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Influence of lubricant-mediated droplet coalescence on frosting delay on lubricant impregnated surfaces

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ABSTRACT

Condensation frosting causes serious economic and safety problems in many industrial applications. Recently, lubricant-impregnated surfaces (LIS) have been attracting much interest with their excellent anti-frosting ability. The facilitated removal of drops due to the low contact angle hysteresis of LIS has been suggested as the frosting suppression mechanism. Here, we demonstrate a hitherto-unexplored microscale frosting suppression mechanism on LIS by investigating microscopic condensation and freezing dynamics on LIS by varying the viscosities of the lubricants. Based on the ice propagation model, we show that the frosting propagation is suppressed on LIS with a low viscosity oil where the coalescence of droplets is promoted by the presence of oil. On the contrary, the coalescence between droplets is interrupted on LIS with a high viscosity oil, which facilitates the frost propagation. The criteria for the delay of condensation frosting were explained based on the competition between the lubricant drainage time and the drop growth time scale. Finally, we verify that microscopic frosting suppression mechanism of LIS persists up to macroscopic level by demonstrating that LIS is effective in suppressing condensation frosting on heat exchangers.

1. Introduction

Ice formation/accumulation can cause serious performance degradation as well as economic/safety problems in many industrial and residential applications including aircraft, ships, wind turbines, dams, power transmission lines, heat pumps, refrigerators and air conditioners [1–8]. Frost normally accumulates on a surface when supercooled liquid droplets contact the surface. However, in thermal management systems such as heat exchangers, frost formation often proceeds by the condensing water vapor. The latter type of frost formation is called as ‘condensation frosting’ and it has been considered as a major impediment to the heat and mass transfer in heat exchangers in a winter season [9–15].

Previous studies have reported that the condensation frosting mechanism is different from the freezing of a sessile droplet since its propagation is mainly governed by the inter-drop freezing dynamics. In inter-drop freezing, frost spreads over the surface in a way that one frozen droplet induces the freezing of neighboring liquid droplets, initiating a chain-reaction-like freezing spreading over the entire surface [16–24]. Although no surfaces can perfectly prevent the condensation frosting phenomena, recent studies have shown that water-repellent coatings/surfaces such as superhydrophobic surfaces (SHPo) and lubricant-impregnated surfaces (LIS) can suppress the condensation frosting by delaying the frost spreading governed by the inter-drop freezing [25–27].

The excellent anti-frost performance of those water-repellent surfaces is often attributed to their ability to quickly remove droplets from the surfaces before the freezing occurs [16–18,20,28–30]. For example, very low contact angle hysteresis (CAH) (<5°) of SHPo surfaces helps droplets to easily slide off from the surface. In addition, their low surface energy and low viscous dissipation allow droplets to spontaneously jump away from the surface through the coalescing event [31–37]. As a result, the frost spreading velocity on SHPo was reported as only one third of that on hydrophobic surfaces (HPo) [17].

Meanwhile, LIS, thanks to high droplet mobility on a surface and self-healing characteristics of the lubrication oil layer, have emerged as another candidate for icephobic surfaces [25,27,30,38–42]. The lubricating oil locked within nano/microstructures endows the surface with very low CAH (<5°) of droplets, resulting in the efficient shedding of droplets from the surface by gravity. Indeed, previous study reported that the frost propagation slows down on LIS compared with untreated and

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HPo aluminum surfaces [38]. Moreover, even after frost spreads over the entire LIS, it can be easily removed from the surface due to the low ice adhesion strength and excellent de-frosting performance of LIS [38,41,42].

Although the aforementioned studies have demonstrated that LIS effectively delays the condensation frosting process, detailed microscopic mechanisms of freezing delay on LIS need further clarification. For example, most previous reports have focused on the condensation frosting performance of LIS at millimeter length scales, where gravity plays an active role in droplet removal [38,41,43]. However, the presence of any microscopic anti-frosting mechanisms on LIS remains as unclear. In addition, as a part of the study on the anti-frosting performance of LIS, the influence of the lubricant viscosity on anti-frosting ability needs to be investigated in the context with the lubricant stability and durability issues [39,44–46]. The higher viscosity of LIS would provide more resistance to lubricant loss caused by external impact [44,45] and delay the performance degradation associated with lubricant drainage during condensation and freezing [46]. Therefore, in practical applications, such higher viscosity may be desirable for surface durability. However, it may adversely affect the droplet mobility and anti-frosting performance of LIS due to increased energy dissipation by higher viscosity lubricant [47].

Hence, we experimentally investigate microscopic condensation and freezing dynamics on nanostructured Aluminum (Al) surfaces impregnated with lubricants having different viscosities, while comparing their frosting behavior with other surfaces including superhydrophobic (SHPo), hydrophobic (HPo), hydrophilic (Bare), and superhydrophilic (SHPi) surfaces. We chose aluminum as a base material considering that it is the most popular material for industrial applications such as heat exchangers. Through the microscopic experiments inside a temperature/humidity controlled environmental chamber and the ice propagation model, we suggest that the competition between the lubricant drainage time and the drop growth time scale determines the frost suppression or enhancement on LIS. In addition, we show that the anti-frosting performance of LIS is preserved in macroscale application, where gravity becomes more important.

