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EVALUATION OF SURFACE ROUGHNESS AND NANOFLUID CONCENTRATION ON THE SURFACE WETTABILITY AND THE WALL-TEMPERATURE DISTRIBUTIONS

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Abstract: *The pool boiling phenomena can be large affected by fluid/surface interaction caused by changes in the surface roughness or in the properties of the working fluid by adding nanoparticles to the base fluid. This work focuses on the effect of surface roughness and nanofluid concentration on the surface wettability and the wall-temperature distributions. It also discusses their effects on nanofluid pool boiling heat transfer. The tests were performed on copper heating surfaces with different roughness values, in order to analyze the interaction between the surface roughness and nanoparticles deposited on the heating surface. Nanostructured surfaces were produced through the boiling process of Al2O3-water based nanofluid for different mass concentrations. The surfaces were submitted to metallographic, roughness, wettability and thermal image analysis. As nanofluid concentration increases, the surface roughness also increases and the contact angle decreases, showing a hydrophilic behavior. It was observed that the smooth surface has the lowest heat transfer performance compared to the other surfaces. The nanolayer formed on rough surfaces increases the thermal resistance of the surface, degrading the heat transfer; however, for smooth surfaces, the nanoparticle deposition increases the boiling heat transfer only for low nanofluid concentrations.*

Keywords: *nanofluid pool boiling, HTC, surface wettability, thermal analysis.*

1. INTRODUCTION

Studies on the influence of nucleated pool boiling encouraged the scientific community to investigate new techniques for intensifying the boiling heat transfer coefficient (HTC), such as the use of nanoparticles suspended in a base fluid (nanofluids) and micro and nanostructured surfaces.

The use of nanofluids in the nucleate pool boiling has been extensively investigated because of its ability to change the wettability due to the formation of nanoscale structures deposited on the heating surface. However, the influence of nanofluid on the HTC was not fully understood. Quan et al. (2017), Manetti et al. (2016) and Shahmoradi et al. (2013) studied the influence of the nanostructured surface on the wettability, varying the nanofluid concentration.

The deposition rate of nanoparticles is proportional to the concentration of nanofluid, i.e., for high concentrations of nanofluid it leads to the decrease in the number of active nucleation sites and then increase the thermal resistance on the heating surface (Vafaei, 2015). Sarafraz et al. (2013) reported that wettability increased due to the deposition of nanoparticles, reducing nucleation sites and the degradation of the HTC.

Several studies have been applying the IR technique to observe the thermal behavior of heated surfaces in the boiling and condensation problems such as Sefiane et al. (2008), who used IR thermography to visualize the spontaneously occurring hydrothermal waves within evaporating methanol, ethanol, and FC-72 droplets. Golobic et al. (2009) and Stephan (2009) used an IR camera to measure the heat transfer distribution under single nucleating bubbles as they grew on a thin metal foils.

Also Gerardi et al. (2010) used a high speed IR camera in combination with a video camera to measure bubble behavior. The IR camera measured the temperature distribution at the surface, while a video camera was used to visualize the fluid behavior.

Krebs et al. (2010), Shen et al. (2010) and Mani et al. (2012) used IR thermography to study flow boiling in microchannels, droplet evaporation, and jet impingement, respectively. In these studies, an IR camera was used to visualize in great detail the temperature distribution at the substrate/water interface. In Kim et al. (2012), a midwave IR camera was used to measure the temperature variations within a multilayer silicon substrate coated with a thin thermal insulator that is partially transparent to IR. The insulator amplifies the temperature variations and provides a strong signal for the IR camera. Since silicon is largely transparent to IR radiation, the temperature of the inner and outer walls of the multilayer could be measured by coating selected areas with a thin IR opaque film.

Based on the literature review, this work focuses on the effect of surface roughness and nanofluid concentration on the surface wettability and the wall-temperature distributions by analysis of pictures of a sessile droplet and thermal image analysis, respectively. Also, the nanofluid pool boiling heat transfer was analyzed.

