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Defrosting behavior and performance on vertical plate for surfaces of varying wettability

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ABSTRACT

The defrosting behaviors and performances of super-hydrophilic, bare, and super-hydrophobic surfaces were experimentally investigated along different frost layer densities on a vertical plate. The defrosting behavior can be divided into three types based on the size of the water permeation layer. The defrosting behaviors of bare and super-hydrophilic surfaces were similar, whereas the super-hydrophobic surface behaved differently by allowing the frost layer to be easily removed from its surface. Defrosting performance was evaluated based on defrosting time and water retention ratio. Within the low frost layer density range, defrosting time did not depend on surface characteristics. However, as the density of the frost layer increased, defrosting time increased in the bare and super-hydrophilic surfaces, whereas in the super-hydrophobic surface, that time tended to decrease rather than increase. Water retention ratio was highest on the super-hydrophilic surface and lowest on the super-hydrophobic surface in all frost layer densities. Therefore, the defrosting performance of a super-hydrophobic surface was outstanding over a wide range of frost layer densities.

1. Introduction

The technique of fabricating micro- and nano-structured layers was inspired by how Lotus leaves in nature produce non-wettability and along these lines, many studies are being conducted [1,2]. These nano-unit microstructures have hydrophobicities that can retard the formation of frost because of high static contact angles and Gibbs energy barriers [3,4]. Research on hydrophobic surfaces first focused on surface treatment techniques to produce nano-unit microstructures [5,6], and then expanded to studies related to phase change mechanisms such as condensation and freezing [7,8]. These studies confirmed the frost retardation effect under conditions in which the metal surface temperature was lowered to 0 °C or below [9,10]. Thus, the hydrophobic surface is expected to prevent degradation of thermal performance and increased energy consumption caused by frosting. However, frost formation itself cannot be completely prevented, and when frost is formed on a surface, hydrophobicity disappears. To reactivate the surface characteristics, a defrosting process that melts the frost layer is required [11,12]. However, excessive defrosting operations may result in reduced system performance [13]. Accordingly, it is important that the defrosting operation completely removes the frost layer as quickly as possible. The frost retardation effect of a hydrophobic surface was found to be highly effective under frosting conditions used in refrigeration cycles such as refrigerators and heat pumps [14,15], but the results of research on defrosting operations are insufficient. Therefore, it is necessary to investigate defrosting behaviors according to surface characteristics and evaluate the defrosting operation.

Defrosting studies based on surface characteristics began when Jhee et al. [16] suggested the use of an index of defrosting efficiency using a heat exchanger specimen. They reported that defrosting efficiency was high on a hydrophobic surface because such a surface had a short frost layer melting time. Kim and Lee [17] compared frosting and defrosting characteristics by fabricating hydrophilic, bare, and hydrophobic surfaces on small test samples. Defrosting performances were compared by using the water retention ratio and defrosting time. The results showed that the difference between defrosting times were not significant. Moreover, retained water was lower in the hydrophilic surface as it appeared only as a film on that surface, whereas droplets formed on the hydrophobic surface. Rahman and Jacobi [18–20] performed defrosting experiments by fabricating a hydrophobic surface with microgrooves. These microgroove structures were found to be very effective in reducing the amount of retained water and lowering the tilt angle of the droplet on the surface. Liang et al. [21,22] and Wang et al. [23] analyzed defrosting characteristics for

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Nomenclature

A	area, m^2
E	energy, J
F	force, N
I	light intensity, cd/m^2
l	length, m
m	mass, kg
N	normalized intensity in Eq. (3)
RH	relative humidity,%
t	time, s
T	temperature, °C
y	height, m
Greek symbols	
γ	ratio
δ	uncertainty
ε	error
ρ	density, kg/m^3
σ	surface tension, N/m
θ	angle, °

Subscripts	
a	air
ad	adhesion
adv	advancing
avg	average
d	defrosting
f	frost
int	interfacial adhesion-induced dissipation
k	kinetic
LV	liquid and vapor
max	maximum
min	minimum
p	plate
rec	receding
s	surface
st	static
vis	viscous flow-induced dissipation

hydrophilic, bare, hydrophobic, and super-hydrophobic surfaces. A super-hydrophobic surface with a high contact angle resulted in outstanding defrosting performance because of the short defrosting time and lower water retention. Wang et al. [24] proposed a defrosting method using forced convection on a low adhesion super-hydrophobic surface. Overall, previous research (except that of Kim and Lee [17]) showed that super-hydrophobic surfaces exhibited superior defrosting performance.

