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Pool boiling of nanofluids on biphilic surfaces

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Introduction

Pool and flow boiling is being widely explored to develop liquid cooling systems to dissipate high thermal loads, within a broad range of applications, from solar panels [1] to electric vehicles [2]. The highly demanding cooling conditions required, encouraged researchers to further improve the pool and flow boiling heat transfer processes, either by altering the surface or the liquid properties. Dealing with customized surface properties, most authors propose changing surface topography, by means of a variety of micro-and-nano structuration techniques. However, given the paramount role of wettability in bubble dynamic mechanisms, recent studies have shown interesting heat transfer enhancement achievements, by combining extreme wetting scenarios [3]. On the other hand, the use of nanofluids has also been widely explored for cooling purposes within the last decade [4]. Nevertheless, relevant issues must still be clarified, mostly regarding the reproducibility of the nanofluid properties, depending on the fluids preparation, the stability of the nanofluids and a detailed analysis of the local wettability modifications, which may explain the discrepant and sometimes contradictory results reported in the literature, on the role of the nanofluids in the effective enhancement of pool boiling heat transfer processes.

In this context, the current work addresses combining customized surface modification with the use of nanofluids, to further enhance pool boiling heat transfer. Hence, biphilic surfaces, i.e. hydrophilic surfaces patterned with superhydrophobic regions are prepared and used to boil nanofluids, and infer on the effect of the nature and concentration of the nanoparticles in bubble dynamics and consequently in heat transfer processes. The analysis performed here combines high-speed visualization with time and spatial resolved infrared thermography to derive a detailed description of bubble dynamics phenomena, which is then used to explain the obtained surface temperature fields and the heat transfer processes.

Experimental set-up and procedures

The nanofluids are prepared as solutions of water DD with nanoparticles of aluminum, silver and gold, with mass concentrations varying between 0.05% and 1%. All the solutions are characterized in terms of density, dynamic viscosity, specific heat, conductivity and surface tension. These properties are evaluated at room temperature (20º±3ºC), except for conductivity, which is measured at different ambient temperatures, between 20ºC and 60ºC.

The biphilic surfaces were prepared on a 20µm thick stainless-steel foil (AISI304). The biphilic patterns were obtained by applying a mask on the foil, which was then sprayed with a superhydrophobic coating (a commercial compound called Neverwet, from RustOleum). The patterns were varied in terms of the size of the superhydrophobic regions and of the distance between them. Hence, the diameter of the superhydrophobic regions was varied between 1.5mm and 5.2mm, while the distance between them was varied between 0.5 and 2 times the characteristic bubble diameter, which is limited by the size of the superhydrophobic region.

Each pair liquid-surface was characterized in terms of wettability, measuring the static and quasi-static contact angles, using an optical tensiometer (THETA from Attention). The surfaces were also characterized in terms of their topography, using a Dektak 3 contact profilometer (Veeco) with a precision of 0.02µm. The superhydrophobic regions depict a regular roughness, with an average roughness value of R_a = 4.59µm and a peak-to-valley roughness value of R_z = 19.25µm, measured in the direction perpendicular to the view of the high-speed camera. In the direction parallel to the view of the high-speed camera, R_a =7.17µm and R_z =25.9µm. The hydrophilic regions are smooth within the precision range of the equipment used. A confocal microscope (SP8 from Leica) was further used in the transmission mode to reconstruct the surface topology and qualitatively assess possible surface defects or large topographical heterogeneities.

Preheated and degassed water enter a boiling chamber and is kept at saturation temperature T_{sat} = 100ºC (at atmospheric pressure) with a PID controller, which regulates the heating of a cartridge heater. Two electric resistances and a coil heater help to keep the working fluid at the required temperature. Pressure and temperature of the working fluid were monitored using a pressure transducer (OMEGA DYNE INC) and two type K thermocouples. These sensors allow keeping the temperature and the pressure inside the boiling chamber controlled with a precision of 1ºC and 1.6 mbar, respectively.