2. EXPERIMENTAL PROCEDURE

The analysis of nanofluid pool boiling heat transfer were based on data from Manetti et al. (2016), which was carried out on copper heating surfaces with different roughness values, corresponding to a smooth surface (R_a = 0.05 μm, namely SS) and a rough surface (R_a = 0.23 μm, namely RS).

Six different copper surfaces, four of them being nanocoated were analyzed: two smooth surfaces with nanoparticle deposition, at low and high concentration of Al_2O_3-water based nanofluid (namely Al-SS-LC and Al-SS-HC) and two rough surfaces with nanoparticle deposition, at low and high concentration of Al_2O_3-water based nanofluid (namely Al-RS-LC and Al-RS-HC). The nanocoated surfaces were obtained by boiling process of Al_2O_3-water based nanofluid, applying a heat flux range of 100 to 800 kW/m².

The Al_2O_3-water based nanofluid was prepared by the two-step method and then submitted to ultrasonic agitation during three hours to ensure full dispersion of nanoparticles. Two different nanofluids concentrations, 0.029 g/l (corresponding to low nanofluid concentration, LC) and of 0.29 g/l (corresponding to high nanofluid concentration, HC), were used.

The techniques used to obtain the surfaces characteristics consisted of scanning electron microscopy (SEM), average surface roughness given by a rugosimeter (R_a), static contact angles measured by analysis of pictures of a sessile droplet (experimental apparatus showed in Fig. 1) and, wall-temperature distribution by thermal imaging camera.

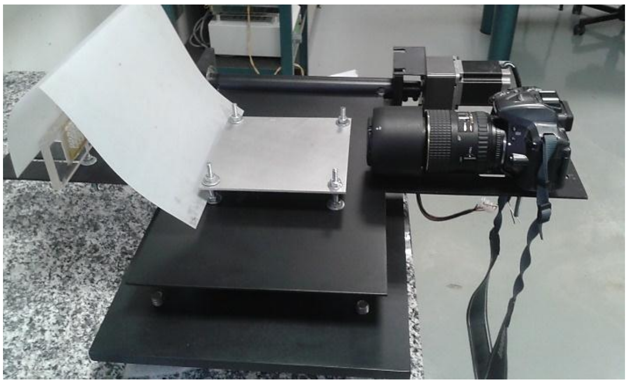


Figure 1. Experimental apparatus for measuring the contact angle. (the measurement procedure is described by Manetti et al., 2016)

Figure 2 shows the schematic layout of the experimental setup to analyze the wall temperature distribution. Firstly, the uncoated rough heating surfaces (RS) were used as the impingement targets and, DI water and Al_2O_3-water based nanofluid droplets (with different mass concentration) were studied by recording the impingement process with a Nikkon D- 5300 digital camera. Thermal distribution was measured with a Fluke Ti-09 infrared camera.

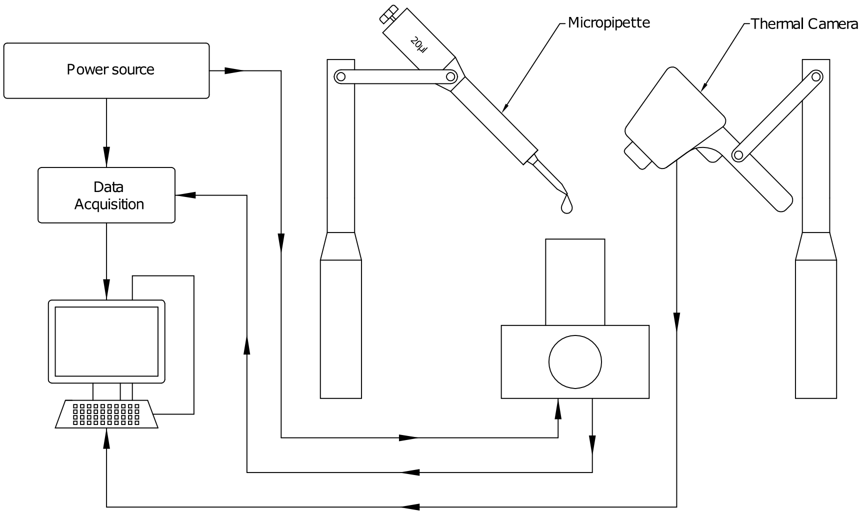


Figure 2. Schematic of the experimental setup to analyze the wall-temperature distribution.

