PROGRESS IN NATURAL SCIENCE Vol. 16, No. 4, April 2006

Experimental investigation of the influence of electric field on frost layer growth under natural convection condition*

ZHANG Xinhua, LIU Zhongliang**, WANG Jieteng, GOU Yujun,
MENG Sheng and MA Chongfang

(Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education; Key Laboratory of Heat Transfer and Energy Conversion, Beijing Education Commission, Beijing University of Technology, Beijing 100022, China)

Received June 28, 2005; revised July 22, 2005

Abstract The influence of direct current (DC) electric field on the thickness and mass of frost on a cold vertical plate was investigated. The photos of frost layer growth were taken with and without the presence of electric field, and results showed that the electric field has a strong influence on the frost thickness. The influences of cold plate temperature and ambient temperature on frost thickness and frost mass were also investigated under the natural convection condition with electric field. Experimental results demonstrated that the cold plate temperature has very strong effect on the frost layer thickness, but its influence on frost mass is minor; the influence of ambient temperature on the frost mass is more obvious than that on the frost thickness.

Keywords: **frost formation, electric field, natural convection.**

When the temperature of a surface is lower than the air dew point, condensation will occur on the surface. Furthermore, if the surface temperature is lower than 0 ℃, vapor will be finally turned into frost. Frost formation is a complex transient process, in which both heat and mass transfer occur simultaneously. Frost formation and growth depend on the surface energy, surface temperature, air temperature and humidity, and air velocity. Frost accumulation has a strong effect on refrigeration, cryogenic and many other engineering systems due to the increased flow and heat transfer resistance and the reduced energy transfer rate. Therefore, people have made great efforts to seek effective defrosting and frost-controlling methods.

Frost formation on cold surface is a typical interface phenomenon, so the cold surface characteristics should have an important influence on the process of frost formation. Many researchers have been trying to improve the qualities of the cold surface including using various coatings to restrain frost formation. So far, although many endeavors have been done, no good results were obtained by changing the surface conditions of the cold surface.

On the other hand, since water molecule has strong polarity, and frost formation is a water molecule transfer process, electric field should have strong influence on frost formation. According to Swanson et al.[1], the electric field influences the way of water molecules diffusion through the air in the vicinity of the frost layer. When a crystal grows, a strong electric field will be produced around the crystal, and the electric field near the sharp ends of the crystals will be much stronger than that in the other region. Since water molecules have an intrinsic electric polarizability, the electric field will tend to further polarize the water molecules. If the electric field has a strong gradient, the polarized molecules will be attracted in the direction of the electric field applied. Wang et al.[2] also found that, with the presence of electric field, the ice columns are pulled up towards the electrode, and the skinny and fragile shape and the weak structure of the ice columns can easily be broken and fall off due to the influence of gravity.

As far as we know, Schaefer[3] firstly reported the effect of a DC electric field on the frost growth. Schaefer found a rapid growth of ice in the form of whisker-like aggregates at high electric gradients. Munakata et al.[4] reported a 30% decrease in frost formation for an electric voltage of up to 7.5 kV, and the decrement was the largest. Meng et al.[5] studied

---

* Supported by National Natural Science Foundation of China (Grant No. 50376001) and the Major State Basic Research Development Program of China (Grant No. G200026304)

** To whom correspondence should be addressed. E-mail: liuzhl@bjut.edu.cn the effects of the electrostatic fields formed between the single-wire/ multiple-wire electrode and copper plate electrode on frost growth on the cold surface, and a preliminary mathematical model for frost formation process with the existence of the external electric field was proposed.

The studies reported focused mainly on the influences of electric fields on the frost layer thickness, and no frost mass information was provided. Although the effects of cold plate temperature and ambient temperature on frost formation are basically clear under convectional frost formation conditions, there are no definite experimental verification of their influences with the presence of external electric fields. In this work, the influences of DC electric fields on frost growth on a cold vertical plate were investigated under the condition of free convection, and the effects of cold plate temperature and ambient temperature on frost formation with the presence of electric fields were studied.

1 Experimental apparatus and procedures

The experimental system is shown in Fig. 1, and it consists of a test section, a data acquisition system and an electrostatic generator unit.

