

MINIMISING FROST GROWTH ON COLD SURFACES UNDER NATURAL CONVECTION CONDITIONS BY MEANS OF A HYDROPHILIC COATING

*Gou Yunjun, Liu Zhongliang, Wang Jieteng, Huang Lingyan, Cheng Shuiyuan
Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education
and Key Laboratory of Heat Transfer and Energy Conversion, Beijing Education
Commission, College of Environmental and Energy Engineering, Beijing University of
Technology, Beijing, 100022, PR China*

Abstract: This paper reports our new achievements in the development of the new hydrophilic anti-frosting paint. The coatings formed by the new paint have bigger surface hardness, much thinner film thickness ($\sim 50\mu\text{m}$) and longer life period. The performance in restraining frost formation of the new paint was tested with wide air relative humidity (from 35.5% to 76.0%) cold surface temperature (from -7.1°C to -20.8°C) conditions. The frost deposition on the hydrophilic surfaces formed by new paint coatings was delayed at least 3 hours compared with the plain copper surface under the conditions of a cold plate temperature above -10°C and relative humidity below 55%. The new paint has better effects to retard frost growth than the old paints under the conditions of plate temperature below -15°C and relative humidity above 70% and under this condition frost deposition was delayed for 90 min on the hydrophilic surface made by the new paint. Finally polarity of water molecule, formation mechanism of frost crystals and the characteristics of substances used in these paints were discussed to explain the effectiveness of the new hydrophilic paints in anti-frosting.

Key Words: *Frost deposition, hydrophilic, anti-frosting, surface coating*

1 INTRODUCTION

Frost formation is a very common phenomenon in nature. Water condensation is often encountered on a cold surface with temperature below the dew point that is exposed to humidity air. Frosting will also ensue if the surface temperature is below freezing point. Frost formation and deposition process is a complex heat and mass transfer process. There are many factors that influence this process; these may include the temperature of cold surfaces, the humidity and temperature of air, air velocity, the characteristics of the cold surfaces and system pressure.

The frost crystals deposited on these heat transfer surfaces initially act as fins and enhance the heat transfer process between the surfaces and air. However, this phenomenon is still undesirable because after a continuous layer is formed, the frost layer will become a thermal insulator and thus the heat transfer is degenerated seriously. Furthermore, if the deposited frost is not removed on time or without effective control, then, as the thickness of the frost layer increases, the pressure loss of the air flow system increases and the blockage of air flow may finally take place and result in serious malfunction of cryogenic equipment and systems. For instance, frost formation on heat exchanger surfaces can be extremely detrimental to their efficient operation, frosting on the wings of an aircraft affects the maneuver performance as well. Therefore, many researchers have tried to find effective methods to control frost deposition. Though many possible methods have been proposed for

combating frosting, the most commonly used techniques are still the use of electrical heaters, heat recovered from other parts of the process and regular shutdown of the system for active or passive defrosting. Obviously, these methods are all energy consuming and accompanied by a reduction in overall efficiency.

Under the same conditions, the frost deposition on different surfaces is of different characteristics; some of the deposited frost layers are dense and some are loose, some are thick and some are thin. Therefore, many efforts have been made to find various functional surfaces that can reduce frost deposition or result in an easily removed frost layer. Among these surfaces hydrophilic one was found effective to prevent frost particles from sticking to the surface.

Hydrophilic anti-frosting paint has been developed to restrain frost formation since 1980s [Okoroafor 2000, Liu 2006a, Liu 2006b]. However, up to now it still has many shortcomings, such as short operating life of paints, soft coatings surface with low resistance to external impact forces, thick coating thickness (usually larger than 0.3mm) and, most importantly, the poor anti-frosting performance under lower cold surface temperature and high air humidity conditions. So in this study against these shortages a new hydrophilic paint was developed by introducing new additive into our original anti-frosting paint [Liu 2006a and b]. Through these modifications, the coatings made by the new paint have bigger surface hardness, thinner film thickness (only about 0.06mm) and longer life period. The anti-frosting performance of the new coatings was tested under wide air humidity and cold plate temperature conditions.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

