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# Frosting and defrosting behavior of slippery surfaces and utilization of mechanical vibration to enhance defrosting performance

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ABSTRACT

We experimentally investigate the frosting and defrosting performance of slippery surfaces which have low sliding angles of water droplets and low ice adhesion strengths. The frosting and defrosting characteristics of slippery surfaces are compared with those of bare aluminum, hydrophilic, and superhydrophobic surfaces. The enhanced sliding properties of water droplets on the slippery surfaces effectively promote the drainage of the condensate on their surfaces, which not only leads to significant frost retardation under frosting conditions, but also substantially reduces the mass of the retained water on the surfaces after defrosting by heat. In addition, when mechanical vibration is applied together with heating during defrosting process, the low ice adhesion strengths of the slippery surfaces enable the effective detachment of the lumped frost layer from their surfaces, thereby significantly reducing the defrosting time.

## 1. Introduction

Many studies to control the surface wettability of the fin surfaces of heat exchangers have been carried out to improve the frosting and defrosting performance of heat exchangers [1–6]. Specifically, the strategy to improve the frosting and defrosting performance of heat exchangers using the wettability control of their fin surfaces is retarding the frost formation on the fin surfaces, while effectively draining the residual water on the surfaces after defrosting. One representative way is to make their fin surfaces hydrophilic. The hydrophilic fin surfaces have been commonly used as the fin surfaces of heat exchangers due to their excellent capabilities to drain residual water after defrosting, thereby improving their defrosting performances [7]. However, in frosting conditions, a hydrophilic surface forms a thin ice layer through the formation of a water film on the surface at the beginning of frosting, limiting further improvement of frosting performance (*i.e.* frost retardation) [3,8,9]. To overcome the drawbacks of a hydrophilic surface, rendering the fin surfaces superhydrophobic has been actively studied. With a superhydrophobic surface, the initial condensate forms micron-sized droplets with a spherical shape, which effectively delays the phase change of the condensed droplets to ice [2,10]. For example, it has been experimentally shown that the thickness of the frost on a superhydrophobic surface was reduced to 37% of that on a bare aluminum surface under a −10 °C cooling condition, verifying the frost retardation performance of a superhydrophobic surface [11]. In addition, a superhydrophobic surface, which has a low surface energy, has excellent sliding angle characteristics of water to facilitate the drainage of residual water after defrosting, thereby improving the defrosting performance [12–16]. It has been reported that a superhydrophobic fin-tube heat exchanger reduced the defrost time by 27.2%, and the mass of residual water by 48.7%, compared to a bare fin-tube heat exchanger [17].

Recently, slippery surfaces have attracted attention due to their anti-frosting properties. These slippery surfaces are typically fabricated by injecting oils onto the micro-scaled surface structures. The oils of the surface lower the surface energy, which easily slides the condensed water droplets on the surface to delay the frosting [18]. In addition, due to the lubricant properties of oils on the surface, the slippery surface has a low ice adhesion strength. For example, the ice adhesion strength of a slippery surface fabricated using silicone oil was reduced to 5% of that of a bare aluminum surface [19]. Although the slippery surface holds the promise of new fin surfaces of heat exchangers, many previous studies, however, have observed the frosting behavior of a slippery surface under a relatively high surface temperature condition or measured the

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ice adhesion strength by directly forming ice rather than through frosting [20–22]. Therefore, it is necessary to quantitatively investigate the frosting and defrosting performance of a slippery surface, compared to conventional surfaces under frost-forming condition. Here we experimentally investigate the frosting and defrosting performance of bare aluminum, hydrophilic, superhydrophobic, and slippery surfaces. In addition, we utilize the low ice adhesion strength of a slippery surface to propose a method to improve the defrosting performance of the fin surfaces by mechanical vibration.

## 2. Experimental

### 2.1. Fabrication of surface treated samples

Al-3102 (1 mm thickness) was used as the base metal for all the surfaces fabricated in this study. The hydrophilic surface was prepared by dip coating the 20 vol% organic-inorganic hybrid polymer (TC-120R, CNB chemical) in water onto the aluminum base metal, followed by heating at 250 °C for 30 s. The superhydrophobic surface was fabricated using a chemical etching process. A base metal plate was first immersed in an aqueous solution of 0.5 M NaOH (Samchun chemical) at 80 °C for 5 min and then soaked in an aqueous solution of 1 M HCl (Daejung chemicals) at 80 °C for 2 min to form a rough surface. Finally, a self-assembled monolayer (SAM) was formed by coating the etched surface by perfluorodecyltriethoxysilane (PFDTS, Sigma Aldrich) and by subsequently drying it in an oven at 100 °C for 1 h. In order to fabricate the slippery surfaces, a base metal plate was first immersed in a 1 M NaOH solution at room temperature for 5 min, which was then dip-coated in a Teflon coating solution (DISP 30, DuPont) at a rate of 5 cm/min. The sample was dried in a furnace at 230 °C for 1 min. Subsequently, the Teflon-coated aluminum base material was immersed in a lubricant (Krytox 103, DuPont). Then, the sample was set up vertically and stabilized until all the excessive lubricant flew down.