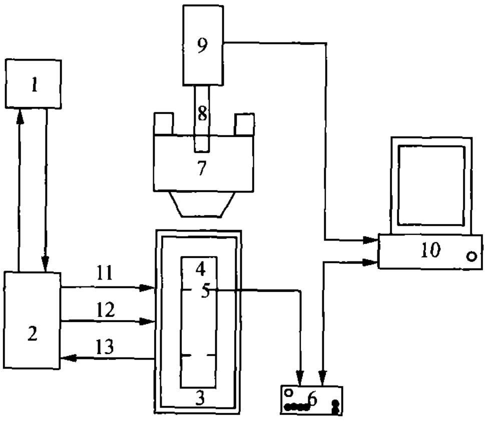

Fig. 1. Schematic diagram of the experimental system. 1, Cooling water source; 2, power source for thermoelectric cooler; 3, thermoelectric cooler; 4, cold plate; 5, thermocouples; 6, HP data acquisition system; 7, microscope; 8, camera lens; 9, CCD; 10, computer; 11, power supply cable; 12, inlet cooling water; 13, outlet cooling water.

A thermoelectric cooler was used as a cooling source for the frosting surface. It can provide a temperature as low as −26 ℃. A copper plate of 150 mm × 52 mm × 6 mm was mounted on the cooling unit. The surface temperature of the plate was measured by 4 T-type thermocouples that were buried beneath the test surface 0.5 mm through 4 holes of 1 mm in diameter and 13 mm in depth drilled into the plate. The temperature data recorded by a HP data acquisition system were finally transferred to a personal computer for further analysis. The cold surface temperature was the average of the temperature readings of the 4 thermocouples. The thermocouples were all pre-calibrated with a resolution of 0.1 ℃. The maximum uncertainty in the plate surface temperature measurements was estimated to be less than 0.5 ℃, including the error resulted from the position errors.

A microscopic image system consisting of a CCD camera, a microscope and a capture card was used for micro and transient observations of the frost deposition process and for measuring the frost layer thickness. The CCD camera and microscope with a maximum magnification of 110 were mounted right over the cooled surface to take photographs and observe the frost growth with the help of an optical fiber luminescence. The frost deposition process was recorded by the microscopic image system at a speed of 30 f/s and the frost thickness was measured by a micro-measurement system that was integrated into the microscopic image system every 5 minutes with an accuracy of ±0.05 mm.

An electrostatic generator system consists of a DC electrostatic generator and an electrode formed by parallel wires. The DC electrostatic generator can provide DC voltage of 0—100 kV, and the shape of the electrode is shown in Fig. 2. The bare wire used in this work is nickel chrome wire and its diameter is 0.3 mm.

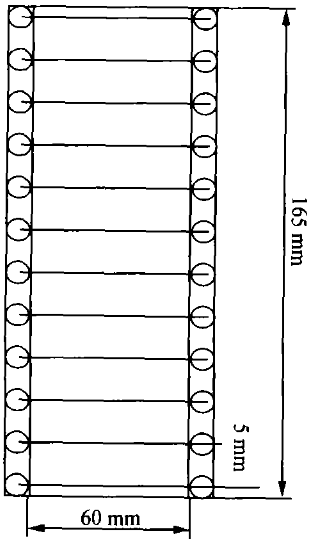

Fig. 2. The size of the parallel electrode.

During testing, the cold plate was protected by a large Plexiglas box to maintain the natural convection condition. The plate was vertically placed. The temperature and the humidity inside the closure were regulated at the given values by an air-conditioning system and a humidity controller. A thermo-hygrometer was used to monitor the environmental conditions, including the temperature and relative humidity. A humidity sensor with an uncertainty of 5% was used to measure the air humidity.

Before each experiment, the microscope was adjusted to focus on the copper plate. The gap between the copper plate and the electrode was set at the given value, and then the DC electrostatic generator and the cooling water of the thermoelectric cooler were turned on. After that, the power for the thermoelectric cooler was switched on and the cold plate temperature was set, and finally the refrigeration switch of the thermoelectric cooler was turned on. The observation scope was illuminated by an optical fiber luminescence. After each experiment, the DC electrostatic generator was turned off, the frosting copper plate was rapidly taken off, and put in a closed container, and the frost was weighed using an electronic balance with a resolution of 10 mg.

