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# Dynamic wettability evaluation of nanoparticles-coated surfaces

E. dos Santos Filho, F.J. do Nascimento, D.C. Moreira*, G. Ribatski

*Heat Transfer Research Group – Department of Mechanical Engineering, São Carlos School of Engineering, University of São Paulo, São Carlos, SP, Brazil*

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## ABSTRACT

The present study concerns an investigation on the variation of wettability of flat aluminum plates covered with porous thin-films of nanoparticles. Since the contact angle of the obtained surfaces is small, and in many cases the deposited droplet has not achieved a static state, dynamic top-down analyses of spreading droplets were performed. Surface roughness and morphology of the deposited layers were also investigated, in order to provide additional information about the nanotextured surfaces that could be related to their wettability behavior. Aluminum oxide (20–30 nm and 40–80 nm) and silicon oxide (15 nm and 80 nm) nanoparticles were deposited on aluminum plates through a nucleate boiling process. Depositions were obtained through pool boiling of water/$Al_2O_3$ and water/$SiO_2$ nanofluids containing 0.01%, 0.1% and 0.5% in volume of nanoparticles. According to the wettability evaluation, a change in spreading mechanism could be identified, varying from inertially-driven during the first few milliseconds to capillary-driven effects, which in some cases sustained the spreading process even after 1 s. Although deposition of nanoparticles has generally increased surface roughness, no relation between roughness and wettability was found in the present investigation. On the other hand, super-wetting behavior was related to the presence of more particles' clusters on top of the surfaces, possibly enhancing the connections through porous layers.

## 1. Introduction

Heat transfer between solids and fluids is a subject of major concern for science and technology, since the search for highly efficient industrial processes and equipments is usually associated to improved heat transfer. During the last years, advances in micro- and nano-fabrication techniques have enabled various investigations concerning heat transfer in micro- and nanostructured surfaces that, in general, showed significant augmentation of single and multi-phase heat transfer coefficients. Enright et al. [1] conducted a literature review about dropwise condensation on micro- and nanostructured surfaces, and presented a large number of works concerning condensation phenomenom on enhanced surfaces, usually with tailored wettabilities. In their review, they have drawn some recommendations regarding feasibility and applicability of superhydrophobic, byphilic, and lubricant-infused surfaces for enhanced condensation. Micro- and nano-structured surfaces were also highlighted as promising solutions to enhance pool and flow boiling heat transfer in an extensive review carried out by Shojaeian and Kosar [2]. Recently, Kandlikar [3] pointed out that the potential for boiling heat transfer in microchannels is yet to be achieved, and that the most promising way to do so is through optimized designs for each desired application, including micro- and nanostructures on microchannels.

Among numerous parameters that may influence solid-fluid heat transfer, surface wettability seems to strongly affect such behavior [4] and can be readily tuned with micro- and nano-structuring. In this sense, several authors have investigated surfaces' wettability and related it to enhanced heat transfer. Betz et al. [5] fabricated surfaces containing hexagonal micropillars with alternating wettability and measured the density of active nucleation sites during pool boiling experiments. They concluded that these surfaces with juxtaposed wettabilities have better performance than surfaces with uniform wettability because of wetting lines movements and capillarity phenomena. Jo et al. [6] conducted an experimental study on pool boiling heat transfer on identical surfaces with distinct wettabilities and examined the effect of this parameter on heat transfer coefficient and critical heat flux (CHF). In this work, they suggested that both surface wettability and capillary wicking effects contribute to improve CHF and heat transfer coefficient. In another work, Jo et al. [7] also studied nucleate boiling heat transfer on surfaces with designed heterogeneous wettabilities. A hydrophilic monolayer acted to separate vapor and liquid paths, and improvements in boiling heat transfer were observed, especially higher CHF. Pool boiling on silicon surfaces containing micropillars was also studied by Chu et al. [8], and they concluded that the microstructures could be tuned to maximize the CHF, which was related to the increase in surface roughness. Dhillon et al. [9] also

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* Corresponding author.
*E-mail address:* dcmoreira@usp.br (D.C. Moreira).

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investigated the influence of surface texturing on critical heat flux, and they noted the existence of a maximum in CHF enhancement. They investigated the dynamics of dry spot heating and rewetting phenomena, relating the CHF enhancement to rewetting of a hot dry spot on the boiling surface. Yang et al. [10] used the plasma immersion ion implantation method to produce black silicon surfaces and investigated the wettability and boiling heat transfer performances of the fabricated surfaces. Both the active nucleation sites and the contact angle were increased in black silicon surfaces.

Although the use of microfabrication techniques has proven to effectively alter the wettability of surfaces and improve heat transfer behavior, their applicability may be limited due to high costs, difficulties to implement up-scaled fabrication or accessibility to the surface that should be textured. Thus, some other ways to texture surfaces have also been investigated, like the deposition of nanoparticles through the boiling process of nanofluids or in-situ growth of nanowires and nanosheets, for example. Liu et al. [11] developed a method to fabricate superhydrophobic CuO hierarchical structures with controlled morphology on copper substrates. Kim and Kim [12] boiled water-based nanofluids in order to deposit nanoparticles on NiCr wires and showed that not only wettability is related to enhancement in CHF, but also the capillary wicking, which plays an important role on rewetting due to liquid suction by the porous layer on dry spots caused by growing bubbles. Li et al. [13] reported an augmentation of 17 times on the heat transfer coefficient of nanostructured porous surfaces produced through electrochemical deposition, if compared to the original plates. Forrest et al. [14] have coated nickel wires with polymer/$SiO_2$ multi-layers employing the layer-by-layer method and obtained hydrophilic and hydrophobic surfaces, all of which presented higher CHF than the bare wire, but only the hydrophobic coating has increased the heat transfer coefficient. Nanoparticle deposition on nickel wires was also studied by Huang et al. [15], who heated water-based $TiO_2$ nanofluids at various concentrations, varying the heat flux in order to obtain different coatings. These authors observed a decrease in contact angle with increase in the applied heat flux during the deposition process and an increase in CHF for higher nanofluids' concentrations. In addition, it was stated that CHF enhancement occurred only due to nanoparticles deposition, such that the boiling behavior of nanofluids on bare wires was similar to that of water boiling on coated wires [15]. Alumina-coated surfaces have also presented higher CHF, and smaller contact angles than copper bare surfaces under pool and flow boiling conditions with generally smaller heat transfer coefficients, as reported by Ahn et al. [16].

