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Effects of nanoparticle behaviors and interfacial characteristics on subcooled nucleate pool boiling over microwire

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ABSTRACT

The flow and heat transfer characteristics of nanofluid were attracting many researchers during the last two decades. Convection heat transfer in it is especially important for its potential applications. Therefore, it is crucial to study the nanoparticle behaviors near the near wall region and the interfacial property, which are dominant in nanofluid convection heat transfer. In this investigation, stable nanofluid was prepared with alumina nanoparticles (30 nm in diameter) and deionized water. The nanoparticle behaviors near the liquid wedge of bubbles were observed by high-speed CCD camera. The effects of nanoparticle behaviors in this region and the interfacial characteristics at the liquid–vapor interface on convection of nanofluid were experimentally investigated. Flocculent nanoparticle clustering was observed swirling near the liquid wedge, when the heat flux is relatively small. The microscopic morphology of the nanoparticle deposition layer at the heated surface was characterized by SEM images. It seems that the deposition layers could modify the morphology, but it also delays the detachment of small bubbles from the heated surface. While n-butanol was included as surfactant which will change the liquid/vapor interfacial property, it intensifies the nanoparticle deposition for low heat flux conditions. The analysis shows that the critical heat flux of nanofluid can be obviously improved when n-butanol was included in the nanofluid. It also shows that the inhibited bubble growth and enhanced nanoparticle clustering in the liquid wedge region are the main reason for the heat transfer deterioration when increasing the amount of surfactant in nanofluid. A comparative experiment indicates that the effect of surfactant on convection heat transfer is greater than the unstable deposition formed by nanoparticles.

1. Introduction

Recent researches on nanofluid for enhancing the heat transfer in various thermal systems have shown to be promising for dissipating ultrahigh heat fluxes. Its practical application, however, is thus far hindered by the lack of understanding for the role of nanoparticles in the heat transfer of fluids [1]. For example, it is well recognized that while heat transfer deterioration in the nucleate boiling regime could be observed, an enhancement of the critical heat flux is always obtained [2–8]. The heat transfer deterioration can be attributed to the changes in nucleation site density and surface roughness because of nanoparticle deposition, but the critical heat flux enhancement cannot be explained by adopting Zuber's hydrodynamics model [9]. It is suggested that nanofluid boiling heat transfer is attributed to the nanoparticle pinning effect in the contact line region through the structural disjoining pressure creating from the ordered layering of nanoparticles in the confined wedge of the evaporating meniscus [10]. Recent experiments have also shown that ordered structures can form near the three-phase contact line of a drop on a solid surface [11,12]. The structural disjoining pressure dominates on scales larger than the nanoparticle diameter, below which other disjoining pressure components, such as van der Waals and electrostatic forces, are prevalent [13]. Meanwhile, our previous investigation [14] also indicates that nanoparticle motion in the near wall region is crucial in the mechanism of convection heat transfer in nanofluid. Therefore, understanding the complex nature of nanoparticle behavior and the interactions between the nanoparticles and the solid surface is critical to the comprehension of nanofluid boiling heat transfer.

Although there have already been significant researches into the critical heat flux (CHF) enhancements in nucleate boiling of nanofluids, further research on CHF enhancements of nanofluids with self-rewetting fluids as surfactant was investigated to a lesser

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Nomenclature

d_b	bubble diameter (m)
d_w	heater diameter (m)
f_a	mass fraction of SHMP (%)
f_p	mass fraction of nanoparticles (%)
f_s	mass fraction of n-butanol (%)
I	current (A)
l_w	heater length (m)
q	heat flux (Wm^{-2})
q_{cr}	critical heat flux (Wm^{-2})
R	electric resistor (Ω)
T	temperature (°C)
T_w	wall temperature (°C)
T_0	reference temperature (°C)
U	voltage (V)

Greek symbols

β	proportional constant

Subscripts

a	sodium hexametaphosphate
b	bubble
cr	critical
p	nanoparticle
s	surfactant
w	wire

extent [15]. The self-rewetting fluids were investigated as new heat transfer fluids that have unique surface tension property in the high temperature region that increases with increasing temperature [16–18]. The self-rewettability of dilute aqueous solutions of high carbon alcohols, e.g., butanol, pentanol, etc., was expected to prevent the development of local dry patch and to improve the CHF to some extent. Within two-phase heat transfer device, such as heat pipes, condensed liquid is spontaneously driven to the high-temperature area improving the CHF and the maximum heat transport rate. Further investigations on thermal performs of self-rewetting fluids were conducted by inclusion of nanoparticles, e.g., single-wall carbon nanohorns [15]. However, rare research paid attention to the convection heat transfer of nanofluid with self-rewetting surfactant on micro heated source. The interfacial characteristics changed by surfactant and its effect on convection heat transfer near the three-phase contact line are needed to be investigated.