A thermoelectric cooler is used as the cooling source for the frosting surface and it can provide a temperature as low as -26°C . A copper plate of 150mm $\times$ 52mm $\times$ 6mm is mounted on the cooling unit and the plate was polished by an 800# polishing cloth. During tests, the plate and the data acquisition system are placed in a large closure (2.5 m $\times$ 2m $\times$ 1.5m) in order to maintain the controllable natural convection condition. The plate is vertically placed for all the experiments reported in this paper. The temperature and the humidity inside the closure are regulated at the given values by an air-conditioning system and a humidity controller. The surface temperature of the plate is measured by four T-type thermocouples that are buried beneath the test surface 0.5 mm through four holes of 1 mm in diameter and 13 mm in depth drilled into the plate. Temperature data recorded by a HP data acquisition system are finally transferred to a personal computer for further analysis. The cold surface temperature is the average of the temperature readings of the four thermocouples. The thermocouples are all pre-calibrated with a resolution of 0.1°C . The maximum uncertainty in the plate surface temperature measurements is estimated to be less than 0.5°C , including the error resulted from the position errors and the fact that these thermocouples are not placed exactly at the surface. A microscopic imaging system that consists of a CCD camera, a microscope and a capture card is used for micro and transient observations of the frost deposition process and measuring the frost layer thickness. The CCD camera and microscope with a maximum magnification of 110 are mounted right over the cold surface for taking photographs and observing the frost growth with the help of an optical fiber luminescence.

temperature is set to the prescribed value. During cooling process of the cold plate, the test surface is covered with a thin plastic film to isolate the surface from air. When the plate temperature reaches its prescribed value and the whole system is steady, the plastic film is ripped away and timing and data acquisition are started.

3 EXPERIMENTAL RESULTS

3.1 Frost thickness comparison with the uncoated metal surface

In order to prove the effectiveness of the novel anti-frosting paint in reducing frost deposition on the coated surface, a series of comparative experiments were carried out for both the coated and the uncoated copper surfaces. Figures 3~5 are some of the typical experimental results under various conditions. Figure 3 compares the frost growth on the coated surface with that on the uncoated surface under low air humidity (about 35%) and different cold plate temperature conditions. One can see from Figure 3(a), after 3 h of testing, although the thickness of the frost layer on the uncoated copper surface is as large as 1.6mm when the cold plate temperature is about -11.2°C , there are no frost deposition at all on the coated surfaces. Actually, under this condition the coated surface keeps free of frost for more than 3

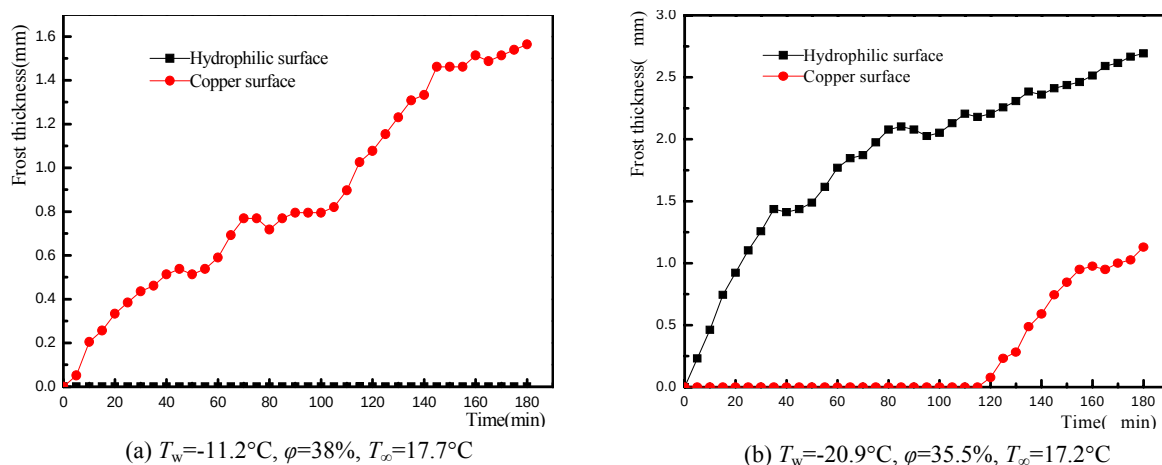


Figure 3: Comparison of frost deposition processes on the coated and uncoated surfaces: Different plate temperature and low humidity conditions

hours since no frost deposition on the coated surface was observed during the entire 3 hour test. Figure 3(b) gives the comparison under the lower cold plate temperature of -20.9°C and the same humidity (35.5%) conditions. The coated surface shifts the onset of frost formation to the time of 120 min. At 3 h, the frost layer thickness on the coated surface is only about 1.3 mm, while the thickness on the uncoated copper plate is as large as 2.6 mm, which corresponds to a reduction of 50% in frost thickness.