2 Results and discussion

2.1 Observation of the experimental phenomena

A high voltage electrostatic field was formed by using a set of parallel bare wires as the cathode and a cold plate as the anode, and the effect of the electric field on frost formation was studied experimentally. The duration of each experiment was 120 minutes. During the experiment, we observed intensive local discharging with blue electric sparks between the parallel bare wire electrode and the frosting copper plate, and very strong corona was formed. This corona may lead to intensified heat and mass transfer. When the electric field was applied, the frost crystal appeared earlier than that without electric filed. The frost layer formed with the existence of the electric field is generally dense and difficult to remove, and the surface of the frost layer is smooth. However, under the conditions of high ambient humidity, we can see long and needle-like frost crystals, and this kind of frost crystals is fragile and may fall off from the frost layer surface due to the effect of gravity. Some of the frost crystals are attracted to the bare wire electrode by the electric field force, but we did not observe long needle-like frost crystals for low ambient humidity. In order to observe the effect of the electric field on frost layer growth, we conducted a series of experiments with and without the presence of electric fields, and shot the photos of frost layer growth. Fig.3 presents some of these photos. In Fig. 3, the experimental conditions without external electric field applied are: the ambient temperature $T_\infty = 19.3$ ℃, the air relative humidity $\varphi = 69\%$, and the cold plate temperature $T_W = -9.3$ ℃; the experimental conditions with an external electric field of 12 $kV \cdot cm^{-1}$ applied are: the electric-field intensity is $\boldsymbol{E} = 12\ kV \cdot cm^{-1}$, $T_\infty = 19.3$ ℃, $\varphi = 70\%$, and $T_W = -10.5$ ℃. From Fig.3, we can see that within the first 35 minutes of the experiment, the electric field accelerates the frost crystal growth due to the fact that the electric field force makes the water molecules arrange along the direction of the electric field, so the frost layer is thicker than that without electric field. With the experiment going on, the frost crystals gradually become longer, and the formed needle-like frost crystals will break up and fall off the plate very quickly because it cannot endure its gravity. So the frost layer is thinner with the presence of electric field than that without electric field.

2.2 Effect of electric field on frosting

Due to the presence of electric field force, the polar water molecules will be arranged along the direction of the electric-power line, and the needle-like frost crystals will have a fast growth rate along the direction of the electric-power line. This will result in the formation of the fragile needle-like crystals, and these fragile crystals will fall off the cold plate under the effect of gravity. Therefore, the presence of electric field will significantly influence the frost layer growth rate. Here, a series of tests were carried out to test this effect. Four experiments were carried out with $\boldsymbol{E} = 0\ kV \cdot cm^{-1}$ (no electric field), $4\ kV \cdot cm^{-1}$, $8\ kV \cdot cm^{-1}$, and $12\ kV \cdot cm^{-1}$, respectively, while keeping all the other conditions unchanged ($T_\infty = 20.4$ ℃, $\varphi = 80\%$, $T_W = -13.2$ ℃). During the experiment, the frost thickness readings were taken every 5 minutes. At the time of $t = 120$ m, the frosting copper plate was taken off rapidly and put in a closed container, and the mass of the frosted plate was weighed. The frost mass was obtained by subtracting the weight of the dry cold plate from the weight of the frosted plate. Fig. 4 shows the effect of electric field on frost deposition . From Fig. 4(a),