Some interesting phenomena in the experiments, such as bubble sweeping and bubble-top jet flow, were observed in the researches on microscale nucleate boiling [19–21]. It was suggested that these phenomena could be explained by the asymmetric temperature, pressure or surface tension distribution on both sides of the sweeping bubble [22–25]. Therefore, the surface tension induced Marangoni effect is a crucial factor that influences the bubble interactions. For nanofluid with self-rewetting surfactant, however, it is unclear what is the role of nanoparticle behaviors in the convection heat transfer, especially in the near wall region. In this paper, alumina nanofluids with surfactant, n-butanol, will be used to employ both the class of nanofluid and self-rewetting fluid. The novel nanofluid will be experimentally investigated using high-speed CCD camera system for microscale convection heat transfer, with depiction of nanoparticle behaviors in the near wall region, the surface characterization of nanoparticle deposition, and the heat transfer characteristics for various nanofluids with or without surfactant.

2. Nanoparticle behaviors

Preparation of well-dispersed and stable nanofluid is critical for enhancing heat transfer. We adopted the effective but simple two-step method to prepare the nanofluids. The nanoparticle is α-Al_2O_3 (manufactured by Nachen Beijing), 30 nm in diameter (d_p). Deionized water is used as the base fluid. Sodium hexametaphosphate (SHMP), 0.1% in mass fraction (f_a), is employed for adjusting the pH value at 8. The mixture of nanoparticle, deionized water and SHMP is vibrated by an ultrasonic oscillator for an hour. Using this method, nanofluids with different mass fractions (f_p) are prepared, namely 0.03% and 0.06%. It is observed that these nanofluids are stable for months.

Nanoparticle behaviors in the near wall region are observed with a high-speed CCD (Luster LightTech MC1310, 500 fps), using a data acquisition module (Agilent 34970). Fig. 1 shows the schematics of the experimental set-up for observing nanoparticle behaviors during convection heat transfer over a micro platinum wire. The diameter (d_w) of platinum heater is 30 μm, and the length (l_w) is 65 mm. The size of the glass container is 25 × 25 × 25 cm. The wire is connected on the electric connectors, heated by a DC Power Supply (Dahua DH1720A-3), and fixed on an adjustable bracket, recording the voltage U and current I at the wire ends, to calculate the heat flux by $q'' = UI/(\pi d_w l_w)$. The recorded voltage and current is further used to calculate the mean surface temperature by using the resistance–temperature relation for electric resistor, or $R = R_0[1 + \beta(T - T_0)]$, where $R = U/I$ is the electric resistance of heating wire, R_0 is the electric resistance at the reference temperature T_0, T is the temperature, and β is the proportional constant. The wall superheat can be obtained with the surface temperature calculated and the fluid temperature measured by the thermocouple which is far away from the wire, as shown schematically in Fig. 1. The container is kept in an environment at atmospheric pressure. The central part of the heating wire is observed.

The error for heat flux can be calculated by the error transfer formula, or $\Delta q''/q'' = \Delta U/U + \Delta I/I - \Delta d_w/d_w - \Delta l_w/l_w$, where Δx represents the measurement error for x, and the error is estimated to be less than 1.0×10^3 W/m^2 when x is q''. The error for average

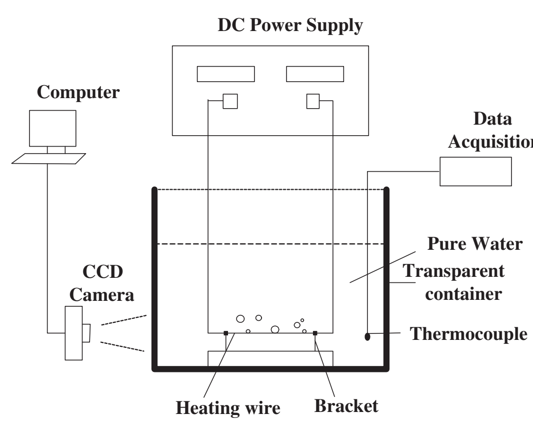

Fig. 1. Schematics of experimental set-up.