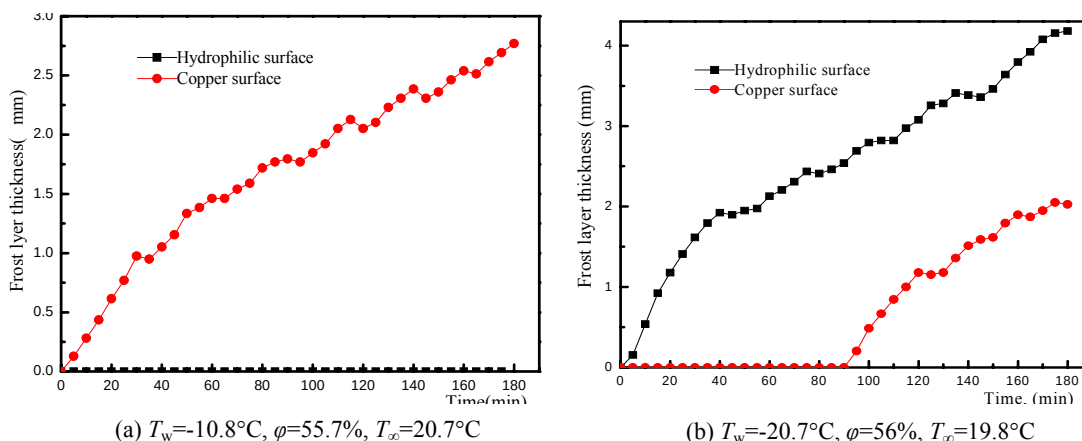


Figure 4: Comparison of frost deposition processes on the coated and uncoated surfaces: Different plate temperature and moderate humidity conditions

Figures 4 depict some of the typical experimental results under moderate relative humidity conditions. From Figure 4(a) one can see, after 3 h of testing, although the frost layer thickness on the uncoated copper surface is as large as 2.8 mm, there is no frost deposition at all on the coated surfaces. Figure 4(b) gives the comparison under the lower cold plate temperature of -20.7°C . The coated surface shifts the frost formation onset to the time of 95 min. At 3 h, the frost layer thickness on the coated surface is only about 1.9 mm, which is only 43% of that on the uncoated copper plate.

Figures 5 present some of the typical experimental results under high relative air humidity conditions. From Figure 5(a) one can see, after 100 min of testing, there is no frost deposition at all on the coated surfaces if the cold plate temperature is -15.1°C . Figure 5(b)

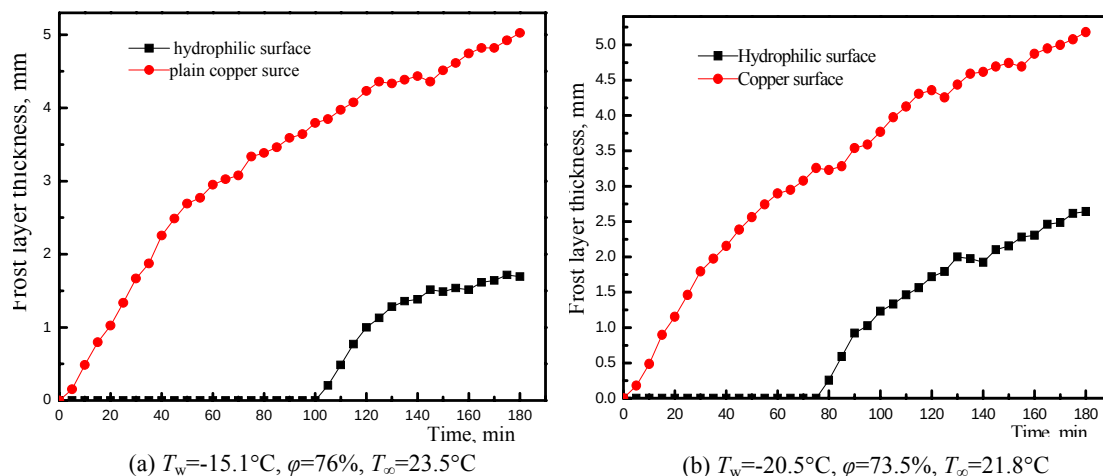


Figure 5: Comparison of frost deposition processes on the coated and uncoated surfaces: Different plate temperature and high humidity conditions

shows the coated surface can shift the onset of frost formation to the time of 80 min under the lower cold plate temperature of -20.7°C .