The heating surface was a stainless-steel foil (AISI304), heated by Joule effect, by controlling the current provided by a HP6274B DC power supply. Current values varying between 3A and 9A allowed imposing a heat flux to the heating surface ranging between of 0.025 W/cm^2 and 0.229 W/cm^2

Bubble dynamics and heat transfer were obtained from synchronized high-speed and thermal images, using a high-speed camera (Phantom v4.2), placed on a frontal glass window of the boiling chamber and an infrared camera (Onca MWIR-InSb-320), which was placed below the surface. The frame rate of the high-speed camera was set to 2200 fps while the high-speed infrared camera images were recorded at 1000 fps. The pixel size µm/pixel, for the optical arrangements used here was 100µm for the infrared camera and 40µm for the high-speed camera.

Sample results

The results show that bubble growth is restricted to the size of the superhydrophobic regions, thus the entire bubble growing and detachment processes are affected by the size of the superhydrophobic regions. The detailed analysis of bubble dynamics that will be shown in the final presentation indicates that although lager superhydrophobic regions produce large vapor bubbles, their detachment frequency is significantly lower, so that larger regions become less efficient in promoting liquid evaporation. Such trend is quite evident in Figure 1 a) which depicts the evaporated mass flux as a function of the imposed heat flux, for different base diameters of the superhydrophobic region. This trend naturally affects the term of the heat flux associated to the latent heat of evaporation, which is therefore promoted for smaller superhydrophobic regions. Regarding the distance between superhydrophobic regions, the results based on bubble dynamics show that for distances larger than two bubble diameters, each superhydrophobic region behaves as a single nucleation site. For distances smaller than one bubble diameter, coalescence effects become dominant, endorsing the formation of large vapor blankets that insulate the surface, leading to a “quasi-Leidenfrost” boiling regime, as reported by [5] in superhydrophobic surfaces. The optimum distance between superhydrophobic regions seems to be of the order of one bubble diameter. Such distance, favor bubble coalescence, but in a controlled way, maximizing the evaporated mass flux (Figure 1b) and consequently, the heat transfer term associated to the latent heat of evaporation. On the other hand, the thermal images show that this controlled coalescence further promotes an induced flow between the bubbles and the surface, in-between the superhydrophobic regions, thus promoting surface cooling. This trend is supported by heat flux calculations performed based on the data that obtained from the post-processing of the thermal images.

Concerning the use of the nanofluids, large nanoparticles concentrations (>1%) quickly lead to unstable solutions, depicting fast aggregation and deposition of the nanoparticles. For relatively low nanoparticles concentration (between 0.05% and 1%) there is not a significant change in the boiling mechanisms, regardless of the nature of the particles, but there is a mild improvement in the heat transfer, which is attributed to the mild increase of the thermal properties of the resulting nanofluid solutions and to a local increase of the wettability due to the deposition of the nanoparticles, that after the early onset of boiling promoted by the biphilic patterns to occur at very low superheats (1 to 3ºC above saturation), later helps in the rewetting of the induced liquid flow occurring between the bubbles and the surface.

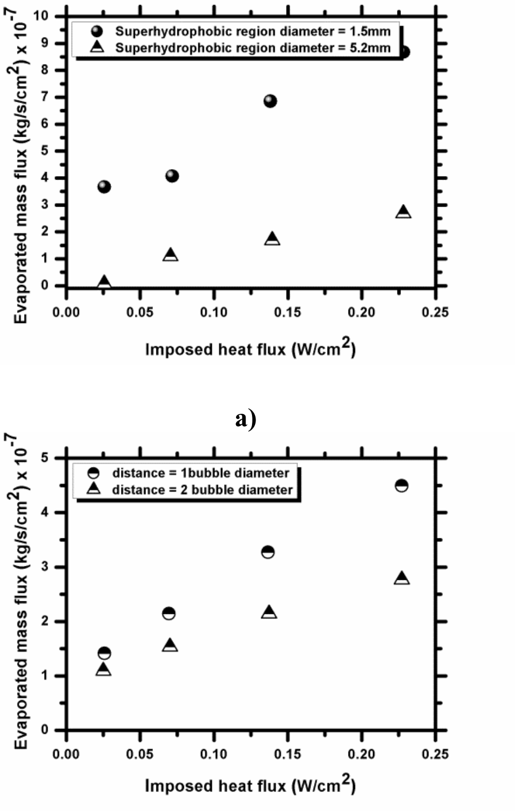

Figure 1: Evaporated mass flux as a function of the imposed heat flux, for water boiling on a biphilic surface. a) Effect of the size of the superhydrophobic regions, b) effect of the distance between adjacent superhydrophobic regions.

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