EXPERIMENTAL STUDY OF SURFACE PROPERTIES INFLUENCE ON FROSTING FORMATION

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ABSTRACT

The objective of this paper is to experimentally investigate the effect of surface properties on frost formation. In the experiments, two surfaces, bare and a coated copper surface, were tested with forced convection. The shape and distribution of frost crystals were observed using a CCD system during the frost formation. The height of the frost formed on the hydrophobic surface was lower than that on the bare surface. The hydrophobic surface tended to retard frost formation.

Key words: frost crystals, hydrophobic surface, evaporator, contact angle

1. INTRODUCTION

Frost will form when moist air is exposed to a cold surface whose temperature is below the triple point of water and the dew point of the moist air. Therefore, frost always affects the refrigeration industry. Frost formation in refrigeration exchangers increases thermal resistance and reduces the airflow through the heat exchangers, so the system must include a defrost cycle.

Various defrosting methods have used mechanical frost removal, washing the frost and melting the frost, but all these methods cause additional problems. The problems include increased energy consumption, increased equipment cost, and reduced system efficiency. Defrosting is required after a frost layer develops. If the frost growth is controlled before frost layer forms the frost formation will be prevented, various problems will be alleviated and the evaporator performance will be significantly improved. For this reason, some researchers have sought to prevent frost formation on the cold surface by: 1) dehumidifying the inlet moist air[1]; 2) providing a uniform electrostatic field[2]; and 3) changing the cold surface properties by coated the surface with a hydrophobic polymer [3,4].

However, dehumidifying the inlet moist air and applying a uniform electrostatic field are not suitable for general use because the operating conditions such as the air temperature, the air humidity, the air velocity and the cold surface temperature can not be controlled and a electrostatic field need additional equipment and may be dangerous. But the third suggestion is more practical since the cold surface properties can be more easily controlled without the need for additional equipment. Most previous investigation neglected the effect of surface properties such as surface contact angle and surface roughness. For example, Hayashi et al.[5] suggested that the frost formation can be subdivided into three periods; Barron[6], Yonko[7] and Brian[9] researched the influences of air temperature, air humidity, air velocity and the cold surface temperature on frost formation. However, all these frosting experiments were based on a bare surface.

In a recent work, Wu et al.[10] found that the surface properties affect the frost crystal shapes, so the shape and distribution of frost crystals on a hydrophobic surface differs from that on a hydrophilic surface. The present work investigates the effect of surface properties on frost formation, distribution and growth.