From these results one may therefore conclude that the frost growth on the coated surface made by our new anti-frosting paint is restrained effectively under various temperature and air humidity conditions.

The strong anti-frosting performance of the novel paint is also described by Figure 6. Figure 6 presents the pictures of the frost layer on the coated and uncoated surfaces at 60, 120, 150 and 180 min, respectively, under the conditions of the cold plate temperature of -15.3°C , the air relative humidity of 73%, and the air temperature of 17.9°C . From these figures we

can see clearly that at different test time, although a dense, continuous and relatively uniform frost layer has already formed at the central area of the uncoated copper surface, there are no appreciable frost crystals at the central area of the coated surface even after 3 h, though

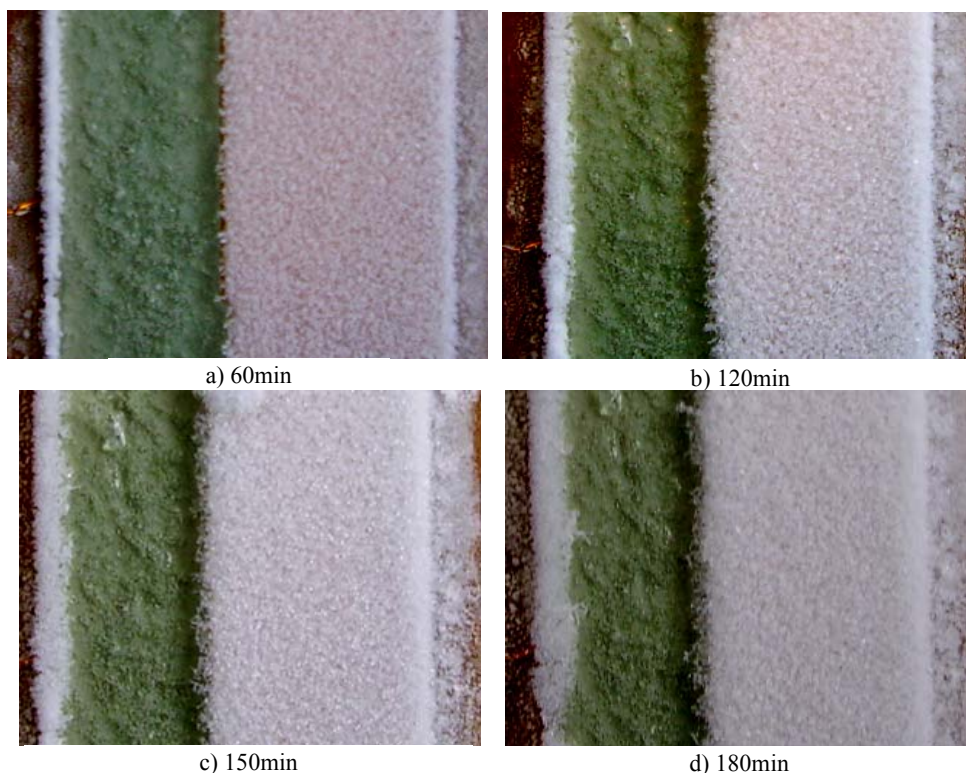


Figure 6: Comparison of frost deposition in the central area of the coated (left) and uncoated (right) surfaces ($T_w = -15.3^\circ\text{C}$, $\phi = 72\%$, $T_\infty = 19.3^\circ\text{C}$)

the measured frost layer thickness at the top edge of the coated surface is 1.7 mm at this case at 3 h. It should also be noted that the difference between the frost layer thickness at the top edge and that at the central area of the uncoated surface is much smaller compared with the coated surface. Therefore, the anti-frosting performance of the paint is actually much better than it is described by our measured frost thickness.