Table 1 summarizes the main findings and the investigated parameters of some recent works concerning wettability and boiling heat transfer on micro- and nanostructured surfaces through nanoparticles deposition. In the works listed in Table 1, the deposition of nanoparticles occurred due to nanofluid pool boiling, flow boiling, or evaporation at atmospheric pressure. Despite the number of recent studies on textured surfaces, the relation between physical characteristics of nanostructured layers and wettability behavior is not clear yet [17,18]. This was also indicated by Vaikuntanathan and Sivakumar [19], who conducted an experimental study concerning the maximum spreading of droplets impacting on grooved surfaces and proposed a unified model to predict the maximum spreading factor with an average error lower than 9%. The effect of surface and liquid properties on the maximum spreading of droplets was investigated by Lee et al. [20] as well, and they concluded that surface parameters only influence the spreading behavior for low impact velocities. Raman et al. [21] performed Lattice Boltzmann simulations of droplets impacting on surfaces with chemical wettability gradient, but textured surfaces were not investigated.

According to Table 1, it is possible to observe that the maximum heat flux in the experiments generally increased while contact angle decreased. However, it should be remarked that increases in CHF were observed even for similar values of static contact angle, which was attributed to capillary wicking effects [12]. In this context, the present work comprises a dynamic wettability evaluation of neat and nanoparticles-coated aluminum plates. The nanostructured surfaces were produced by nanofluid pool boiling process, which is a facile fabrication method. The employed water-based nanofluids were prepared in three distinct volumetric concentrations of aluminum oxide and silicon oxide nanoparticles. Influences of the deposited materials, nanofluids concentrations, and size of nanoparticles were evaluated. Results show complete spreading of water droplets over surfaces with deposited nanoparticles through pool boiling of alumina-water nanofluids and some silicon oxide nanofluids as well, characterizing a superwetting behavior [29], in which a change from inertially- to capillarity-driven spreading mechanisms could be noted. Roughness measurements and microstructural analyses with an SEM were carried out, in order to reveal structural characteristics that could be related to the wetting behavior, and a correlation between super-wettability and cluster size distribution was noticed.

## 2. Materials and methods

### 2.1. Samples fabrication

All samples analyzed during this study were manufactured through pool boiling of nanofluids in order to deposit metal oxides nanoparticles over flat aluminum plates. Thus, the first step on each sample's fabrication process was the nanofluid preparation through the two-step method. Nanofluids containing 0.01%, 0.1%, and 0.5% in volumetric concentration ($\phi$) of four distinct nanoparticles dispersed in deionized water (DI-water) were produced. Two distinct size ranges of γ-aluminum oxide ($\gamma$-$Al_2O_3$) and silicon oxide ($SiO_2$) nanoparticles provided by NanoAmor® were employed, and the characteristics of these particles provided by the manufacturer are presented in Table 2.

To produce each nanofluid, the desired amount of nanoparticles was added to a beaker containing 300 ml of DI-water, according to the targeted volumetric concentration, and then a ColeParmer CP505 ultrasonic homogenizer was employed to break the clusters and disperse the nanoparticles in the mixture. According to Weng and Ding [30], the average size of agglomerates and clusters in nanofluids rapidly decreases during the first 50 min of sonication. However, Motta [31] concluded that the probe of the equipment might be corroded due to cavitation, resulting in contamination of the nanofluid. In order to minimize such contamination, the agitation time adopted in the present work was 30 min, resulting in stable solutions for the first hour after ultrasonication [32], which was enough for the proposed objectives.

After ultrasonication, the homogenized nanofluid was transferred to the boiling apparatus, depicted in Fig. 1. This apparatus consists of a bottom aluminum base (9) heated by a cartridge resistance (10) of 245 W that promoted a heat flux of 100 kW/$m^2$, an aluminum plate (8), which is the sample where the deposition occurs, a rubber disk (7) and a rubber ring (5) to seal the whole bottom part, a borosilicate glass tube (4) that is accommodated on an aluminum ring (6) forms the recipient for the nanofluid, and the cooling aluminum block (3) to condense the water vapor, maintaining the same amount of water in the system. A thermal bath connected to a water loop is responsible for cooling the aluminum block (3) through machined channels and to ensure that the process occurred at atmospheric pressure. The superior aluminum block allocates a sphere valve (2) that is used to insert or remove the nanofluid. It also contains a schrader valve (1) that is responsible for making vacuum, allowing the entrance of nanofluid, or the pressurization, above the atmospheric pressure to facilitate the removal of the nanofluid at the end of each test. The boiling procedure was set to 3 h and after each deposition, the sample was rinsed in deionized water, such that loose particles would be carried away, and then stored, so the system could be cleaned up with water and acetone for the next deposition procedure.

Three samples covered with each type of nanoparticles were obtained after the deposition process, one for each nanofluid containing