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An experimental study on deposited surfaces due to nanofluid pool boiling: Comparison between rough and smooth surfaces

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ABSTRACT

This paper presents an investigation of the boiling heat transfer of iron oxide/de-ionized water nanofluid on a flat copper surface under atmospheric pressure. Measurements were conducted to evaluate the effects of nanofluid concentration, surface type, surface roughness, sedimentation thickness, and heat flux on the roughness of the surface after boiling experiments. For this purpose, the effect of sedimentation of the nanofluid on both the smooth and the rough surfaces on the boiling heat transfer of the nanofluid was investigated through some experiments. Results showed that after the boiling test on the rough surface, boiling heat transfer of nanofluids reduced at low heat fluxes, while it increased in high heat fluxes. Moreover, after the boiling test on the smooth surface, boiling heat transfer of nanofluids increased at low heat fluxes, while it did not change in high heat fluxes. Results also indicated that the effects of surface deposition were more evident at high nanofluid concentrations. Furthermore, for rough surfaces with high heat flux and smooth surfaces with low heat flux, it was observed that boiling heat transfer can be increased by making a deposit on the surface.

1. Introduction

Boiling is one of the efficient mechanisms of heat transfer employed in different engineering applications, and its enhancement has been a topic of interest to many researchers in recent years. Different methods for enhancing of heat transfer are divided into two categories, namely the active and passive methods. Passive methods include rough surfaces, extended surfaces, and addition of materials to the fluid, and examples of active methods include use of electrostatic fields and inducing vibrations to the surface or the fluid [1,2].

Nanofluids are known as suspension of solid nanoparticles with sizes smaller than 100 nm in conventional fluids. Addition of nanoparticles is considered a passive technique in enhancement of boiling heat transfer. Numerous researches have been conducted on heat transfer and thermophysical properties of nanofluids [3–23].

Review of previous researches shows that nanofluids boiling heat transfer is performed in different experimental conditions. Some studies have been done on thin wire and other studies have been completed on a flat surface as a boiling surface. Boiling heat transfer on a flat surface is very useful and reliable compared to that on thin wires [24]. Recent studies of nanofluids boiling on thin wire and flat surface, respectively, are summarized in Tables 1 and 2.

According to the literature studies, no consistent results exist regarding the coefficient of boiling heat transfer when the nanoparticles increase. Although some researchers reported no changes in the coefficient of boiling heat transfer, some other reported its reduction, and other reports indicated its increase. Hence, in order to achieve consistent results on this matter, further studies are to be conducted on the parameters affecting the boiling characteristics of nanofluids including geometry and topology of the surface [24,30].

With regards to the significance of the changes in the boiling surface caused by the boiling heat transfer, some of the major studies on this issue are briefly introduced in the followings.

Suriyawong and Wongwises [43] investigated the boiling heat transfer of water/titanium oxide on both copper and aluminum surfaces. The pool boiling heat transfer coefficient of the copper surface was higher than the aluminum surface. This difference in the heat transfer coefficient is probably due to the characteristics of the surface of heaters and nanofluid interfaces affecting the triple contact line, formation of bubbles, and their separation.

Kim et al. [27] investigated the characteristics of pool boiling heat transfer for suspensions of nanoparticles of aluminum,

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Nomenclature

C_p	specific heat (J/kg K)
C_{sf}	coefficient in Rohsenow correlation
d	distance (mm)
h	heat transfer coefficient (W/m^2 K)
h_{fg}	fluid's latent heat (J/kg)
K	thermal conductivity (W/m K)
n	power in Rohsenow correlation
Pr	Prandtl number
q''	heat flux (W/m^2)
R_a	average roughness of the surface (μm)
T	temperature (K)
t	time (min)
U	uncertainty

Greek symbols

μ	dynamic viscosity (N/m^2)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ς	electrical charge
φ	roughness parameter

Subscripts

l	liquid
s	surface
sat	saturated
v	vapor

zirconium oxide, and silicon in water for low volume concentrations (lower than 0.1 wt%) .A stainless steel wire of 0.381 mm with a length of 120 mm was used as the heating source. According to the results, some of the nanoparticles precipitated on the heater surface. The precipitated layer increases the wettability of the surface by reducing the static contact angle on the heater surface. Hence, this increase in the wettability of the surface results in lower chances for the nanoparticles to fill the nucleation cavities, lower density of nucleation sites, and lower coefficient of boiling heat transfer.