3.2 Influences of cold plate temperature and air humidity on the anti-frosting performance of the coated surface

Figure 7 depicts the influences of the cold plate temperature on the frost layer thickness growth on the surfaces coated by the anti-frosting paint. From the figures one can see that the cold plate temperature has a very strong influence on frost deposition processes. As the plate temperature decreases, the frost thickness growth rate thus the frost deposition rate increases sharply. In Figure 7 when the cold plate temperature is -8.5°C , the frost layer thickness is zero. There was no frost deposition observed during the whole testing period that lasted for more than 3 h. The frost layer thickness at 3 h is 1.28 mm for the cold plate temperature of -10.3°C , 1.69 mm for the plate temperature of -15.1°C and 2.64 mm

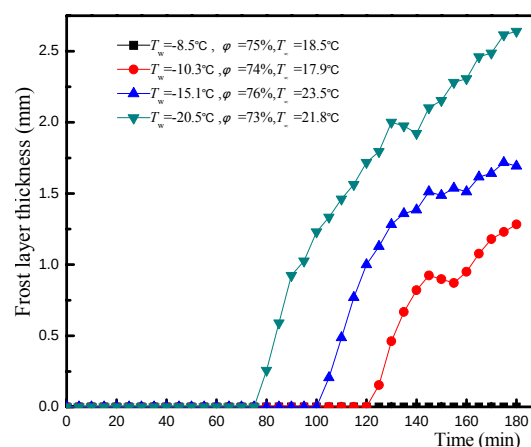


Figure 7: Frost thickness on the coated surface vs. time: Influence of the cold plate temperature

for the cold plate temperature of -20.5°C . It should be also pointed out that the anti-frosting paint has a very strong frost formation onset delay effect, and this effect is strongly affected by the cold plate temperature. The time delay of the onset for frost deposition on the coated surface is more than 3 h for the cold plate temperature of -8.5°C , 125 min for -10.3°C , 105 min for -15.1°C and 80 min for -20.5°C .

As one may expect, air humidity should also have a strong influence on the frost deposition processes of the coated surface. Figure 8 presents the influences of the air relative humidity on the frost deposition process under the cold plate temperature of about -20.7°C . The results show that the thickness of the deposited frost layer increases rapidly with air humidity. The thickness of the frost layer at 3 h is 1.13 mm for the situation of the air relative humidity of 37%, 2.03 mm for the relative humidity of 56% and 2.63 mm for 74%. The anti-frosting paint has a very strong frost formation onset delay effect, and this effect is also strongly affected by the air relative humidity. The time delay of the onset for frost deposition on the coated surface is 120 min for the air relative humidity of 37%, 95 min for 56%, and 80 min for 74%.

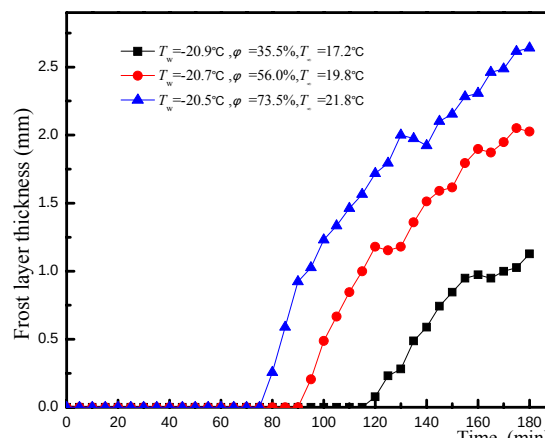


Figure 8: Frost thickness on the coated surface vs. time: Influence of the air relative humidity

4 MECHANISM ANALYSIS

As the experimental results demonstrated in this paper, our new anti-frosting paint can both retard the frost formation and minimize the frost growth on the cold heat transfer surfaces. The frost layer deposited on the coating surface of the paint has a loose, weak and fragile

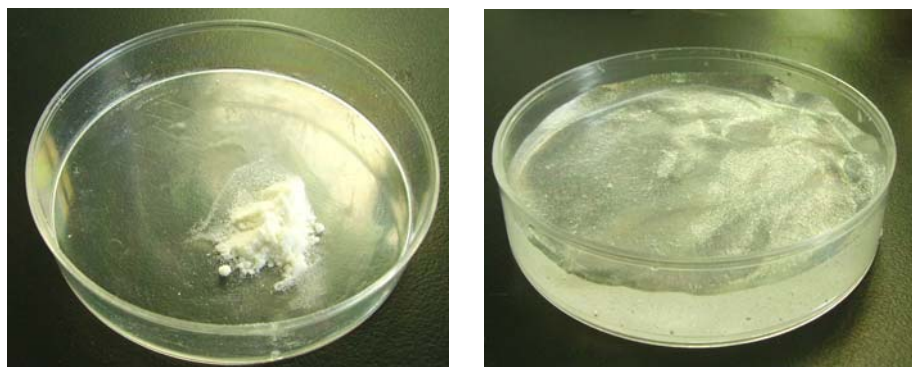


Figure 9 Water absorption test about the polymer

structure and thus can be easily removed by external force. Therefore, the paint is very effective in anti-frosting. However, its mechanism is still not clear. It might be related to the fact that the material can absorb a large amount of condensed water and can remain the absorbed water in liquid state even when its temperature is well below the ice point of water. Highgate 1989 and Rault 1995 studied the freezing behavior of water in a similar coating and found out that the water contained in the polymer coating will not freeze until its temperature goes as low as -20°C .

