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Appearance of a low superheat “quasi-Leidenfrost” regime for boiling on superhydrophobic surfaces☆

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ABSTRACT

Pool boiling experiments were performed with degassed water on stainless steel substrates with different surface topographies and wettabilities. Boiling curves and visual observations of the boiling process have been carried out. The onset of nucleate boiling (ONB) has been measured and the influence of roughness and wettability has been quantified. Boiling curve shape is different between the hydrophilic and the superhydrophobic cases; superhydrophobic surfaces reaching the ONB heat flux at a lower superheat and presenting a "quasi-Leidenfrost" regime, without showing the typical boiling curve. Bubbles are easier to form on superhydrophobic surfaces, therefore the nucleation temperature is smaller, and bubbles are larger and stable. The ONB appears after less than 5 K of superheat on superhydrophobic surfaces, while on hydrophilic surfaces, with the same surface roughness, the superheat is above 7 K. Furthermore, superhydrophobic samples with a different roughness present the same boiling curve, meaning that, when the contact angle exceeds a certain value, the wettability has a predominant role on the surface roughness.

1. Introduction

Boiling is the rapid vaporization of a liquid and it occurs when a liquid is heated above its boiling point. Considering the effect of the surfaces in heterogeneous boiling, the vaporization phenomena and the local heat transfer depend mainly upon two parameters: the surface topography [1,2] and the surface wettability [2,3]. Both parameters are known to play an important role in boiling heat transfer and they are strongly related. Many studies on boiling are performed with changes both in the surface roughness and the topography [4–6]. Only recently authors have used glass or silicon wafer surfaces with self-assembling monolayer over the substrate in order to modify the wettability of a solid without affecting its topography [7,8]. The role of surface roughness and surface cavities on nucleation is known since about 1960, even if experimental investigations on roughness effects in pool boiling began systematically about 30 years ago, when enhanced pool boiling with porous coatings received greater attention. Investigations on enhanced boiling from heated surfaces with micro-pin-fin arrays and micro-cavity arrays [9,10] began in 1990s, and with nanowires and nanocavities [4,10] in 2000s. The surface topography has a major role in increasing the nucleation site number and the sites must satisfy particular geometric and energetic minimal conditions to become active. Altering the surface topography mainly acts on the nucleation site density and consequently on interaction mechanisms, such as bubble coalescence, which should improve the heat transfer coefficients, but may promote the critical heat flux (CHF) condition to occur at lower superheats. Several works have shown that even nanometric features influence nucleation by using highly smooth surfaces [11]. Differences of roughness on highly polished bronze surfaces down to few nanometers in amplitude modify the superheat needed to activate the boiling phenomenon [7]. On the other side, single cavities with a size of the order of 10 μm on silicon wafers trigger the boiling [12,13], and their shape is also of primary importance [14,15] for the nucleation.

The wettability quantifies the extent at which the surface keeps wetted by the liquid, and since 1980s many experimental studies have reported that surface wettability is an important factor affecting the boiling heat transfer [7,16]. Measurements on wettability effects on bubble nucleation [7,16], boiling heat transfer coefficients (HTC) [5,6, 16,17], critical heat flux [5,17–19], bubble departure diameter [6,20] and influence of wettability on the onset of boiling [2] have been carried out. It has been shown that the wettability affects the pool boiling triggering the nucleate boiling to start at a lower superheat. At low heat fluxes higher contact angles (hydrophobic/superhydrophobic conditions) promote the activation of the nucleation sites [21] and the regular departure of larger bubbles, which are more likely to coalesce and have buoy. This mechanism is consequently associated to an

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improvement of the heat transfer coefficient [22]. Obviously, the wettability affects the bubble dynamics (bubble growth, bubble departure diameter and bubble departure frequency). Bourdon et al. [16] performed experiments of incipient pool boiling of degassed water on glass substrates using surfaces with sub-nanometer roughness and different wettabilities. The reduction of the wettability induced a reduction of the onset of boiling: bubbles appear on the surface with lower superheat (3.5 K) on a hydrophobic surface with respect to a hydrophilic one (22 K). As the heat flux increases and the regime of slugs and columns occurs, large bubbles will actually be less beneficial because they decrease the heat transfer coefficient and promote the establishment of a critical heat flux condition. Hydrophobic surfaces lead to a fast formation of large vapor blankets thus CHF is reached at a lower superheat. Betz et al. [23] suggest that dissimilar wettability conditions are required for the different heat transfer regimes. The use of biphilic surfaces, i.e. juxtaposition of hydrophilic and hydrophobic regions, is proposed. They show experimentally an overall better performance of these surfaces in pool boiling, when compared to those with spatially uniform wettability, both in terms of critical heat flux and heat transfer coefficient. The heat transfer coefficients measured on the so-called super-biphilic surfaces are up to three times higher than on state-of-the-art nanostructured surfaces with uniform wettability. Rioboo et al. [8] investigated a similar phenomenon for the flow boiling few years before, explaining the phenomenon with the presence of dissolved air nanobubbles on the superhydrophobic/hydrophilic borders. Takata et al. [24] studied experimentally pool boiling from a copper with the super-water-repellent (SWR) coating of checkered and spotted patterns and TiO_2-coated surface with polytetrafluoroethylene (PTFE) spotted patterns. Bubble nucleation occurs from the hydrophobic domain (SWR and PTFE) at very low superheating. In lower heat flux, bubbles with uniform size are generated on the SWR or PTFE domain of the heat transfer surface, and these bubbles depart from the heat transfer surface when the contact line reaches the boundary of SWR or PTFE domain. In the case of subcooled condition, the nucleation begins at a surface temperature below saturation temperature and the bubbles generated and attached on the SWR surface merged into each other and finally formed film boiling. During this process there were no bubbles detaching from the surface and the observed transition to film boiling is completely different from that usually observed. Moreover, under decreasing of the heating power, surface temperature starting from the film boiling regime, a vapor film did not disappear, even if the surface temperature fell below the fluid saturation temperature.