Das et al. [33,34] investigated the characteristics of pool boiling heat transfer of water/alumina oxide nanofluid on horizontal cylinders with different surface roughness. Nanofluids of 4–16 weight percent were used in these experiments. The authors reported a surface roughness of 0.37–0.45 μm, which was larger than the nanoparticle sizes by an order of one. The reported results indicated that sedimentation of nanoparticles on the surface caused filling of the cavities, and consequently, a reduction in the heat transfer. Moreover, the coefficient of boiling heat transfer decreased as the concentration of nanoparticles increased. Therefore, heat transfer was dependent on the surface roughness and the weight percent of the nanoparticles.

Bang and Chang [36] studied the boiling heat transfer of the water/alumina oxide nanofluid on a smooth surface. This experiment was conducted on a rectangular surface of 400 mm^2 area. The surface roughness was 37.22 nm, which was 10 nm smaller than the average size of the nanoparticles (47 nm). Nanofluids of 2–14 wt% were used in these experiments. According to their observations, although the roughness of the heater surface increased, the coefficient of boiling heat transfer decreased with increases in the concentration of the nanofluid. Moreover, heat transfer performances of natural convection and nucleate boiling decreased compared to water. With increases in the concentration, they reported decreases in the coefficient of heat transfer, and on the contrary, increases in the critical heat flux.

Chopkar et al. [37] conducted pool boiling heat transfer experiments on a rough heater (0.5–0.7 μm) with suspension of zirconium oxide in water as the nanofluid (nanoparticle diameters of 20–25 nm) at low concentrations (lower than 15 wt%). According to their observations, although the roughness of the heater surface decreased during boiling of the nanofluid (with 0.005 wt%), but the coefficient of heat transfer increased.

Narayan et al. [38] conducted experiments on the boiling of water/alumina oxide nanofluid (with average nanoparticle diameters of 47 and 150 nm) on vertical pipe heaters with different roughness (48, 49 and 524 nm as reported). According to their reports, for high weight percentages of nanofluids (4–16 wt%), the boiling heat transfer decreased as the nanofluid concentration increased. They also investigated the nanofluids with low concentrations (0.32–1.25 wt%). The coefficient of pool boiling heat transfer for an average nanoparticles size of 48 nm was reduced by up to 70 percent for a roughness of 524 nm and at a concentration of 0.5 wt%, and up to 45 percent for a roughness of 48 nm and at a concentration of 2 wt %. They introduced the surface interaction parameter defined as the ratio of the surface roughness divided by the average size of the particles. For parameter values larger than 1, they concluded that the heat transfer increases as the roughness of the surface is far larger than the size of the particles. In this case, the nanoparticles deposit on to large cavities, nucleation sites are divided into several ones, and as their density as well as the number of locations for formation of bubbles increase, the heat transfer also increases. According to their conclusions, in case the particle dimensions are smaller than those of surface roughness, the number of nucleation locations significantly decreases, causing occlusions in these location and, hence, decreases in the heat transfer.

Shahmoradi et al. [24] investigated the pool boiling of water/alumina oxide nanofluid with concentrations smaller than 0.1 wt % on smooth surfaces. In their study, different parameters including the coefficient of heat transfer, critical heat flux, the changes in the structure of the boiling surface, and the wettability of the surface were investigated. For surface interaction parameter values lower than unity, the coefficient of heat transfer decreased, while the critical heat flux increased. Reportedly, the main reason for the decrease in the heat transfer was filling of the nucleation sites by the precipitated layer of nanoparticles during the boiling process, which caused a thermal resistance. Moreover, the increase in the critical heat flux was attributed to the increase in the wettability of the surface. The images obtained from atomic force microscopy (AFM) showed that the surface roughness could either increase or decrease, depending on the initial conditions of the surface.

Raveshi et al. [2] investigated the pool boiling heat transfer of water-ethylene glycol/alumina nanofluid with different concentrations lower than 1 wt% on a cylindrical heater. The roughness of the heater surface was twice the size of the nanoparticles, meaning that the value of the interaction parameter was greater than one. Unlike other studies where a direct approach was taken to measure the surface temperature, extrapolation was used to measure the surface temperature in their study. The authors reported that with increases in the concentration, the density of the nucleation sites, the surface roughness and the coefficient of boiling heat transfer also increased. The heat trans-