



Sessile drop evaporation on (super)hydrophobic surfaces: Effect of low pressure on the contact line dynamics



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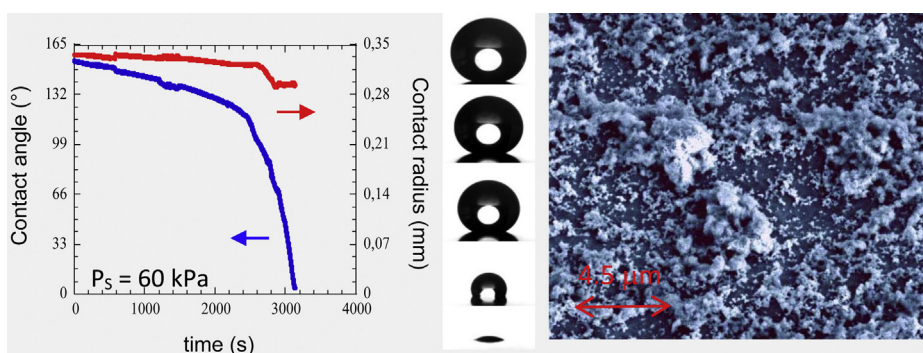
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HIGHLIGHTS

- Hydrophobic and superhydrophobic surfaces were produced using aluminum substrates.
- The evaporation kinetics of water droplets were studied under low surrounding pressures.
- The evaporation process is driven by the contact line dynamics (pinned/moving).
- The superhydrophobicity property of micro-structured surfaces is lost under low pressures ($P < 20$ kPa).
- The water contact angle decreases with pressure.

GRAPHICAL ABSTRACT



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ABSTRACT

In this article, we experimentally study the influence of the surrounding pressure ranging between 1 kPa and 101 kPa on the evaporation dynamics of drops on hydrophobic and superhydrophobic substrates. These surfaces were, initially, constructed by nanocoating of etched and/or nonetched aluminum substrates. The evaporation of droplet is observed to occur in two distinct regimes: pinned contact line (PCL) and moving contact line (MCL). Their contribution to the full spectrum of the drop evaporation is modulated by both wetting properties and pressure values. It is shown that the triple line and its interfaces exhibit a remarkable dependence on the surrounding pressure through a significant decrease in the water contact angle. The influence of the pressure on the stability of the superhydrophobic state is also evidenced as well. A critical pressure value is experimentally determined ($P_s \approx 20$ kPa). Under lower pressures a Cassie-Baxter to Wenzel transition occurs, which is shown to be quasi-instantaneous for the lowest pressures ($P \leq 5$ kPa). The superhydrophobicity of micro-structured surfaces is lost in such conditions.

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1. Introduction

In the last few years, experiments dealing with evaporation of drops have regained considerable interest [1–12], due to at least two main reasons. First, from a fundamental point of view, these experiments aim at contributing to a better understanding and control of the droplet contact line dynamics on textured

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surfaces, especially superhydrophobic surfaces. Second, from a practical point of view, numerous applications of such surfaces deal with the evaporative behavior of droplets. The identification of the main parameters allowing to control the evaporation kinetics is of critical importance for applications dealing with, for example, micro-nano devices [13–15] and thermal energy systems [16,17]. For instance, thermodynamic machines operating with water as a refrigerant fluid (such as LiBr–H₂O absorption machines) constitute one of the most relevant areas of application concerned by low-pressure phase change conditions. It is well established that the evaporation process is strongly influenced by the surface properties of the substrates and the surrounding parameters (such as temperature, pressure and humidity). Among these different contributions, the effect of the surface roughness on the droplet evaporation kinetic have been, up to date, the most investigated. Several of these studies focus on the evaporation modes [1,5,9,10] including a constant contact angle (CCA) mode, a constant contact radius (CCR) mode, a combination of both of these modes, or a wetting transition occurring in the last stage of the evaporation. However, despite the extensive progress, the greatest part of these works dealt essentially with the natural evaporation process. The influence of external parameters like the sub-atmospheric pressure on the evaporation process and on the contact line dynamics remains less studied [18–22]. Indeed, to our knowledge, a relationship between the pressure and the evolution of the wettability regimes (homogenous or heterogeneous wetting) has not yet been clearly established. The evaporation mechanisms on such surfaces also remain unclear and more extensive and systematic investigations are still lacking in this field of research.