2. Experimental setup and sample fabrication

Fig. 1 shows schematics of temperature/humidity controlled environmental chambers used in the present study for microscopic and macroscopic anti-frosting testing. Fig. 1a is the experimental setup for investigating the microscale condensation frosting. Here, the test surfaces are placed horizontally on a temperature-controlled cooling stage and water-saturated nitrogen gas flow is supplied to control humidity. Detailed condensation and freezing propagation process are observed under the microscope with a

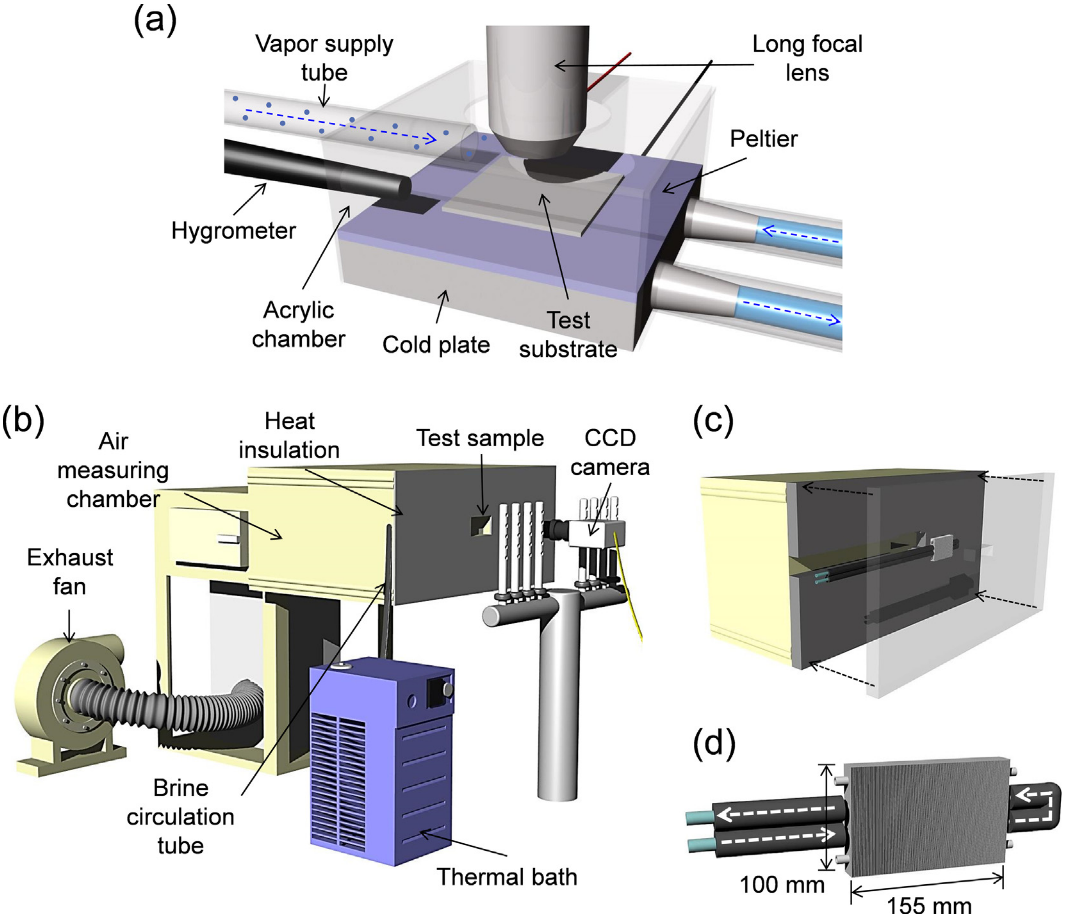

Fig. 1. Schematics of temperature/humidity controlled environmental chambers for (a) microscopic and (b–d) macroscopic frosting tests. (a) In the microscopic experimental setup, test samples are placed horizontally on a temperature-controlled cooling stage and water-saturated nitrogen gas flow is supplied to maintain target humidity. A microscope with a long focal lens is used to observe microscale condensation and frosting behavior on the sample. (b) The macroscopic frosting test setup is located inside a temperature and humidity controlled environmental room. The cooling brine is circulated inside the test heat exchangers using a large capacity chiller. (c) The test heat exchanger is located at the opening of the air wind tunnel consisting of dry/wet-bulb thermocouple, a differential pressure transducer and an exhaust fan. (d) The test heat exchanger is composed of 4 tubes and about 110 wavy-fins. Cooled brine circulated from the bottom to the upper tube as indicated by white dashed arrows.