



Dropwise condensation on superhydrophobic nanostructure surface, Part I: Long-term operation and nanostructure failure



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ABSTRACT

Dropwise condensation heat transfer (DWC) on superhydrophobic nanograsses surface (NGS) was investigated for long-term operation. For DWC of pure water-vapor on fresh NGS, two heat transfer regimes are identified: higher heat transfer coefficients with droplet jumping, and constant heat transfer coefficients with droplet rolling. The one-week operation not only deteriorates heat transfer performance, but also changes jumping or rolling mode to sliding mode. The condensation heat transfer coefficients are apparently decreased from first to third day, but they approach a limit value since the third day. In order to identify if the single-molecule-layer of polymer (SML) modified on nanograsses was destroyed, DWC on a smooth single-molecule-layer of polymer surface (SSML) was tested to display stable heat transfer with drop sliding for one-week operation, concluding no failure of the polymer layer. The collapse and breakage of nanograsses were observed to explain the decayed heat transfer versus time on NGS. Compared with SSML, the NGS has smaller droplet departure size but lower heat transfer coefficients, indicating positive and negative effects after introducing nanostructures. Three nanostructure failure mechanisms are proposed. This work suggests a new research field of the nanoscale fluid-wall interaction.

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1. Introduction

In 1930, Schmidt et al. [1] found dropwise condensation on a chrome plated copper surface. Compared with filmwise condensation, dropwise condensation can have one order of magnitude higher heat transfer coefficients. Since then, condensation heat transfer was investigated on gold or silver surface. The enhanced heat transfer is due to the surface pollution by organic substances, which is related to the surface carbon content [2–4]. Due to high cost of gold or silver material, investigators turned to coat organic substance layer on metal surface by self-organization or plasma injection techniques.

Dropwise condensation displays the cycle behavior. Each cycle contains four processes: drop nucleation, growth, coalescence and detachment [5]. After drop departure, a new cycle begins at the location that is initially occupied by the drop before departure. Among the four processes, the drop departure is key to influence heat transfer [6]. If a surface has a small contact angle hysteresis,

heat transfer is improved due to the easy droplet removal. A surface with appropriate lubricant behaves low contact angle hysteresis [7,8]. A conventional method is to use the surfaces with coating layer of fluorocarbon polymer, resin, sulfuret, graphene or rare earth oxide [9–14], which are believed to satisfy the “large contact angle and small contact angle hysteresis” criterion.

In recent years, with fast development of micro/nano fabrication techniques, scientists are interested in various superhydrophobic nanostructure surfaces to improve dropwise condensation. Such surfaces do satisfy the “large contact angle and small contact angle hysteresis” criterion. However, with deep understating of dropwise condensation, such criterion is questioned. Here, we gave a brief review on the advantages of nanostructure surface first. In the environment such as moisture air, low pressure pure vapor, or small wall subcooling (low condensation heat flux), condensation heat transfer is better on nanostructure surface. Miljkovic et al. [15] demonstrated a 25% higher overall heat flux and 30% higher condensation heat transfer coefficient on nanostructure surface compared to smooth polymer surface at supersaturations less than 1.12, which is attributed to coalescence induced jumping. The self-actuated jumping yields one to two orders magnitude smaller drop departure size, compared with the sliding mode [16,17]. Zhu et al. [18] performed

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condensation experiments in 3–7 kPa vapor environment. They showed over 125% condensation heat transfer enhancement by using nanostructure surface compared with smooth polymer surface. Not only coalescence induced jumping, but also increased drop nucleation sites account for heat transfer enhancement. Similar conclusion was drawn by Kim and Nam [19], in which they stated 60% heat transfer enhancement with nanostructure surface.

Many condensers practically operate in higher pressure/temperature environment than above. For example, the saturation pressure and temperature are above atmospheric pressure and 100 °C respectively, for pure water-vapor. Under such circumstances, nanostructure surface may not sustain long-term operation to resist surface failure. Miljkovic et al. [15] noted that when the vapor supersaturations are larger than 1.12, nanostructure surface has lower heat transfer performance than smooth polymer surface. Instead, the coalescence induced jumping mode is replaced by the shedding mode. Some surface locations are covered by liquid film to form flooding. In a following paper, they stated that the added nano-porous thermal conduction resistance is another reason to worsen heat transfer [20]. Zhang et al. [21] noted that hydrophobic surface increases the energy barrier for droplet nucleation, which also behaves a negative effect to improve DWC. For superhydrophobic nanostructure surface, Zhu et al. [18] reported decreased heat transfer enhancement factors when the saturation pressure is increased. When the saturation pressure is increased to atmospheric pressure, Lan et al. [22] showed poorer condensation heat transfer on nanostructure surface than that on smooth hydrophobic surface, who attributed the decreased free energy difference in solid-liquid-vapor phase system as the reason. Ma et al. [23] reported that, only when the non-condensable gas content is extremely large, nanostructure surface has better condensation heat transfer than smooth polymer surface. When the non-condensable gas content is decreased, nanostructure surface may not behave obvious advantages. Similar conclusion was drawn by Hu et al. [24]. These authors highlighted the importance of wetting state (Cassie, Wenzel, or partial Wenzel) on condensation heat transfer [22–24].

