An experimental study on minimizing frost deposition on a cold surface under natural convection conditions by use of a novel anti-frosting paint. Part II. Long-term performance, frost layer observation and mechanism analysis

Zhongliang Liu*, Hongyan Wang, Xinhua Zhang, Sheng Meng, Chongfang Ma

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, China

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Abstract

In this part of study, the comparative observations of the structure and the surface temperature of the frost layer of both the coated and uncoated surfaces were carried out and a preliminary analysis was presented. A series of the repeated cycling tests were completed that lasted for more than 2 months, and the influences of the coating thickness were also investigated. The results show that the frost layer deposited on the coating surface has a very fragile structure and can be removed easily by external force. The coating thickness has an important effect on the anti-frosting performance of the paint. The results also show that the coating of the paint on the copper surface is durable and presents a very good repeated cycling performance.

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Keywords: Experiment; Coating; Paint; Frost formation; Surface; Performance; Comparison; Growth

1. Introduction

In the first part of the paper, the experimental research results were reported for the anti-frosting performance of our newly developed anti-frosting paint. The results showed...
that by coating the paint on a cold metal surface the onset of
the frost formation may be delayed at least 15 min and the
frost deposition may be reduced by at least 40% compared
with that on the uncoated copper surface. Under some
preferable conditions (air relative humidity <60%, cold
plate surface temperature >−10 °C), the coating surface
may keep free of frost deposition at least for 3 h. Although it
was shown to be effective in short-term tests, there are
several important questions to be answered. What is the
mechanism of the anti-frosting paint? How is its long-term
and repeated cycling performance? In what way does the
coating thickness influence the anti-frosting performance?
To answer these basic questions, the comparative obser-
vations of the structure and the surface temperature of the
frost layer on both coated and uncoated surfaces were
carried out, and a preliminary analysis was presented. A
series of the repeated cycling tests were completed that
lasted for more than 2 months, and investigations on the
influences of the coating thickness were also presented in
this part. A NEC TH5102 infrared thermographer is used to
measure the surface temperature of the frost layer. The
measurement range of the thermographer is 20–800 °C
with a resolution of 0.1 °C. Its thermal picture elements are
255(H) × 233(V), and two different emissivities can be set
simultaneously for different target regions. In order to
reduce the influences of the environmental radiation, the
calibration is carried out against the environmental reflection by using a black surface. In this study, the
emissivity of the coating surface is set to be 0.88, and the
emissivity of the frost layer surface is 0.9. The experimental
set-up and method are the same as described in the first part of the paper.

### 2. Experimental results and discussions

#### 2.1. Frost layer structure observation and frost surface temperature measurement

In order to understand the anti-frosting mechanism of the
paint, observations were made to compare the frost crystal
nucleation and growth process. It was found that not only
the frost deposition rate on the coated surface was smaller
than that on the uncoated copper surface, as indicated by our
frost thickness measurements, but the frost crystal nuclea-
tion and growth process was also different. As it has been
already mentioned in the first part of this paper, the onset of
the frost formation on the coated surface is much later than
that on the uncoated copper surface. There are only a limited
number of the incipient crystals that are formed sparsely on
the coated surface, while a continuous frost layer may
already have been deposited on the uncoated surface. The
crystals on the coated surface were clearly dendritical in
structure, and the dendrites were large, bulky, and thick.
Therefore, the frost layer on the coated surface is loose,
weak, and fragile and can be easily removed by external
force. This seems contrary to our common knowledge that
the frost layer on a hydrophilic surface is dense. Therefore,
the dendritical growth on the coated surface is not a result of
its hydrophilicity. One possible explanation to this abnormal
phenomenon is that the coated surface is rough, coarse,
bumpy and uneven. The surface tension effects at different
positions of the heaves are different and this may result in
different frost crystal nucleation and growth rates on different positions and directions. Fig. 1 presents the
pictures of the frost layer on the coated and uncoated
surfaces at 30, 60, and 120 min, respectively, under the
conditions of the plate temperature of −16.0 °C, the air
relative humidity of 73%, and the air temperature of 19.6 °C.
The coating thickness is 0.3 mm. From this figure we can
see clearly that at the time of 30 min, although a dense,
continuous and relatively uniform frost layer has been
already formed on the uncoated copper surface (the
measured thickness is 2.1 mm), there are only several frost
crystals distributed sparsely on the coated surface. Most of
the coated surface has not been covered by any frost
although the measured ‘frost layer’ thickness is 0.75 mm at
this moment. Thirty minutes later, at the time of 60 min, the
measured thickness of the deposited frost layer on the coated
surface is as large as 1.35 mm, but as one can see from
Fig. 1(b), the frost layer has hardly covered the surface and
there are still a great number of void areas that are not
covered by frost crystals. From Fig. 1(c), one can further
find that not only is the thickness of the frost layer on the
coated surface thinner than that on the uncoated copper
surface, but the frost layer structure on the coated surface is
also more loose and fragile than that on the uncoated
surface.