The test section consists of a copper block (20 mm diameter) with K-type thermocouples fixed in the cylindrical part to determine the wall temperature. The copper block is heated by one cartridge resistance with a maximum power of 300 W and the surface temperature used in the present study was 80 °C. The thermal insulation of the test section consists of polytetrafluoroethylene and vermiculite. The undersides of the test section were coated with a black spray paint, allowing temperature measurement by thermal imaging camera.

Alumina nanofluid droplets, for low nanofluid concentration and for high nanofluid concentration, were applied to the upper part of the heating surface to modify the surface wettability; one heating surface was left uncoated by using DI water droplet as the reference surface.

The temperature uncertainty was ± 0.4 ºC. For all surfaces tested, the experimental uncertainty for the heat flux and for the heat transfer coefficient varied from 1.7% to 15%, and from 3.1% to 17.5%, respectively.

3. RESULTS AND DISCUSSION

Two different copper surfaces were analyzed. Images of the copper heating surface can be seen in Fig. 3, as well as the scanning electron microscopy (SEM), obtained by the EVO LS15 Zeiss®.

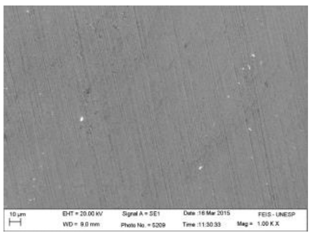
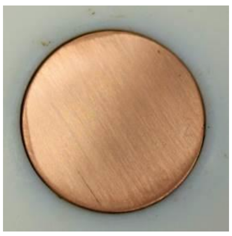
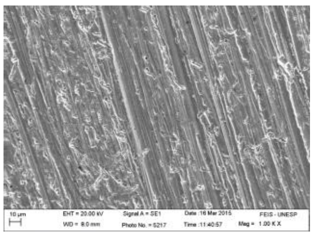
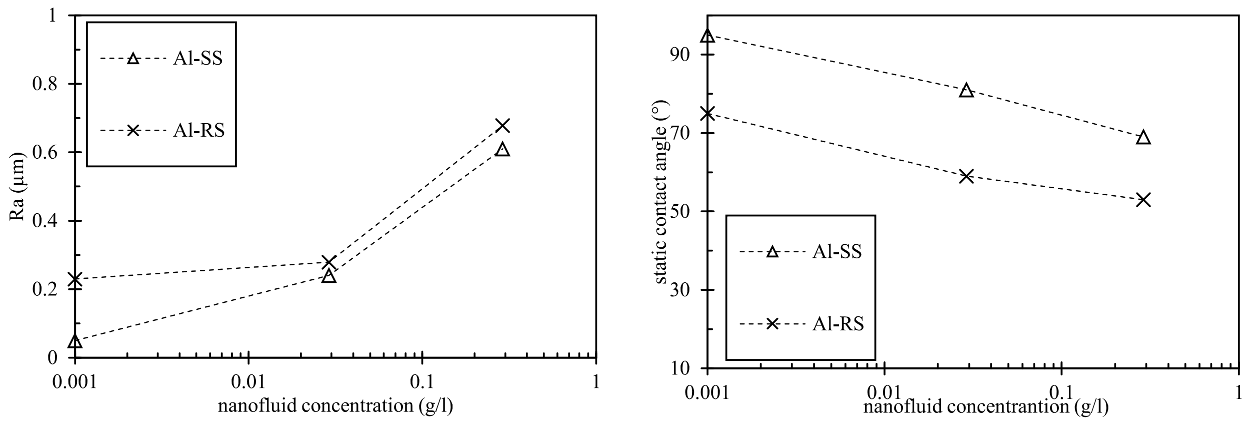
Surface	SEM Image
 SS	
 RS	

Figure 3. Test section before boiling process. Smooth surface (SS) and rough surface (RS).