Zhang et al. [21] reported the decayed DWC on hydrophobic coating surface. The decayed DWC data on superhydrophobic nanostructure surface is less reported. The long-term operation changes surface topology to influence nucleation sites, contact angle, contact angle hysteresis, drop detachment and nanoporous thermal conduction resistance. Thus, heat transfer performance is altered. The analysis is not reported in the literature. The objective of this paper is to: (1) compare dropwise condensation on superhydrophobic nanograsses surface (NGS) and smooth single-molecule-layer of polymer surface (SSML); (2) analyze the changes of surface nanostructure, droplet detachment mode and heat transfer performance on NGS and SSML during one-week operation. Three nanostructure failure mechanisms are proposed in the end of this paper. The phenomenon observed in this part will be theoretically analyzed in Part II of this paper series [25].

2. The experimental setup

2.1. The experimental system

Fig. 1a shows the experimental system, including a saturation vapor supplier loop, a chiller water loop, a test sample package and a measurement system. A cooling chamber, a copper test sample and a condensing chamber were integrated to form the test sample package. The test sample had a 30.0 mm diameter and a 20.0 mm length. The test surface was vertically positioned. Parallel fins were fabricated on the left side surface, dissipating heat to the chiller water. Both the fin width and gap were 2.0 mm respectively.

The right side of the test sample was the test surface. Three test samples were prepared: a hydrophilic smooth copper surface without micro/nano fabrication (SCS), a superhydrophobic nanograsses surface (NGS), and a hydrophobic smooth single-molecule-layer of polymer surface (SSML). Their fabrication processes will be described in the next section. Along the test sample axial length, three thermocouples were penetrated to the copper block centerline with a 15.0 mm depth. The first thermocouple T_1 had a 6.0 mm distance from the test surface (see Fig. 1b). The distances from T_1 to T_2 , and from T_2 to T_3 , were 4.0 mm. The heat conducting glue was filled between thermocouple and penetrating hole. In order to prevent heat from releasing to environment, the whole copper test sample was tightly inserted inside a Teflon cylinder. The heat insulation thickness was 15.0 mm.

Pure saturation vapor was supplied by a steam generator, which was controlled by an electric heater. Deionized water was in the steam generator bottom. A two-phase separator was in the steam generator top to prevent water droplet from entering the condensing chamber. The vapor mass flow rate was measured via a pressure drop transducer across an orifice. Before formal experiment, the relationship between pressure drop and flow rate was calibrated, while the flow rate was determined by weighing condensed water during a specific time. During experiment, the condensed water was collected and further cooled in a post-condenser. When the liquid level in the post-condenser was increased to a specific value, water was pumped to the steam generator.

Our experiment was performed at a saturation pressure of ~20 kPa, having a saturation temperature of ~60 °C. Typically, the vapor mass flow rate was $m_s = 1.10$ kg/h, the corresponding vapor velocity was $u \sim 3.0$ m/s over the condensing chamber cross section. Because the condensing chamber was running in vacuum pressure, the non-condensable gas effect is obvious [26]. The following procedure was performed to remove non-condensable gas: (1) The vapor supplier system was vacuumed to a 20 Pa pressure. Maintaining the 20 Pa pressure without vacuuming by 48 h concludes no system leakage. (2) Deionized water was boiled by one hour. Then, the condensed water was charged into the initially vacuumed vapor supplier system. (3) Water in the steam generator was heated to a temperature of 110.0 °C to reach the pressure of 143.4 kPa. Manual opening the safety valve of the steam generator discharged vapor to environment. The pure vapor state was ensured by examining the relationship between vapor pressure and temperature. For example, when the measured pressure is 19.9 kPa in condensing chamber, the measured temperature is 60.1 °C, which approaches the pressure determined saturation temperature of 60.0 °C.

The chiller water loop generated spray cooling to the test sample. The chiller water temperature could be adjusted in the range of 0.5–40.0 °C to reach different wall subcoolings and heat fluxes for the condenser surface. For each run, the chiller water temperature was quite stable with oscillation less than 0.5 °C. A gear pump circulated the chiller water. A nozzle generated droplets spray that was impacting on the left side surface of the test sample.

2.2. Fabrication of the test surface

The fabrication procedures are as follows.

Step 1 (base surface preparation): The copper block surface was polished by sand papers and fine diamond polishing paste consecutively. It was rinsed by acetone and methanol consecutively to remove the oil contamination. It is noted that the polishing process was performed using a rotating machine. The friction induced heat during the polishing process may generate surface oxidization. In order to ensure the surface without oxidization layer, the polished surface was further immersed in a 0.2% weight

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