The new anti-frosting paint we developed also contains a kind of polymer that can absorb a large quantity of water. To demonstrate the large capacity of the polymer that we used as the mother material of the paint, we put 0.1g this polymer into a utensil and then add water in it.

The simple weighting test showed that 18g distilled water had been completely absorbed by the mere 0.1g polymer, as shown in Figure 9.

Furthermore, several strong polar substances that work as additives are also used in the paint, and perhaps, this may enhance polymer's ability to keep water unfrozen at very low temperatures.

When condensed water was absorbed by the polymer in the coating, the polar substances contained in the paint may play a role in preventing the absorbed water from freezing. This is because water molecules are of strong polarity, and they should be attracted by the charged particles. When the polar material was dissolved in water, ionization will happen and then there will appear positive and negative ions in water.

The water molecules and those ionized particles attract each other as Figure 10 and Figure 11 show. This process will finally result in the breakdown of hydrogen bonds that hold many water molecules together to form macro-water-molecule groups in normal water.

Therefore, due to these effects, macro-water-molecule groups that are normal states of water are significantly reduced in the absorbed water. Ice skeleton structure is formed based on these macromolecule groups through hydrogen bonds. Therefore, the breakdown of these hydrogen bonds may help water to remain at liquid state at very low temperature and this might explain the phenomenon that the absorbed water in coating remains unfrozen state.

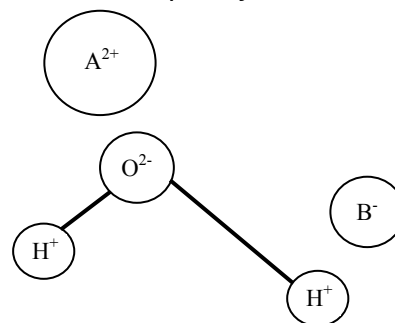


Figure 10: Attraction of positive and negative ions to a water molecule

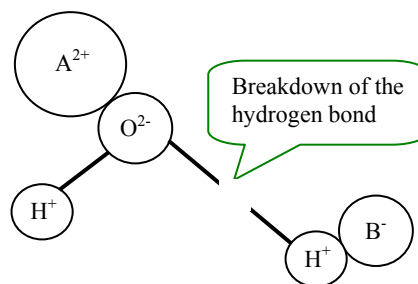


Figure 11: Breakdown of the hydrogen bond

5 CONCLUSION

The performance of a new anti-frosting paint has been studied experimentally. From the experimental results and the above discussions, the following conclusions can be made: (a) The coating of the paint on a cold surface can both effectively retard the frost crystal nucleation and reduce frost layer growth. The time delay for the onset of the incipient frost crystal formation is at least 80 min under the tested conditions. The reduction in the thickness growth of the deposited frost layer is greater than 40%. Since the frost layer thickness in the central area of the uncoated surface is much smaller than the thickness measured, the anti-frosting performance of the paint is actually much better than our measured results. (b) Under the conditions of low air humidity (<56%) and relative high cold plate temperature (>-10°C), the surface that is coated with the paint is free of frost for more than 3 h though the uncoated copper surface that is exposed to the same conditions is completely covered by a dense and thick frost layer. (c) The edge effects of the coated surface are much stronger than that of the copper surface. Under many situations although we measured an appreciable frost layer thickness from the upper edge of the coated surface, there was hardly any frost deposition in reality on the most part of the surface. Therefore, the actual anti-frosting performance of the paint is much better than what is indicated by the frost thickness measurements. (d) Cold plate temperature and air humidity both have very strong influences on frost deposition process on the surfaces coated by the anti-frosting paint. With the cold plate temperature decreases and air humidity increases, frost layer thickness growth rate increases sharply.

6 ACKNOWLEDGMENT

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