The Effects Of Surface Characteristics On Liquid Behaviors Of Fins During Frosting And Defrosting Processes

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The effects of surface characteristics on liquid behaviors of fins during frosting and defrosting processes

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ABSTRACT

Liquid behaviors, including droplet condensation and frost melt water retention, of fins during frosting and defrosting processes on three aluminum fins with different surface characteristics under winter operating conditions of an air source heat pump were investigated. The effects of the surface characteristics, including the contact angle and the contact angle hysteresis, were analyzed. Droplets were observed firstly on a bare fin and on a super hydrophobic fin last, and exhibited different sizes and shapes under the effects of the surface characteristics. The droplet distribution was sparser on the super hydrophobic fin than on the other two fins because of the consolidation, rolling and departure of droplets. There was an obvious difference on frost melt water retention between the three fins. Residual water formed a thin water film on a hydrophilic fin, while only a few spherical droplets of small sizes stayed on the super hydrophobic fin. The effects of the surface characteristics were found to be significant on the mass of residual water, which decreased by 79.82% on the super hydrophobic fin compared with that on the hydrophilic fin. Finally, the effects of the contact angle and the contact angle hysteresis on frost melt water retention were quantitatively analyzed. Results indicate that the super hydrophobic fin can restrain the droplet condensation and frost melt water retention.

1. INTRODUCTION

An air source heat pump (ASHP) has been widely used in many areas because of its advantages such as energy-saving, environmental protection, flexibility and convenience (Hakkaki et al., 2014). However, the phenomenon of frosting on fin surfaces of an outdoor heat exchanger is unavoidable when the ASHP is used for heating in winter. Frost layer may reduce the efficiency of the heat exchanger and even result in the mechanical failure of the ASHP unit (Lenic et al., 2009; Zhang et al., 2012). Therefore, researchers worldwide focused on exploring effective anti-frosting technologies. So far, researchers have put forward some anti-frosting methods, such as liquid desiccant (Kinsara et al., 1998), mechanical vibration (Cheng and Shiu, 2003), external electric field (Zhang et al., 2006) and ultrasonic vibration (Wang et al., 2012). However, the mechanism and availability of these anti-frosting technologies require further study.

The study of hydrophilic surface on delaying and suppressing frosting started from the early 80s. Okoroafor and Newborough (2000) tested the restrained frost ability of a hydrophilic surface in over two hours, and found that the reduction in the frost growth rate and subsequently frost thickness lied in the range 10%–30%. Shin et al. (2003) carried out frosting experiments with a hydrophilic surface, and the thickness, density and thermal conductivity of the frost layer were reported. Huang et al. (2009) developed a fin-tube heat exchanger with the hydrophilic coating thickness of 30μm, and conducted a series of comparative experiments to test its effectiveness in restraining frosting, where the results demonstrated that the anti-frosting time of the coated heat exchanger was longer compared with the uncoated heat exchanger. In recent years, with the development of various kinds of new materials, the hydrophobic surface has become a hot research area for restraining frost growth. Liu et al. (2008) prepared a super
hydrophobic surface whose contact angle was 162°, and the frost on the surface was delayed for 55 min compared with plain copper surface under the tested conditions. Huang et al. (2011) prepared a flower-like super-hydrophobic surface on the copper foil, and a series of micro-observations of initial frost crystals growth and frost layer melting process were carried out on both the super-hydrophobic surface and the plain copper foil surface. These works mainly focused on the growth and characteristics of the frost layer rather than liquid behaviors. Liquid behaviors during frosting and defrosting processes include droplet condensation on the cold fin during the initial stage of frosting and frost melt water retention after melting frost. It is significant to have a good understanding of the effects of surface characteristics on liquid behaviors of fins. Droplet condensation is the foundation of frost growth, and has a direct influence on the frosting process. In addition, there is still some water retention on the fin surface after melting frost, much more time and energy will be required to evaporate the residual water, otherwise it will freeze directly and then form dense frost layer in next frost period. There also have been some studies of droplet condensation on treated surfaces which were horizontally arranged (Wier et al., 2006; Jung and Bhushan, 2008; Dietz et al., 2010; Miljkovic et al., 2012). The fins of the ASHP are vertically arranged in practice, and the experimental operating conditions of these studies were different from the winter operating conditions of the ASHP. Thus, these studies were of limited reference value to liquid behaviors of fins. Rahman and Jacobi (2010, 2011) carried out experiment researches of condensation, frost formation, and frost melt water retention characteristics on microgrooved brass surfaces under natural convection. Microgrooved brass is rarely used for the fin surface on the ASHP, and the frosting process of the ASHP is under forced convection. Jhee et al. (2002) and Kim et al. (2011) investigated the effect of the contact angle on the mass of residual water. However, as one of equally important parameters reflecting the surface characteristics, the contact angle hysteresis needs to be considered. From the above, the effects of surface characteristics (including the contact angle and the contact angle hysteresis) on liquid behaviors of fins during frosting and defrosting processes should be studied systematically.