One may argue that the coating brings an additional
thermal resistance to the process, and it is this additional
thermal resistance that explains the above stated phenom-
enon. However, our surface temperature measurements do
not support this argument. At the very beginning, as one
may expect, the surface temperature of the coated surface is

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$t$</td>
<td>time (min)</td>
</tr>
<tr>
<td>$T_w$</td>
<td>plate temperature (°C)</td>
</tr>
<tr>
<td>$T_s$</td>
<td>frost surface temperature (°C)</td>
</tr>
<tr>
<td>$T_\infty$</td>
<td>air temperature (°C)</td>
</tr>
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### Greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$\delta$</td>
<td>frost layer thickness (mm)</td>
</tr>
<tr>
<td>$\delta_c$</td>
<td>coating thickness (mm)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>relative humidity (%)</td>
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slightly higher than that of the uncoated copper surface. As the process proceeds, however, the frost deposits quickly on the uncoated copper surface, and thus a continuous frost layer is formed. Then the frost layer surface temperature on the coated surface is significantly lower than that on the uncoated copper surface. Fig. 2 depicts the infrared thermography results of the surface temperature distribution at 30, 60, and 100 min under the frost deposition conditions of \( T_{\text{n}} = 26.0 \, ^{\circ}\text{C}, \phi = 60\% \) and \( T_{\text{w}} = -18.3 \, ^{\circ}\text{C} \). The coating thickness on the left half is 0.3 mm. From Fig. 2, one can find out that the surface temperature of the upper part of the frost layer is higher than that of the lower part. This is in agreement with the fact that the thickness of the frost layer on the upper part of the surface is larger than that on the lower part. The same explanation can be given to the fact that surface temperature of the boundary area of the plate is higher than that of the central area due to the edge effect that has been already discussed in the first part of this paper. The
most impressive characteristic of the surface temperature distribution across the plate width is that temperature on the left part of the plate is lower than that on the right part of the plate (usually by 1–2 °C). We can see from these temperature distributions depicted by Fig. 2 that not only is the surface temperature of the frost layer on the coated surface (the left part of the plate, the region from \(x = 0–26\) mm on the abscissa of Fig. 2) lower than that on the uncoated surface (the right part of the plate, the region from \(x = 26–52\) mm on the abscissa of Fig. 2), but the surface temperature profile of the frost layer on the coated surface is also uneven and presents more fluctuations compared with that on the uncoated surface. The uneven surface temperature profile is due to the non-uniformly distributed frost crystals and the loose and sparse frost layer of the coated surface. The surface temperature of the frost crystal deposited region is higher than that of the bare region, and this results in an uneven and wavy surface temperature profile of the coated surface. Fig. 2 also tells us that, as time elapses, the thickness of the frost layer on both parts of the plate increases, and this results in the increase of the frost layer surface temperature of both the coated surface and the uncoated surface. The surface temperature of the coated part, however, remains lower than that of the uncoated part even at 100 min.

2.2. Influences of coating thickness

As one may expect, the coating thickness should have some influences on the anti-frosting performance of the paint. Fig. 3 presents the experimental results of the influences of the coating thickness on frost deposition and comparison with the uncoated surface. From the results, we can see that the thickness of the coating has a strong influence on the frost deposition process. Under similar conditions, the thicker coating results in better anti-frosting performance. After 120 min of frost deposition, the frost layer thickness on the surface of the 0.3 mm coating is 1.7 mm, while on the surface of the 0.4 mm coating is 0.17 mm. Our observations of the frost deposition processes on the surfaces of the different coating thickness show that the thicker coating also results in a stronger edge effect. No frost deposition was actually observed in the central part of the surface of the 0.4 mm coating throughout the test, as shown in Fig. 3.

The above results seem to support the conclusion that the thicker the coating the better the anti-frosting performance. However, this may not be always true. The influences of the coating thickness are manifold. The thicker coating also means a larger additional thermal resistance and a larger occupation of the effective space for airflow and thus may degrade the total performance of the system. The thickness of the coating also influences its strength and permanence. Increasing the coating thickness usually reduces the structure strength of the coating. Therefore, there should exist an optimum coating thickness for meeting specific performance requirements, but this is out of the scope of this paper.

