \Delta I/I - \Delta L/L - \Delta W/W$, where Δx represents the measurement error for the variable x. The uncertainty of heat flux is estimated to be less than 0.5%.

Three K-type thermocouples are placed in the copper plates, as show in Fig. 1(c), to monitor the temperature of the heating surface and to obtain the heat flux using Fourier's law. The thermocouple junctions are first placed abreast the heating surface through ϕ 1 mm holes that is produced on the copper plate, then the joints and the holes are sealed by heat conductive adhesive to retain the flatness of the heating surface. The uncertainty of the temperature measurement using K-type thermocouples is less than 1.0 °C after linearization. The mean value of the measured temperatures is taken as the surface temperature of the heating plate. The spherical glass beads packed in the vessel for the experiments have uniform diameters of 6 mm, which will make the experimental study easier. The liquid level is higher than the packed layers. Two



(a) sketch of experimental setup

(b) side view of testing vessel

(c) bottom view of copper plate with thermocouple distribution and geometrical dimensions in millimeters

Fig. 1. Experimental setup.