Pool boiling of nanofluids on biphilic surfaces

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Abstract. This study addresses the combination of customized surface modification with the use of nanofluids, to infer on its potential to enhance pool boiling heat transfer. Hydrophilic surfaces patterned with superhydrophobic regions are prepared and used to act as surface interfaces with nanofluids (water with gold, silver and alumina nanoparticles) and infer on the effect of the nature and concentration of the nanoparticles in bubble dynamics and consequently in heat transfer processes. The main qualitative and quantitative analysis was based on extensive post-processing of synchronized high-speed and thermographic images. The results show an evident benefice of using biphilic patterns, but with well-established distances between the superhydrophobic regions. Such patterns allow a controlled bubble coalescence, which promotes fluid convection at the hydrophilic surface between the superhydrophobic regions, which clearly contributes to cool down the surface. The effect of the nanofluids, for the low concentrations used here, was observed to play a minor role.

1. Introduction
Pool boiling has been widely explored in cooling systems applications to dissipate high thermal loads, e.g. in electronics cooling, UAV’s (for military applications), among others [1]. In this context, several authors have focused on the customization of surface properties to improve pool boiling heat transfer processes. In a recent approach, the so-called biphilic surfaces, i.e. hydrophilic/superhydrophilic surfaces with hydrophobic/superhydrophobic regions show great potential to enhance heat transfer coefficients and delay the occurrence of the critical heat flux e.g. [2]. Apart from a few exceptions focusing on the interpretation of the obtained boiling curves, based on bubble dynamics, combining high-speed visualization and thermography [3] most of these studies address a trial-and-error approach.
to create a biphilic pattern, which is tested to infer if it leads to higher heat transfer coefficients. Accurate description of the intricate relations between bubble dynamics in basic patterns and the associated heat transfer processes occurring during bubble growth and departure are now argued to be vital to devise complex surfaces [4]. On the other hand, nanofluids, i.e. suspensions of a base fluid in the liquid phase with nano-sized particles (1-100 nm) have been widely studied to infer on their usefulness in several industrial applications. While nanofluids theoretically depict improved thermal properties, mainly an enhanced heat conductivity, with respect to their base fluids, they also currently depict several limitations (e.g. molecular-level layering of the liquid at the liquid/particle interface, nature of heat transport in nanoparticles, stability of the suspensions) which restrict their use at the commercial level [5]. Furthermore, their properties (e.g. viscosity, thermal capacity) change, depending on the nature, shape, size and concentration of the nanoparticles in a non-linear way, causing high penalties in terms of the flow hydrodynamic characteristics and fluid pumping which may overcome their potential advantages. In this context, the present work addresses the combination of customized surface modification with the use of nanofluids, to further enhance pool boiling heat transfer. In this case, main emphasis is put on the evaluation of the potential effect of nanofluids concentration together with the use of hydrophilic surfaces patterned with superhydrophobic regions may have on promoting fresh fluid flow within the hydrophilic region (by infrared analysis) and its influence on the surface temperature. The analysis performed here combines high-speed visualization with time and spatial resolved infrared thermography to derive a detailed description of the bubble dynamics phenomena.

2. Materials and methods
Nanofluids were prepared as solutions of distilled water with nanoparticles of aluminum, silver and gold, with mass concentrations varying between 0.05wt% and 1wt%. All the solutions were characterized in terms of density, dynamic viscosity, specific heat, conductivity and surface tension. These properties were evaluated at room temperature (20º±3ºC), except for conductivity, which was 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. The diameter of the superhydrophobic regions was varied between 1.5mm and 3mm, with diameter steps of 0.5mm. The distance between them was fixed to be the size of the bubble characteristic diameter. The surfaces were 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/cm² and 0.229 W/cm². Bubble dynamics and heat transfer were characterized from post-processing of 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 for the optical arrangements used here was 100μm for the infrared camera and 40μm for the high-speed camera. More details on the experimental set-up and experimental procedures is described in [5].