2. EXPERIMENT

2.1 EQUIPMENT

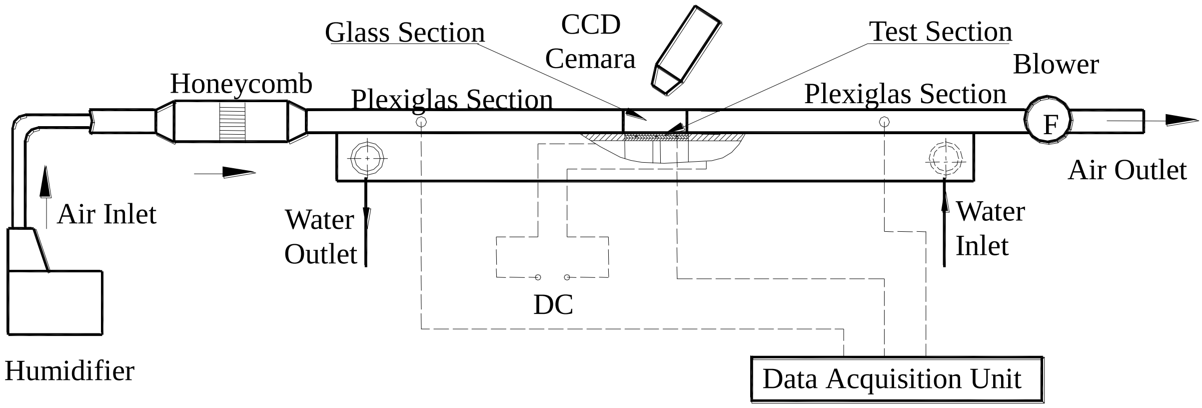


Figure 1. Experimental Setup

The experimental setup (Figure 1) consisted of two parts: the air (primary) loop and the water (secondary) loop. The air loop was a open-loop wind tunnel with the test section. The air was humidified before reaching the test section by the humidifier and they passed through a set of screens and the honeycomb. The blower was arranged at the end of the wind tunnel to not disturb the air stream in any way. The wind tunnel included three parts: two transparent Plexiglas sections at each end and one glass covered section in the center. The tunnel cross-sectional area was 50 mm by 40 mm. The glass cover was removable so the test plate surface could be cleaned before each experiment.

The test section under the glass cover consisted of a copper block, a heat sink and a thermoelectric cooler. The copper block was 50 mm × 50 mm × 1 mm. The top surface of the block was used as the cold surface where the frost would grow. The back of the block had three grooves (figure 2) for three thermocouples. Each groove was 23 mm × 0.5 mm × 0.5 mm.

There were two kind surfaces used in the experiments, a bare surface and a hydrophobic surface. The bare surface was the clean top surface of the copper block without any coating. The hydrophobic surface was the top surface of the copper block coated with a hydrophobic material.

The thermoelectric cooler (TEC) was a small heat pump operated on direct current. The cooled side of the TEC was attached by thermal grease underneath the copper block. A schematic diagram of test section is given in figure 2. An 80 mm × 60 mm aluminum heat sink having 26 fins across the 80 mm width and 40 mm fin height was attached to the hot side of the TEC by thermal grease.

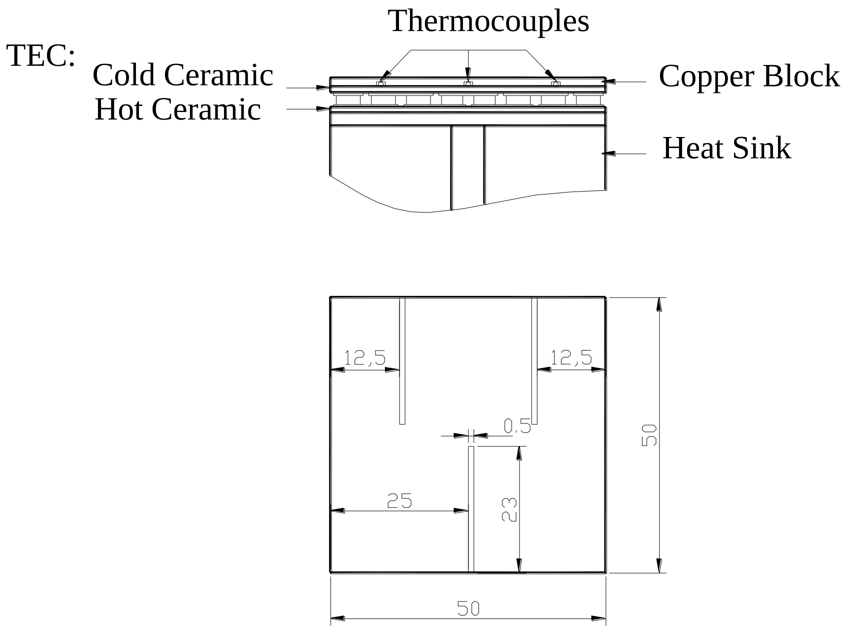


Figure 2 Test section detail (dimensions in mm)

The water loop included a water duct and inlet and outlet water pipes as shown in figure 1. The water duct allowed cooling water to flow through the heat sink to remove heat from the hot side of the TEC.