The study of Kim and Lee [17], and those of Liang et al. [22] and Wang et al. [23] differed from each other. The difference was caused by choosing an experimental defrosting method that had the same duration of frost formation before starting the defrosting experiment. As a result, defrosting experiments were conducted on different densities or masses of frost layers because the frost delay time differs according to surface characteristics. In other words, the frost layer on a hydrophobic surface has a short frost formation time and subsequently, defrosting time and the amount of retained water were inevitably small because of the low frost layer mass and density. However, these only highlight the frost retardation effect, not the defrosting characteristics. In as much as super-hydrophobic surface defrosting characteristics—including weak adhesion [25], low tilt angle [26,27], and jumping droplets [28]—have been reported during the frost layer melting process, it is necessary to investigate how such defrosting characteristics affect defrosting performance.

Therefore, in this study, the defrosting behavior and performance—excluding the frost retardation effect—were analyzed for various surface characteristics through the vertical plate defrosting experiment. The defrosting experiment was conducted after frost layers were formed on the super-hydrophilic, bare, and super-hydrophobic surfaces, and frost densities have been measured. During the defrosting experiment on each type of surface, the defrosting behavior was analyzed, and defrosting time and water retention were measured so as to compare the defrosting performances and characteristics between the three surfaces along the frost layer density.

2. Experiment

2.1. Experimental setup

Etching and coating methods were applied to fabricate super-hydrophilic and super-hydrophobic surfaces. The Al 6061 plate was cleaned using distilled water (DI water) and acetone. Afterwards, the plate was immersed in a 1 M NaOH solution for 5 min to remove the surface oxide layer before it was washed with DI water. Etching was performed using hydrochloric acid (Daejung Chemicals and Metals) to form microstructures on the cleaned Al surface. Then, the washed Al was immersed for 10 min in a solution of DI water and a 35 vol% hydrochloric acid solution diluted 4:1. The super-hydrophilic surface was prepared by treating the microstructured Al with O_2 plasma carried out at 100 W in an oxygen atmosphere for 10 min. A super-hydrophobic surface was prepared with a silane coating. The etched Al was immersed for 10 min in a solution of Hexane (100 mL) and a 1H,1H,2H,2H-perfluorodecyltriethoxysilane (100 μL) solution diluted 1000:1, and afterwards, the plate was dried in an oven at 100 °C for 1 h to complete the super-hydrophobic surface treatment. The surface contact angle measured by dropping water droplets (~20 μL) on each surface and SEM images of the surface structure are both shown in Fig. 1. It was confirmed that the bare surface was smooth, whereas the super-hydrophilic and super-hydrophobic surfaces had microstructures on their surfaces.

The experiments were conducted in a test section where a vertical plate was installed, as shown in Fig. 2. One side of the test section consisted of a test sample and a cooling module [29]. At the top and at the other side of the test section, a CCD camera (Nikon, D880e with Micro ED 105 mm lens) and a luminance meter (Gossen, Mavo-spot 2) were installed to measure the height of the frost layer and its defrosting time. Each treated surface was composed of a single test sample mounted on an acrylic plate. The test sample and the cooling module were mounted on an acrylic plate so that they could be attached and removed, making it possible to directly measure the weight of the frost layer. The cooling module was composed of a thermoelectric element (TEC) to control the temperature of the cooling surface. An Al plate immersed type-T thermocouple was installed on the TEC to control the cold plate temperature uniformly. Cooling fins and a fan were also installed at the bottom of the TEC to maximize the cooling output. Insulation was used to cover the TEC.

2.2. Experimental procedure

Defrosting experiments were carried out after frost layers were first formed under a natural convection state at a cold plate temperature of $T_p = -10$ °C and air temperature of $T_a = 21$ °C. Relative