In this paper, a frosting/defrosting experimental setup was constructed to realize the visualization research of liquid behaviors on three kinds of aluminum fin samples with different surface characteristics, the effects of the contact angle and the contact angle hysteresis on liquid behaviors were analyzed, and all of the experimental conditions used in this study were based on the winter operating conditions of the ASHP.

2. EXPERIMENT

2.1 Experimental setup and parameters measurement

The aim of this study was primarily to investigate and compare liquid behaviors of fins with different surface characteristics during frosting and defrosting processes. As such, the experimental setup was designed simply to generate a cold surface and realize visualization of liquid behaviors. Figure 1 shows the experimental setup, which includes a frosting/defrosting platform and an image acquisition system. The frosting/defrosting platform was used to adjust the temperature of the fin sample surface, which could ensure the frosting and defrosting surface to be under a certain temperature by setting the temperature controller. The platform adopted semiconductor thermo-electric refrigeration. Temperature can be controlled by the temperature controller from -20°C to 150°C. The largest size of the fin sample can be 94mm×94mm. The image acquisition system was used to realize visualization research of liquid behaviors on different fin samples by recording the photographs during frosting and defrosting processes. It includes a CCD video system, two microscopes, a computer, an image acquisition card, etc. Two microscopes were respectively used to record the front and side photographs of liquid behaviors on the fins.

The diameter of residual droplet was measured by the indirect method of measurement. Namely, the grid of the scale plate was recorded under the same magnification, as shown in Figure 2, where the length of each grid was 0.1mm. The photograph of droplet recorded in the experiment was compared with the scale plate, and the diameter of the droplet $D$ is given in Equation (1)

$$D = N \times 0.1 \text{mm}$$

where $N$ is the number of grids occupied by the diameter of the droplet.

The mass of residual water was one of the most important parameters measured in this experiment. A precision weighing scale was used to weight the residual water of fins. The accuracy of weighing scale was 0.0001g and the measuring range was 0–220g. At first, a piece of absorbent paper which attracts water very well was weighted by
using the weighing scale, then, the weighing scale was zeroed. After frost melting, the residual water was absorbed quickly and thoroughly with the absorbent paper, and then was weighed by using weighing scale. The number on the scale was the mass of residual water of fins. Repeated testing indicated that the measuring error was less than 3%.

![Figure 1: Sketch map of experimental setup](image)

**Figure 1:** Sketch map of experimental setup

![Figure 2: The measurement of diameter of residual droplet. (a) The grid of scale plate; (b) A photograph of frost melt water retention.](image)

**Figure 2:** The measurement of diameter of residual droplet. (a) The grid of scale plate; (b) A photograph of frost melt water retention.

### 2.2 Experimental procedures and conditions

Initially, three fin samples were prepared with different surface characteristics, and the contact angle $\theta$ and the contact angle hysteresis $\Delta\theta$ were measured with video optical contact angle measuring instrument, as shown in Figure 3. The size of fins was 5mm $\times$ 5mm. Next, the fin sample was fixed to the platform vertically. Then, the temperature of cold platform was set to -10°C and kept 1 hour for frosting. After frosting for 1 hour, the platform temperature was raised to 50°C for defrosting. When there was no frost melt water flowing out from the fin, the mass of residual water on the fin was measured. In the process of the experiment, all of the experimental parameters were based on the winter operating conditions of the ASHP. Table 1 shows the experimental conditions.