2.2 THE EXPERIMENTAL PROCEDURE

The air temperature and relative humidity were measured before and after the test section using a temperature and humidity transducer (Kunlun Hai'an JWSM-2VBG). The cold surface temperature was measured using an array of three thermocouples (0.1 mm diameter, type-T). The air flow rate was measured with air velocity meters (TSI 8384). Because of the thin thickness of the block and the high thermal conductivity of the copper, the cold surface temperature distribution was assumed to be as uniform at the average of the three thermocouple temperatures whose temperature varied by less than 0.5°C in the experiment. The surface temperature could be adjusted by changing the TEC input voltage or the cooling water flow rate. All temperature and humidity signals were sent to a data acquisition system and stored in a computer.

The frost formation process was observed by a CCD system. The frost crystal images were recorded every 2.5 s at 175× magnification. The frozen water droplet diameters and the frost crystal heights could be calculated by comparing the pixels in the recorded picture and the standard picture.

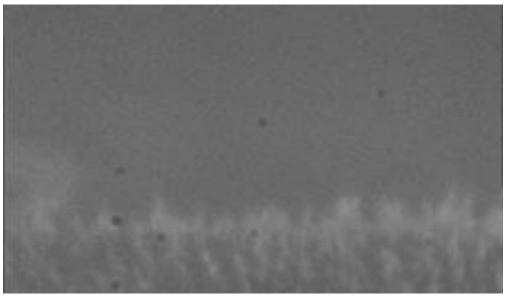
Each experiment was done by first putting the copper block in the test section, then the TEC supply voltage, the cooling water flow rate and the humid air flow rate were set. The temperature and humidity of air were then set to the experimental conditions. Finally, the frost formation on the cold surface was recorded using the CCD system when the cold surface temperature was below -10°C.

2.3 EXPRIMENTAL RESULTS

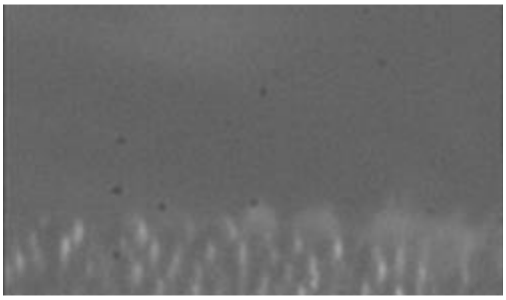
In the experiment, two surfaces were tested: one hydrophobic surface and one bare surface. The contact angles of water on those surfaces were 110° and 56°, respectively, as measured by the Chemical Engineering Department, Tsinghua University. Table 1 gives the environmental parameters along with a summary of the measurement uncertainties for each parameter where T_∞ is the air temperature, RH is the relative humidity of the air and V is the air velocity.

Table 1. Test Conditions

	Value	Uncertainty
T_∞	21°C	0.2°C
RH	75%RH	2%RH
V	1.55 m/s	1% m/s



(a) Hydrophobic Surface (θ = 110°)



(b) Bare Surface (θ = 56°)

Figure 3 Frost Appearance at the Onset of Crystal growth

The appearances of frost on the bare and hydrophobic surfaces are compared in Figure 3 just as frost crystals began to grow. The photo in figure 3a was taken at 70 s after the test started and the photo in figure 3b was taken at 37.5 s after the test started. Figure 3 shows that frost crystals grow on frozen droplets on both surfaces. The maximum frozen droplet diameters were 0.065 mm on the bare surface and 0.132 mm on the hydrophobic surface. Figure 3 also shows that the distribution of frost crystals on the bare surface was more compact than on the hydrophobic surface. It was observed in the experiment that water droplets condensed on the both surfaces before frost crystals formed. Once little droplets formed, they start to coalesce and grow into bigger droplets. The little droplets coalesced faster on the hydrophobic surface.

Figure 4 shows the frost height (h) on both surfaces as a function of time (t). The frost height on the bare surface was higher than on the hydrophobic surface throughout the entire frost growth period. The frost crystals began to appear on the bare surface at 37.5 s after the test began, but the frost crystals began to form on the hydrophobic surface at 70 s. The initial frost crystal height was 0.096 mm on the bare surface and 0.036 mm on the hydrophobic surface.