In this paper, we investigate the influence of the surrounding gas pressure on evaporation of drops deposited on hydrophobic and superhydrophobic surfaces. Starting from aluminum substrates processed by chemical treatments (etching and/or nanocoating), we report in the first part their morphological characteristics as well as their wetting properties. Homogeneous and heterogeneous wetting regimes are identified. The second part is devoted to the investigation of the evaporation dynamics, under surrounding pressures (P_s) ranging between 1 kPa and 101 kPa (atmospheric pressure). From the experimental results, a significant decrease of the contact angle is evidenced at low pressures ($P_s \leq 20$ kPa). As a consequence, a drop on a superhydrophobic surface quasi-instantaneously transits from Cassie–Baxter [23] to Wenzel [24] configuration since the liquid–solid interface is modified. The pressure variation appears as a powerful tool to modify in a controlled way the liquid–solid interface. In the last part of this article, the influence of the surrounding pressure on the contact line mobility and on the evaporation kinetic is discussed in terms of capillary and friction contributions.

2. Experimental procedure

2.1. Sample preparation

Aluminum sheets (purity 99.8%) purchased from Goodfellow were used in order to provide super-hydrophobic surfaces. The previously cleaned substrates were processed twice: First, they were chemically etched in 0.1 M of sodium hydroxide (NaOH) aqueous solution for 1 h at room temperature. Immediately after the etching process, the samples were rinsed in deionized water. Second, fluoroalkyl-silane (C₁₆F₁₇H₁₉O₃Si, named FAS-17) molecules were grafted on such surfaces. The samples were thus immersed into an ethanol solution of 1.0 wt% FAS-17, at room temperature, for 1 h. To remove all excess reactants, these substrates were

rinsed in two successive ethanol baths, dried in N₂ flux and subsequently kept in a closed box for about 12 h prior to further characterization. In order to provide a reference surface, the FAS-17 molecules were also grafted onto the previously cleaned bare aluminum.

The surface morphology of the samples was characterized using a FEI (Nova Nano SEM450) scanning electron microscope (SEM) operated at 30 kV.

2.2. Contact angles and evaporation experiments

The wetting properties of the processed surfaces were characterized by using the sessile drop method. For such experiments, a homemade device was used, allowing the substrate temperature and the pressure inside the cell to be controlled independently. In this device, a heating element underneath the substrate controlled through a PID controller was used. The pressure was controlled using a vacuum pump. The samples were introduced in a glass chamber and the liquid drop was gently deposited on the substrate by an automatic injection pump. Droplets of de-ionized water having a small volume (1–2 μ l) were used to measure the dynamic contact angles. The advancing θ_A and receding θ_R angles were recorded during the expansion and contraction of the droplets by keeping a needle in the liquid and continuously supplying and withdrawing liquid through the needle. From such measurements we determined, for each investigated surface, two fundamental parameters for the wetting phenomenon. The first one is the average contact angle θ_e defined as $\cos \theta_e = 0.5(\theta_A + \theta_R)$, which is related to the average spreading parameter. The second one is the contact angle hysteresis, defined as the contact angle hysteresis $\Delta\theta = \theta_A - \theta_R$, characteristics of each one of the processed surface. All measurements dealing with the wetting characterization were performed optically under a controlled environment in a closed transparent box with an home-made device (temperature: 20 ± 1 °C; relative humidity: $45 \pm 2\%$; atmospheric pressure). Basically, a white and homogeneous lighting system is positioned behind the sample to make the drop to appear black. The images are recorded from the side with a CCD camera for further contact angle measurements. At least five drops placed in different locations were tested.

For the investigation of evaporation kinetics, deionized water droplets of volumes ranging from 1 to 5 ± 0.1 μ l were used. For this range of droplet volume, the characteristic length of the droplet (its radius) lies below the capillary length scale $\kappa^{-1} = (\gamma/\rho g)^{1/2}$, where γ is the liquid–gas surface tension, ρ is the density of the liquid, and g the gravity constant), which is 2.73 mm for water at room temperature. Thus gravity effects may be neglected and a spherical-cap assumption for the droplet holds. In such experiments, the pressure inside (P_s) the chamber was varied from 1 kPa to 101 kPa. The temperature of the substrate was maintained at 20 ± 1 dgrC and the relative humidity was $54 \pm 4\%$ at the beginning of the experiments. Indeed, during the evaporation process the humidity rate inside the box tends to increase linearly. In experiments performed at atmospheric pressure, this increase corresponds to 10% of the initial value and can be up to 75% for experiments under lower pressures ($P_s \leq 20$ Pa). By comparing the different pressures, a linear dependence is also observed between the relative humidity and the gas pressure inside the chamber.

To analyze the evaporation dynamics, the droplets were optically observed during their total evaporation time and the side-view images recorded at 1 s time intervals. Several experiments were performed on each surface, with reproducible results. The temporal variations of the contact angles θ and the contact radii R_c were measured directly from image analysis.

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