![Figure 3: The contact angle and contact angle hysteresis of prepared fin samples. (a) Hydrophilic fin sample: $\theta$=15°, $\Delta\theta$=140°; (b) Bare fin sample: $\theta$=98°, $\Delta\theta$=36°; (c) Super hydrophobic fin sample: $\theta$=160°, $\Delta\theta$=5°.](image)

**Figure 3:** The contact angle and contact angle hysteresis of prepared fin samples. (a) Hydrophilic fin sample: $\theta$=15°, $\Delta\theta$=140°; (b) Bare fin sample: $\theta$=98°, $\Delta\theta$=36°; (c) Super hydrophobic fin sample: $\theta$=160°, $\Delta\theta$=5°.
Table 1: Experimental conditions

<table>
<thead>
<tr>
<th>Experimental conditions</th>
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<tr>
<td>Air temperature/Air relative humidity</td>
<td>5–6°C/59%–66%</td>
</tr>
<tr>
<td>Air velocity</td>
<td>1.2m/s</td>
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<tr>
<td>Frosting temperature/Defrosting temperature</td>
<td>-10°C/50°C</td>
</tr>
<tr>
<td>Time for frosting</td>
<td>1h</td>
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3. RESULTS AND DISCUSSION

3.1 Droplet condensation during the initial stage of frosting

The droplets appeared on the surface of the bare fin after 22s, while appeared on the surface of the hydrophilic fin after 35s and on the super hydrophobic fin after 60s. The hydrophilic coating contains an absorbent material which is capable of adsorbing water into hydrophilic coating in the early stage (Highgate et al., 1989). So the hydrophilic fin showed better resistance to droplet condensation compared with the bare fin. However, the super hydrophobic fin

![Figure 4: Droplets condensation on three fin sample surfaces](image-url)
showed the best resistance to condensation, where the time when droplets appeared was much later than that of the other two fins. This can be explained by free energy of the fin surface. The free energy of the super hydrophobic surface is lower, so the droplet condensation is difficult to happen. In addition, when a droplet is on a surface, it doesn't spread completely but form certain angle with the surface. This angle is called as the contact angle $\theta$. When $\theta < 90^\circ$, the surface is hydrophilic; when $90^\circ < \theta < 150^\circ$, the surface is hydrophobic; and when $\theta > 150^\circ$, the surface is super hydrophobic. The contact angle between condensational droplets and the super hydrophobic fin is bigger than $150^\circ$, and the heat exchange between the cold fin and droplets is small; therefore, the super hydrophobic surface can delay the phenomenon of condensation and slow down the condensation rate.

Figure 5 shows the comparison of droplet condensation on the three fins. The processes of droplet condensation on the three fins were similar. Firstly, some small droplets appeared on the fin surface, and then became bigger and bigger until they were frozen. However, there were some differences between condensational droplets of the three fins. Firstly, the density of initial droplets was different, as shown in Figure 4. The density of initial droplets is determined by nucleation site density, which can be calculated by Equation (2) (Huang, 2011). In this experiment, the supercooling degree of the fin surface was a constant of 10°C. The effect of the contact angle on nucleation site density is shown in Figure 5. Under the same supercooling degree, the nucleation site density decreases as the contact angle increases. Thus, the density of initial droplets of the super hydrophobic is smaller than that of the other two fins. Secondly, the size and shape of droplets were obviously different. The droplets are the biggest on the hydrophilic fin and the smallest on the super hydrophobic fin. The sizes of droplets are irregular on the hydrophilic fin, hemispherical on the bare fin, and almost spherical on the super hydrophobic surface. Thirdly, the fraction of the surface covered is different. The fraction of the surface covered on the three fins is 91%, 63% and 15%, respectively.

\[
N_s = 2.6 \times 10^8 \frac{\Delta T^3}{(2 - 3 \cos \theta + \cos^3 \theta)}
\]  

(2)

where $N_s$ is nucleation site density, $1/cm^2$; $\Delta T$ is the supercooling degree of the fin surface.