2.3. Long-term and repeated cycling performance

The long-term and repeated cycling performance of an anti-frosting paint is, needless to say, of crucial importance for its practical applications. Therefore, we conducted a repeated cycling test on a test sample for more than 2 months. The total number of the experiments conducted on this sample was more than 15. That is, every 5 days a frost deposition test was conducted for 2–4 h. The frost was then allowed to melt and the sample was dried under the room temperature and humidity condition. The coating showed no appreciable degeneration in anti-frosting performance after these long-term repeated test runs. Fig. 4 presents three typical pictures of the frost layer surface on the sample at 30 min frost deposition after 15, 40 and 55 days of coating. The coating thickness on the left half is 0.3 mm. From these pictures one can see that though the testing conditions are different for these three tests, the anti-frosting effects of the coating are all clearly recognizable. There are only a limited number of frost crystals distributed sparsely on the coated part (the left part) of the plate, whereas the uncoated part of the plate has already been covered by a dense and continuous frost layer. Our observations of the coating show that the coating has a good permanence even after a large number of frosting-melting cycles during more than a 2 month testing period. The coating, generally speaking, exhibits a very good adhesivity on copper surfaces. But the repeated expansion and contraction of the coating and the strong edge effect caused a few of the paint particles on the edge of the plate to peel off after more than 2 months of repeated experiments.

3. 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 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. The paint contains a kind of polymer that can absorb a large quantity of water and a hydrophilic agent that may keep water unfrozen under very low temperature conditions. Highgate et al. [1] and Rault et al. [2] 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 $-20 \, ^\circ C$. The crystallization depress in polymer can be explained by the $T_g$ (glass temperature) regulation effect [3] and correlated by the Brun equation [4] to the dimension of the pores in polymer. The $T_g$ regulation effect tells us that the crystallization depression is dependent on the water concentration in polymer: In the low concentration regime, water simply does not crystallize and in the high concentration regime only a certain amount of water can crystallize at low temperature. The Brun equation says that the crystallization depression is in inverse proportion to the pore dimension. The above theory may explain why the water in polymer can remain liquid state at very low temperature. And perhaps this is the reason why this kind of polymer can retard the formation of the incipient frost crystals. However, why and how the unfrozen water within the polymer can depress the frost nucleation on its surface is not known by the authors of this paper. The water inside the polymer is usually in three typical states: the free water, the bonded water in weak interaction with the polymer, and the unfrozen water in strong interaction with the polymer. The unfrozen water will not be frozen even when the temperature is well below water’s crystallization temperature. During the frost formation process, the coating absorbed a large amount of condensed water first, and then the frost crystals deposited gradually on the surface of the swollen coating. Therefore, there are both the frozen and the unfrozen water molecules at the interface of the coating and the ‘frost layer’. The adhesive force of the frost crystals to the coating surface is thus greatly reduced and this might explain the fragile structure of the frost layer on the coated surface. Furthermore, our anti-frosting paint has very good consistency and elasticity and thus can resist the destructive effects that were produced due to the freezing of water. Therefore, the coating can last a very long time and has very good repeated cycling performance.

As it has been mentioned, the frost crystals deposited on the coated surface are loose and weak and even exhibit some of the characteristics of strongly dendritical growth, although our coating is of hydrophilic characteristics. However, the hydrophilicity of the coating is different to the conventional hydrophilic surface. Since the surface of the coating is coarse and uneven, water does not form a homogeneous and continuous film on the surface due to this unevenness and the discontinuous distribution of the hydrophilic agent inside the mother coating. Therefore, the coating surface is only locally hydrophilic, and this may be the main reason why the frost deposition on the coating exhibits a certain characteristics of a hydrophobic surface. We tried to measure the static/dynamic contact angle of the coated surface without success due to the fact that the surface is too coarse and uneven and absorbs the water that was dripped onto it too quickly.
4. Conclusions

From the experimental results and the above discussions, the following conclusions can be made:

(a) Although the polymer contained a hydrophilic agent in the paint, the growth of frost crystals on the surface of the paint coating was more similar to that of a hydrophobic surface. The frost growth exhibited strong dendritical characteristics, and the frost layer formed had a very loose, weak, and fragile structure that could be easily removed by external force.

(b) Although the coating presents an additional thermal resistance to the heat transfer process and the surface temperature was a little bit higher than that of the uncoated surfaces at the very beginning, the surface temperature of the frost layer (if there is any) on the coated surface was lower than that on the uncoated surface during the whole frost layer growth process.

(c) Our limited experimental results showed that the coating thickness has an important influence on the anti-frosting performance, and the thicker coating resulted in the best anti-frosting performance. However, an optimum coating thickness should be determined to meet the specific performance requirements of the system.

(d) The coating of the paint on the copper surface exhibited very good adhesivity and was very durable. After repeated experiments of at least 15 times during a period of more than 2 months, no appreciable degeneration in the anti-frost performance of the coating was observed.

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