To analyze the effect of the nanofluid mass concentration on the surface roughness and the surface wettability, Fig. 4 shows the average surface roughness R_a (by a Mitutoyo Surftest SJ 301 model) and the pure water static contact angle measurement (by experimental apparatus, Fig. 1), before and after Al_2O_3-water nanofluid boiling process as a function of nanofluid concentration, for smooth and rough surface.

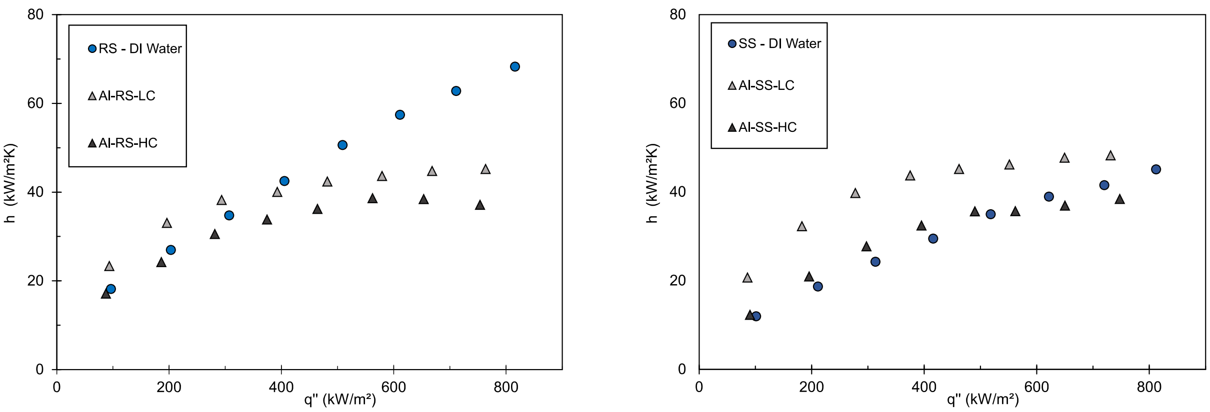


(a) (b)

Figure 4. Heating surface behavior before and after Al_2O_3-water nanofluid boiling process for different mass concentrations. (a) surface roughness and (b) pure water static contact angle.

Figure 4a shows that the surface roughness increases as the mass concentration of the nanofluid increases. This is due to the deposition of nanoparticles on the surface. However, for the static contact angle the increase of the mass concentration of the nanofluid improves the wettability according to the results shown in figure 4b.

The analysis of the experimental results reported by Manetti et al. (2016) shows that the enhancement or deterioration of alumina nanofluid boiling heat transfer is affected by the original surface roughness and the nanofluid concentration and also, the interactions between them (Fig. 5).



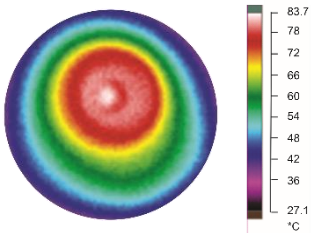
(a) (b)

Figure 5. Boiling HTC curves for DI water and Al_2O_3-water based nanofluids. (a) rough surface. (b) smooth surface.

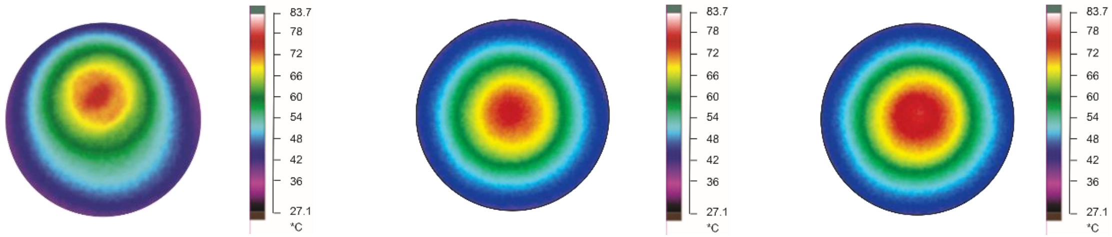
All HTC curves using nanofluids show a change in slope from the 400 kW/m² flow. This effect is due to the deposition of the nanoparticles on the heating surface, which increases with increasing heat fluxes.