Figure 6 shows consolidation, rolling and departure of droplets on the super hydrophobic fin. Droplets on the super hydrophobic surface are likely to combine and roll, which can take away a lot of droplets on the way. This is the reason why the fraction of the surface covered of the super hydrophobic fin is smaller than that of the other two fins. In practice, fins of the fin-tube exchanger of the ASHP are perpendicular to the ground. Droplets on the super hydrophobic fin are very likely to fall off when being shocked or blew, which can keep the fin surface of the droplet coverage in a low level, and improve the heating efficiency. On the hydrophilic and bare fins, droplet condensation was observed, but no rolling and departure was observed. This indicates that the super hydrophobic fin shows good performance in restraining droplet condensation.
3.2 Frost melt water retention after melting frost

There was still some water retention on each fin surface after melting frost. Figure 7 shows the frost melt water retention on three fin sample surfaces. Obvious difference on frost melt water retention between different fin sample surfaces can be found. There was a few frost melt water shed the surface of the hydrophilic fin. Due to the strong wettability, frost melt water was spread out on the surface and formed many serried droplets of big sizes. As a result, residual water looked like a thin water film on the hydrophilic fin. The residual defrosting water was easily adsorbed on the bare fin. These droplets gradually gathered and became hemispherical under the effect of surface tension, which were irregular in arrangement and density. The maximum diameter of the droplets was 1.7 mm. For the super hydrophobic surface, the frost layer rolled up from the edge at the beginning of defrosting and directly departed from the super hydrophobic fin, and only a few spherical droplets of small sizes stayed on the surface.

Figure 7: Frost melt water retention on three fin sample surfaces
Figure 8 shows the mass of residual water on three fin samples. The mass of residual water on three different fin surfaces were 0.109g, 0.064 g and 0.022g, respectively, which decreased with the increase of the contact angle. The mass of residual water on the super hydrophobic surface decreased by 79.82% and 65.63% compared with those of the other two fins. The decrease in residual water will reduce the energy required for evaporation and shorten the evaporation time. The results suggest that a hydrophobic fin can restrain the residual water staying on the fins surface and thus improve the efficiency of defrosting. In defrosting process, the frost layer rolled up from the edge of super hydrophobic fin and directly departed from surface, as shown in Figure 9, the surface looked dry and only a few droplets with small size stayed on it. No similar phenomenon was be observed on other two fins. This can explain why a hydrophobic fin can restrain the residual water staying on the fins surface.

![Figure 9: Frost layer being released from Super hydrophobic fin](image)

When a droplet is on an inclined surface, it rolls under the effect of gravity. The contact angle that liquid-solid interface instead of gas-solid interface and the contact angle that gas-solid interface instead of liquid-solid interface are often different. This phenomenon is called contact angle hysteresis. The difficulty of droplet departure from the surface is closely related to the contact angle hysteresis $\Delta \theta$, which is the difference value between the receding contact angle $\theta_r$ and the advancing contact angle $\theta_a$. The greater the contact angle hysteresis is, the more difficulty the droplet departure from surface is. In this experiment, all fin samples were fixed vertically. Residual droplets would depart from the fin surface under the gravity while the surface would produce a capillary force which was against the gravity. Figure 10 shows the force analysis of a droplet on the fin surface. The capillary force can be simplified as (Kim, 2011)

$$F_c \approx 2\pi r \sin \theta \sigma (\cos \theta_r - \cos \theta_a)$$

(3)
where $\theta_r$, $\theta_a$ and $\theta$ refer to the receding contact angle, the advancing contact angle and the surface contact angle respectively, $c$ is a numerical constant that depends on the shape of droplet and the steepness of fin surface, $r$ is the residual droplet radius, and $\sigma$ is the surface tension.