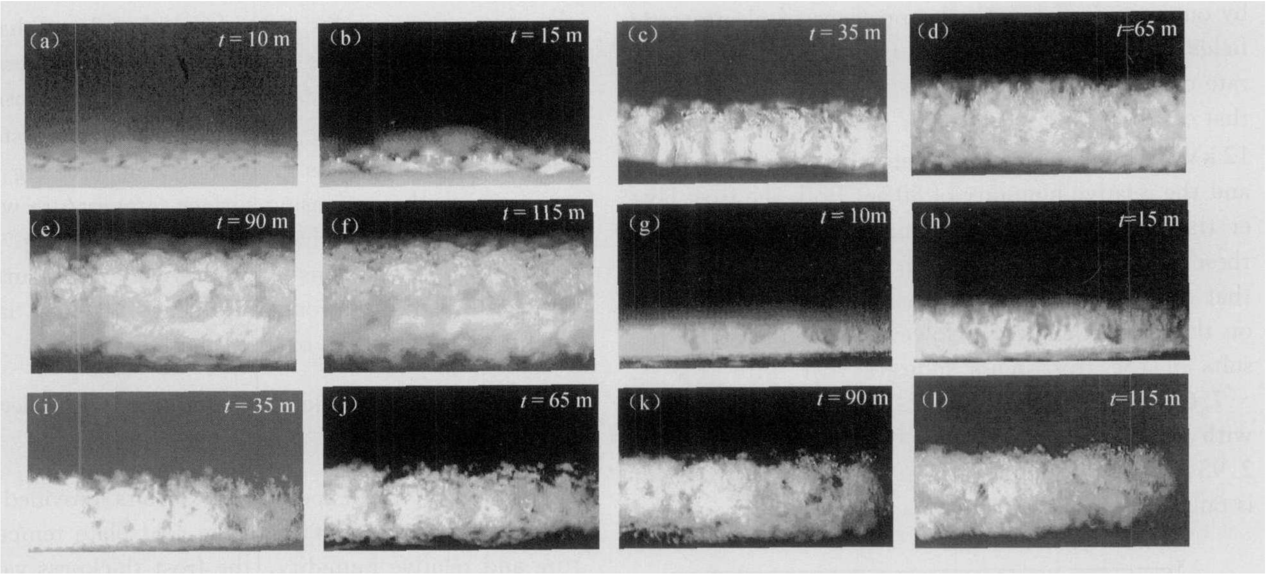

Fig. 3. Comparison of frost layers with and without electric fields. (a)—(f), $\boldsymbol{E} = 0\ \mathrm{kV \cdot cm^{-1}}$; (g)—(l), $\boldsymbol{E} = 12\ \mathrm{kV \cdot cm^{-1}}$.

we can see that the electric field does have a significant influence on the frost layer thickness and can reduce the frost layer growth rate. In addition, an optimal electric field seems to exist that can reduce the frost layer growth most effectively. However, in order to determine this optimal electric field strength, more experiments are needed. Fig. 4(b) shows the frost masses after 120-minute experiments with different electric field strengths. We can find that the presence of the electric field has an obvious influence on the frost mass. Under the experimental conditions of this paper, the frost mass with electric field applied is smaller than that without electric field, and the maximum decrement with electric field is up to 18.8%. Furthermore, from Fig. 4 we can also see that there is an optimal electric field strength that restrains the frost deposition most effectively. The applied electric field can attract water molecules to the direction of electric field, and thus the needle-like frost crystals are formed. These needle-like frost crystals are easily broken up due to the effect of gravity, thus the frost thickness reduces and the frost mass decreases. In addition, intensive partial discharge phenomena exist, so the electric shock also leads to the reduction of the thickness and mass of the frost layer.

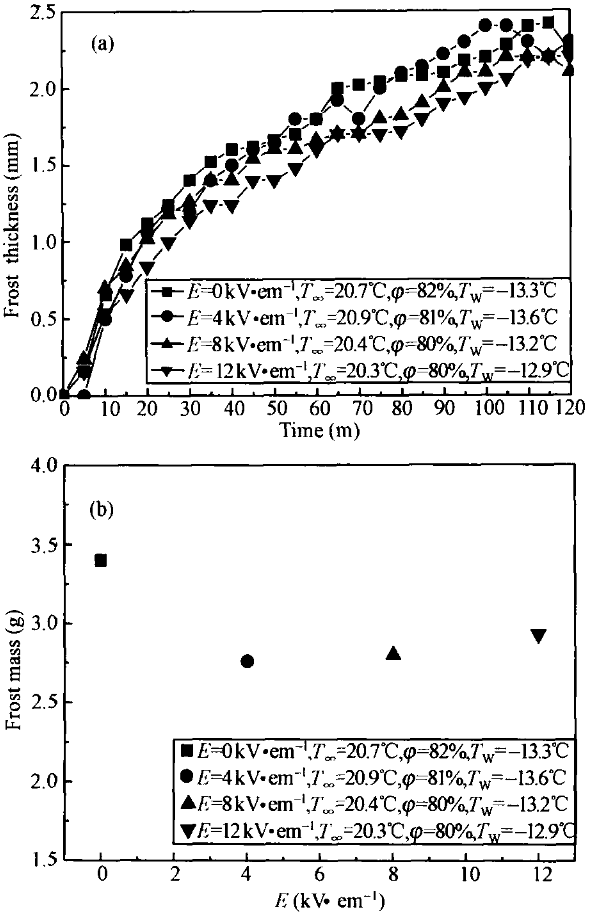

Fig. 4. The influences of electric field strength on frost layer thickness and frost mass. (a) Comparison of the frost layer thickness; (b) comparison of the frost mass at $t = 120$ m.

2.3 Effect of cold plate temperature with electric field

Under the same ambient temperature condition, the lower the cold plate temperature is, the higher the degree of subcooling is. As the subcooling increases, the frost crystal growth shows more dendritical growth characteristics. This conclusion was verified by our experiment with the presence of electrostatic fields. Fig. 5 compares the frost thickness growth rate of the plate temperature $T_W = -7.6$℃ with that of $T_W = -12.9$℃ with an electric strength of 12 kV · cm^{-1}, the ambient temperature of 20.4℃, and the relative humidity of 80%. Both the frost layer thickness and the frost mass were measured in these two experiments. From Fig. 5, we can find that cold plate temperature has an obvious influence on the frost thickness. However, the measured results of the frost mass indicate that with $T_W = -7.6$℃, the frost mass at $t = 120$ m is 2.81 g; and with $T_W = -12.9$℃, the frost mass increases to 2.93 g. The difference of frost mass in the two cases is only 0.12 g, less than 4%.