In this work, pool boiling experiments have been performed with degassed water on stainless steel substrates with different surface topographies and wettabilities. Boiling curves and visual observations of the boiling process have been performed. The superheat needed to have the onset of boiling on hydrophilic, hydrophobic and superhydrophobic surfaces (SHS) has been measured, and the influence of surface roughness and wettability has been quantified.

2. Experiments

2.1. Pool boiling experimental setup

The pool boiling setup is described in [16] in detail. The boiling chamber is made in aluminum and an internal heater (80 W) heats up the water. Moreover, two external heating tapes are placed on the walls of the chamber and are connected to a PID controller to balance thermal leakage in order to maintain the saturation temperature in the chamber. Two K-thermocouples are placed in the water and connected to a proportional–integral–derivative (PID) controller to check

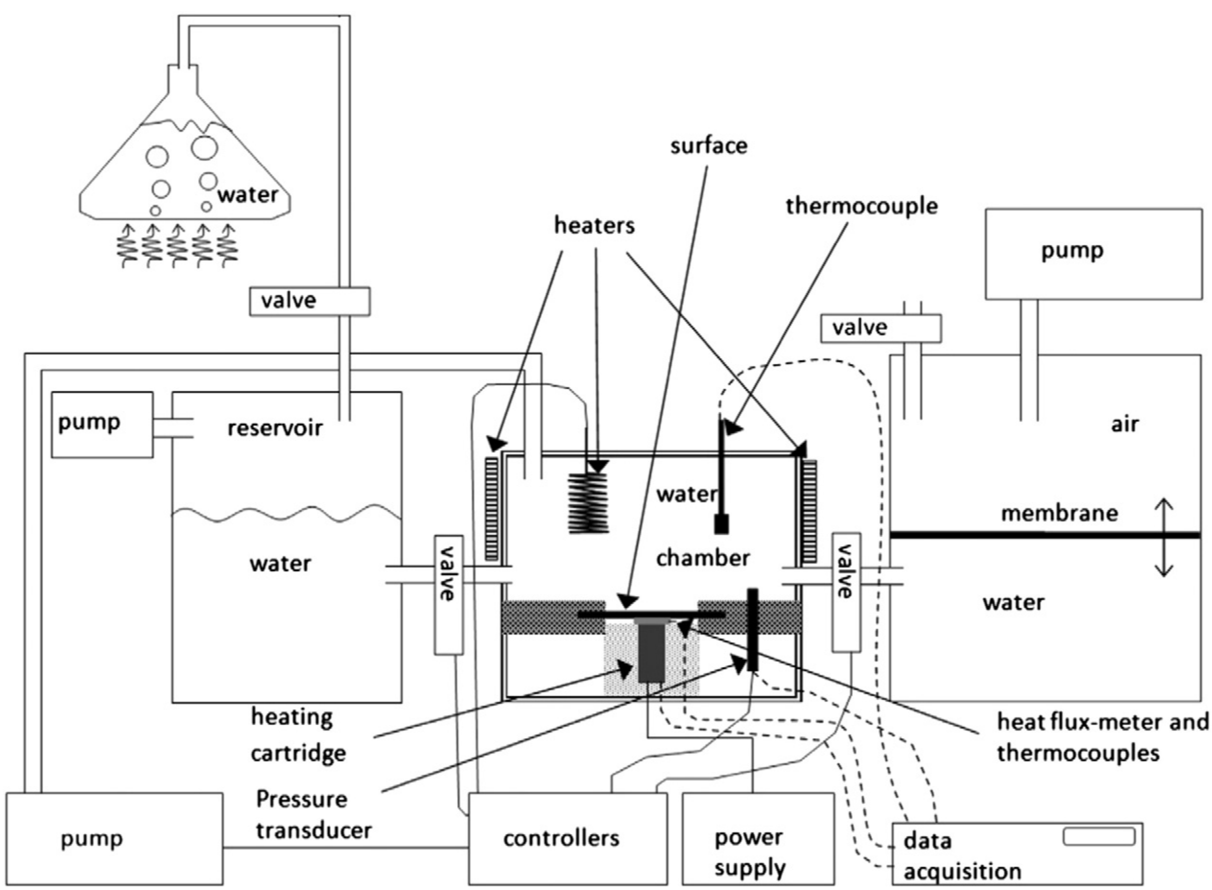

Fig. 1. Experimental setup [16].