### 2.2. Wettability and roughness measurement

The static contact angles of the surface were measured by using a contact angle measurement stage (Surface Electro Optics, Phoenix-10). 10 μl of water droplets were dropped on 10 different portions of the prepared sample [23]. The sliding angles of the surface were measured by monitoring the angles by tilting the substrate on which a 10 μl of water droplet was placed. The roughness of the surface was measured by using a confocal laser scanning microscope (CLSM, Olympus OLS4100).

### 2.3. Ice adhesion strength measurement

The ice adhesion strength was measured under two conditions. In the first condition, 2 ml of deionized water was placed in a glass tube (1 cm in diameter and 5 cm in height) and cooled for 30 min at −15 °C in an environmental chamber to form ice. Then, the tip connected to load cell was pushed against it at a speed of 30 mm/min, and the force was measured as the ice fell off [24]. Under the second condition, ice was formed in the same way as the first condition. Thereafter, the surface temperature of the specimen was heated from −15 °C to 0 °C for 45 s, and the ice adhesion strength was measured.

### 2.4. Frosting and defrosting measurement

Fig. 1 shows a schematic of the frosting and defrosting experimental setup. The square duct of the moist air channel was made of acrylic. A blower was placed at the beginning of the channel to control the flow rate of moist air. The flow rate of the air was controlled by changing the applied voltage to the blower and measured by using a pitot tube installed in the duct. The relative humidity was controlled by using an ultrasonic humidifier. The temperature and humidity were measured with a type T thermocouple and humidity sensor, respectively. To stabilize the air flow, a grid-type stainless steel flow straightener was prepared and installed. In the test section, the cooling and heating equipment used a thermoelectric element (TEC) [2]. The TEC cooling section was made of aluminum plates and the size of the cooling surface was 7 cm × 7 cm. In this study, the size of the measurement sample was fixed at 4 cm × 4 cm. The TEC cooling section with the sample was vertically equipped. The thermal resistance was minimized by applying thermal grease between the cooling surface and the sample. During the frosting and defrosting test, the air temperature, relative humidity, and air flow rate were fixed at 15 °C, 85%, and 3 m/s, respectively. The surface temperatures of the sample were set at −5 °C and −10 °C. The frost thickness was measured using a charge-coupled device (CCD) camera, and the frost mass was measured using an electronic scale. We captured the image of the frost layer on the edge of the sample from the front side to the rear side in terms of moist air flow direction by the CCD camera, and then the average thickness of the entire frost layer was calculated by using image processing. The frost density was calculated from the measured frost thickness and mass. The frosting experiment was repeated five times. The defrosting experiment was performed by heating the surface where the frost had been formed at −10 °C to 10 °C. The heating rate of the TEC was 2 °C/s. The defrosting process was carried out for 5 min unless mentioned otherwise. An electronic scale was used to measure the mass of the residual melted water. The defrosting experiment was repeated five times. In order to measure the mass of frost/retained water, we first measured the mass of frost/retained water and the sample together, and then after thoroughly removing the frost/retained water, we measured the weight of the sample only. Finally, we obtained the frost/retained water mass by subtracting the sample weight from the initially measured weight. The error bar is standard deviation of our measurement. The uncertainties of the measured and calculated values are given in Table 1 [25].

## 3. Results and discussion

### 3.1. Wettability and roughness of surfaces with different wettability

The surface contact angles and roughness of the prepared samples were measured. Fig. 2 shows the contact angle information of each surface. The contact angles of bare, hydrophilic, superhydrophobic, and slippery surfaces are 98 ± 3°, 13 ± 4°, 159 ± 5°, and 115 ± 3°, respectively. The advancing and receding angles of superhydrophobic, and slippery surfaces are 160 ± 3°, 155 ± 4°, and 117 ± 1°, 114 ± 2°, respectively. The contact angle of the slippery surface is larger than that of bare surface, but smaller than that of the superhydrophobic surface, which is similar with the previous report [26]. The sliding angles of superhydrophobic, and slippery surfaces are 6 ± 2°, and 3 ± 1°, respectively. In addition, the roughness ($R_a$) of bare, hydrophilic, superhydrophobic, and slippery surfaces are 0.042 ± 0.019 μm, 0.063 ± 0.023 μm, 4.655 ± 0.504 μm, and 0.253 ± 0.058 μm, respectively. While the bare and hydrophilic surfaces have low roughness values, the superhydrophobic surface has a high surface roughness value, relatively. It is attributed to the wet etching process using NaOH and HCl. The slippery surface has much smaller roughness than the superhydrophobic surfaces, due to the mild etching based on NaOH only and the oil infusing process.