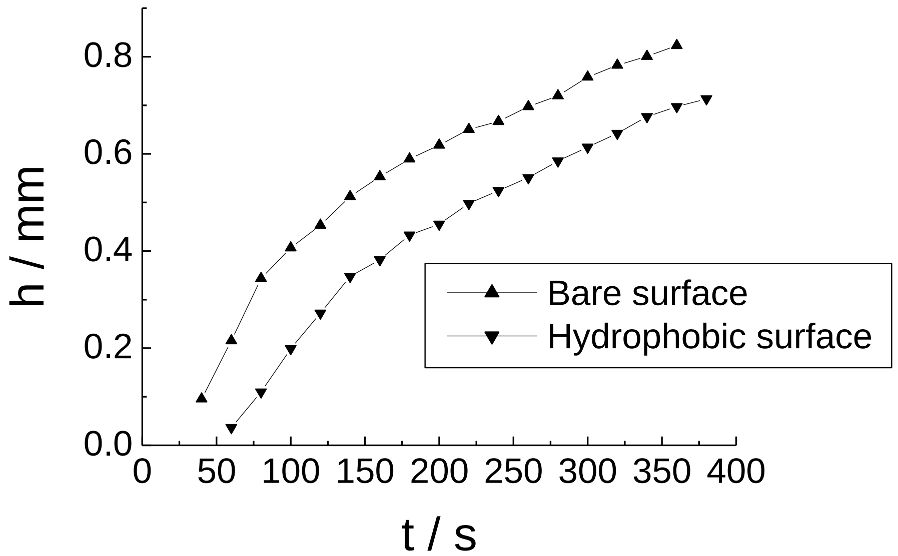


Figure 4 Variation of Frost Height

3. DISCUSSION

The surface properties have a large effect on the frost formation, as seen in the experimental results.

The tests show that water droplets will condense on the surface before the formation of frost crystals. Once the droplets form, they start to grow. The droplets grow for two reasons, coalescence between the smaller droplets and vapor condensation on the droplets. The experimental observations suggest that coalescence is the dominant effect. Because the droplets move more easily on the surface with the larger contact angle[11], they can coalesce more easily. Since the hydrophobic surface has a larger contact angle than the bare surface, bigger droplets tend to form on the hydrophobic surface.

When a critical size is reached, some droplets on the surface will freeze and frost crystals will start forming. The droplets on the bare surface begin freezing earlier. The lager contact angle on the hydrophobic surface means that the water droplet will occupy less surface area for the same water droplet volume. If the other heat transfer conditions are similar, more surface area means more heat transfer. Therefore, the water droplets on the bare surface transfer more heat to the TEC and freeze earlier.

The initial appearance of frost then influences the next stage of frost growth. Figure 4 shows that the frost on the bare surface is thicker than that on the hydrophobic surface. There are two reasons for this. First, the frost crystals form earlier on the bare surface. Secondly, the frozen water droplets occupy more area and the frost crystals spacing is closer and more uniform on the bare surface. Since more heat is removed from the frozen water droplets, the frost crystal temperature on the bare surface will be lower than that on the hydrophobic surface and vapor can more easily sublime on the bare surface which will increase the frost thickness.

4. CONCLUSIONS

The surface properties play an important role in frost formation. The experimental observation of that growth on two types of surfaces shows that:

1) Before frost crystals formed, water droplets condensed on both surfaces. The droplets grew mostly through coalescence as the liquid drops moved around on the surface. The drops moved easier on the hydrophobic surface.
2) The water droplets froze earlier and the frost crystals formed earlier on the bare surface. The maximum diameters of the frozen water droplets on the bare surface were smaller than on the hydrophobic surface.
3) The frost on the bare surface was thicker than on the hydrophobic surface during the frost growth. The hydrophobic surface tended to retard frost growth.

5. REFERENCES

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