3. Results and discussion
Previous work, reported by Pontes et al. [5] show that there is a peak in the heat flux that is dissipated at each event of bubble departure, because of the induced fluid convection as the bubble leaves the surface. Also, a systematic study on the geometry of the basic biphilic surfaces suggests that the biphilic regions mainly enhance the heat transfer by promoting the fluid flow between superhydrophobic regions, when the size of the superhydrophobic regions is of the order of the size of the base of the bubble. The distance between the superhydrophobic regions should also be of the order of the size of the bubble characteristic diameter. To confirm these recommendations, the work presented here tested the use of different biphilic patterns to boil with water and with different nanofluids. The biphilic patterns addressed here consider: 1st Exp – superhydrophobic regions with 2mm diameter separated by 3.3mm;
2nd Exp – superhydrophobic regions with 2.5mm diameter separated by 3.6mm and 3rd Exp – superhydrophobic regions with 3mm diameter separated by 3.9mm. The heat transfer processes were analyzed on the region illustrated in Figure 1a). Specific temperature profiles were taken in the regions identified by A, B and C, which correspond to a point inside the superhydrophobic region (A), to the boundary between the superhydrophobic region and the hydrophilic surface (B) and in the hydrophilic region (C).

![Figure 1](image)

**Figure 1.** Definition of the area (a) area of analysis of the heat transfer mechanisms and of the points identifying the regions where specific profile temperatures were taken from the surface.

At lower imposed heat fluxes, (*i.e.* with an imposed current up to 5A, which corresponds to an overall imposed heat flux of $q'' = 0.07$ W/m², there is a very similar bubble dynamics behaviour and consequent heat transfer between all the tested patterns: all the patterns lead to a controlled coalescence which is a major mechanism to induce the fluid flow between the superhydrophobic regions. As the imposed heat flux increases, the surface temperature decreases more for the 2nd Exp. pattern, as shown in Figure 2a) and b), which correspond to an imposed current of $I = 7$A and $I = 9$A, respectively ($q'' = 0.13$ W/m² and $q'' = 0.22$ W/m²). The sudden temperature drops observed within the various temperature profiles correspond to a peak in the heat transfer occurring at bubbles departure, in agreement with the phenomena observed in Pontes et al. [5]. Besides the absolute value of the surface temperature being lower for the 2nd Exp pattern, which indicates an enhanced heat transfer (from the surface to the liquid), the temperature drops observed at the different temperature profiles are more prominent on this pattern. The lowest temperature profiles are observed to occur in the hydrophilic regions as the bubble release on the superhydrophobic regions promotes the fluid induced convection in the hydrophilic surface between the superhydrophobic regions, thus enhancing the entire heat transfer process.

As for the use of nanofluids, the results were mainly evaluated to hydrophilic surfaces surrounding a superhydrophobic region. The nanoparticles concentration was kept low (up to 1wt%) to assure stability without the need of using surfactants, which strongly affect the physical properties of the base fluid. For these concentrations only mild differences were observed, for instance in the heat transfer peaks measured during bubble release, which were of the order of 2100W/m² for water, against 2800 W/m² for silver nanofluids (1wt% concentration).

4. Final remarks

This paper presents a fundamental study to infer on the combined use of nanofluids with biphilic surfaces, *i.e.* hydrophilic surfaces patterned with superhydrophobic regions. The first results confirm an effective use of the biphilic pattern to enhance the heat flux dissipation, but only for a well-established distance between superhydrophobic regions, of the order of the characteristic bubble diameter. Such distance allows a controlled bubble coalescence, which promotes fluid convection at the hydrophilic surface between the superhydrophobic regions. This cold fluid motion clearly contributes to cool down the surface, as observed in the heat flux peak and surface temperature maps. The effect of the nanofluids, for the low concentrations used here, plays a minor role, being noticed a slightly higher heat flux for the nanofluids (Ag 1wt%) when compared with water.
Figure 2. Temperature profiles obtained for the various biphilic patterns, for an imposed heat flux of a) \( q'' = 0.13 \text{ W/m}^2 \ (I=7\text{A}) \) and b) \( q'' = 0.22\text{W/m}^2 \ (I = 9\text{A}) \).

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