The residual droplet on the vertical fin surface is approximately considered to be spherical crown. According to the geometry theory, the volume $V_i$ and gravity $F_g$ of the droplet are

$$V_i = \frac{2 - 3\cos \theta + \cos^3 \theta}{3} \pi r^3 \tag{4}$$

$$F_g = \frac{2 - 3\cos \theta + \cos^3 \theta}{3} \pi r^3 \rho g \tag{5}$$

Only when the gravity of the droplet is greater than the capillary force, can the droplet fall off. The maximum residual droplet radius can be deduced based on the force balance between the surface tension and the gravity

$$r_{max} = \left( \frac{6c(\cos \theta_r - \cos \theta_a) \sin \theta \sigma}{\pi (2 - 3\cos \theta + \cos^3 \theta) \rho g} \right)^{\frac{1}{2}} \tag{6}$$

When the radius of droplets is smaller than $r_{max}$, the phenomenon of retention will happen. It's worth mentioning that we can find from Equation (6) that $r_{max}$ is related to $\theta_r$, $\theta_a$ and $\theta$. In other words, the value of $r_{max}$ is only determined by the fin surface characteristics. Therefore, regardless of the frost on a fin surface before defrosting, the value of $r_{max}$ will be the same after frost melting. In addition, the capillary force is smaller when the hydrophobicity of the fin surface is better, which causes large droplets to depart from the fin surface more easily and small droplets to stay on the fin surface. The radius of maximum residual droplets can be predicted by using Equation (6). The calculated values of the bare and super hydrophobic fins were 1.58mm and 0.16mm, while the experimental values were 1.70mm and 0.19mm. The calculated values are slightly smaller than the experimental value, indicating that the equation has high accuracy.

### 4. CONCLUSIONS

To investigate the effects of surface characteristics on liquid behaviors of fins during frosting and defrosting processes, frosting and defrosting experiments were conducted on three aluminum fins with different surface characteristics under the winter operating conditions of the air source heat pump. The frosting/defrosting experimental setup was constructed to realize the visualization research of droplet condensation and frost melt water retention. The effects of the contact angle and the contact angle hysteresis on liquid behaviors were analyzed in this paper.

The effects of surface characteristics on droplet condensation were found to be significant. Droplets were observed on bare fin firstly and on super hydrophobic fin last, and exhibited different sizes and shapes under the effects of surface characteristics. The droplet distribution was sparser on the super hydrophobic fin than on the other two fins because of the consolidation, rolling and departure of droplets. However, on the hydrophilic and bare fins, droplet condensation was observed, but rolling and departure was observed. There was an obvious difference in frost melt water retention between the three fins. Residual water formed a thin water film on the hydrophilic fin while only a few droplets of small sizes stayed on the super hydrophobic fin. The mass of residual water on the three different fin surfaces decreased with the increase of the contact angle, which decreased by 79.82% and 65.63% on super hydrophobic surface compared with those of the other two fins. Theoretical analysis showed that the contact angle hysteresis is the primary cause of frost melt water retention. These results indicated that the hydrophobic fin could restrain droplet condensation and frost melt water retention.

In addition, the hydrophilic fin showed better resistance to droplet condensation compared with the bare fin. However, the mass of residual water was bigger than that of the bare fin, which causes higher energy consumption.
for evaporation and longer evaporation time. Therefore, the anti-frosting effect of the hydrophilic fin needs to be considered again for all frosting and defrosting processes.

**NOMENCLATURE**

- $D$: diameter of droplet (mm)
- $\theta$: contact angle (°)
- $\Delta \theta$: contact angle hysteresis (°)
- $N_s$: nucleation site density (1/cm$^2$)
- $\Delta T$: supercooling degree (°C)
- $F$: atress (N)
- $r$: radius of residual droplet (mm)
- $\sigma$: surface tension (N/m)
- $V$: volume of residual droplet (m$^3$)
- $\rho$: density of residual droplet (kg/m$^3$)

**Subscript**

- $r$: receding
- $a$: advancing
- $c$: capillary
- $g$: gravity

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