For smooth surfaces (SS) and for low nanofluids concentration one may observe an HTC enhancement as compared to DI water, which is related to the increase of the microcavities, due to changes in the surface morphology during nanofluid pool boiling. Boiling heat transfer degradation was observed for high nanofluid concentration independently of the surface roughness; the thicker nanolayer formed on the heating surfaces increases the thermal resistance of the surface.

Figure 6 the wall-temperature distribution for rough heating surfaces (RS) for DI water and for Al_2O_3-water based nanofluids to low and high mass concentration, respectively. It was not possible to obtain thermographic images of the smooth surfaces (SS), because the infrared rays reflection is considerable, leading to the infrared camera to interpret the wall-temperature distribution in the wrong way.



(a)



(b) (c) (d)

Figure 6. Wall-temperature distribution on the rough surface (RS): (a) before the impingement process; (b) infrared image of DI water droplet impingement; (c) infrared image of Al_2O_3-water based nanofluid droplet impingement (at low nanofluid concentrations) and, (d) infrared image of Al_2O_3- water based nanofluid droplet impingement (at high nanofluid concentrations).

The droplet impingement on top of the heating surface decreases the surface temperature and the cooled area increases in diameter over time, but its growth rate depends on the working fluid. Figure 6 shows that the area affected by the nanofluid droplet is smaller than the area affected by the DI water droplet, indicating that the DI water droplet removed more heat from the rough surface than the alumina nanofluid droplet, independently of the nanofluid concentration.

The wall-temperature distribution for rough surface agrees with the HTC behavior showed in the Figure 5a. For rough surface and for Al_2O_3-water based nanofluid it was observed HTC deterioration as compared to the DI water. The microcavities are filled by the nanoparticles increasing the nanolayer formed on the heating surface, which leads to an enhancement in the thermal resistance and HTC degradation. The increase in the surface temperature and, consequently, HTC degradation is more pronounced for high nanofluid concentrations.

The nanoparticles deposition due to nanofluid pool boiling process not only changes the surface wettability but also increases the surface roughness. Both nanofluid concentrations increase the surface wettability due to changes on surface tension by adding nanoparticles on the base fluid, as presented by Bhuiyan et al. (2015).

It was observed that as the nanofluid concentration increases the surface roughness, wettability and thickness nanolayer also increases, changing the wall-temperature distribution on the heating surface.

4. CONCLUSIONS

The effect of surface roughness and nanofluid concentration on the surface wettability and the wall-temperature distributions were analyzed. Also, the nanofluid pool boiling heat transfer performance. The tests were performed on copper heating surfaces with different roughness values and the nanocoated surfaces were produced through the boiling process of alumina nanofluid for different mass concentrations. The main conclusions are:

- The nanofluids decrease the static contact angle, and this behavior is most notable in nanocoated surfaces, produced after nanofluids boiling process.

- Surface roughness and the static contact angle depend on the nanofluid concentration. As a result, nanofluid concentration increases the surface roughness; wettability and thickness nanolayer also increase by changing the temperature gradients also in surface thermographic profile. In this work it was observed that the original surface features had less influence on the behavior of wettability.

- The area affected by the nanofluid droplet is smaller than the area affected by the DI water droplet, indicating that the DI water droplet removed more heat from the rough surface than the alumina nanofluid droplet, independently of the nanofluid concentration. Thus, the wall-temperature distribution for rough surface agrees with the HTC behavior.

5. ACKNOWLEDGMENTS

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