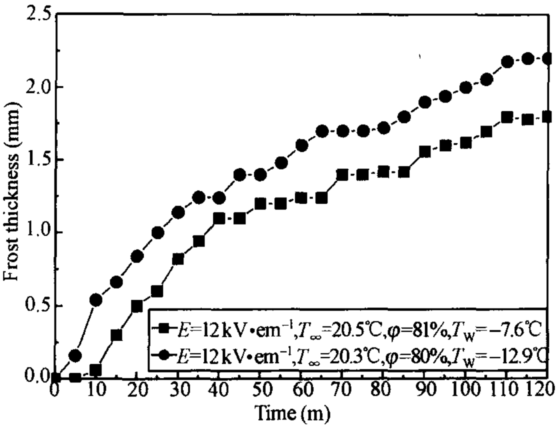

Fig. 5. The influence of cold plate temperature on frost layer thickness with electric field.

In vapor crystal growth system, the large supersaturation is the main reason for dendritical crystal growth. The larger degree of supersaturation means the bigger degree of subcooling and thus the lower surface temperature. Therefore, lowering the surface temperature will result in more serious dendritical growth of the frost crystals. Liu[6] defined a so-called frost thickness growth driving force to predict the frost thickness rate. He considered that the larger the frost thickness growth driving force, the faster the frost layer growth. That is to say, the low cold plate temperature accelerates the increase of the frost thickness:

$$\Delta g_t = \left(\frac{\Delta T}{T_s}\right)\Delta g = R\Delta T \ln\left(\frac{p}{p_s}\right),$$

where Δg_t is the frost thickness growth driving force (J · kg^{-1}), $\Delta T = T_m - T_s$ is the degree of subcooling (K), T_m is the water vapor triple point temperature (K), T_s is the frost layer surface temperature (K), Δg is the phase change driving force (J · kg^{-1}), p is the steam pressure far away from the phase change interface (bar), p_s is the saturated vapor pressure corresponding to T_s(bar), and R is the gas constant of water vapor (J · (kg · K)$^{-1}$). This equation states that the frost thickness growth driving force Δg_t increases with the decreasing surface temperature while keeping the phase change driving force Δg unchanged. This explains why the cold plate surface temperature has a stronger influence on frost layer thickness growth than on frost mass deposition.

2.4 Effect of ambient temperature with electric field

Based on the experimental results provided by Cheng et al.[7], under the same cold plate temperature and relative humidity, the frost thickness variation curves of different ambient temperatures almost overlap each other without the existence of external electric field. Cheng et al.[7] postulated that the water vapor cannot be rapidly cooled to a temperature lower than the ice point under high ambient temperature, so the water vapor cannot be turned into frost crystals on the frost layer surface to increase the frost thickness, instead, they enter the frost layer to increase the frost density. High ambient temperature leads to high frost layer surface temperature, and this may cause the crystals on the frost layer surface melting. Wang[8] from her experimental results of without the presence of external electric field also proved that the moisture content can affect the frost thickness greatly, but the influence of ambient temperature is weak. With the same cold plate temperature and moisture content, the higher the ambient temperature, the thinner the frost layer. The experiments of Cheng and Wang were both carried out without external electric field. Fig. 6 shows the frost layer thickness variations with time with electric field applied under the conditions of the ambient temperature of $T_\infty = 18.4$℃ and 22.4℃. The other conditions for the experimental results displayed in Fig. 6 are all the same: $\boldsymbol{E} = 8$ kV · cm^{-1}, $\varphi = 81\%$, $T_W = -8.5$℃. From Fig. 6, we can see that although the frost layer thickness decreases with the increasing ambient temperature, their difference is very small. This is consistent with the experimental results without the application of the electric field of Cheng[7] and Wang[8]. Although the ambient temperature has a very weak influence on the frost layer thickness, our frost mass measurement results prove that the ambient temperature has a very strong effect on the frost mass. The higher the ambient temperature, the more the frost mass accumulation. For the case of $T_\infty = 22.4$ ℃, the frost mass at $t = 120$ m is 4.78 g; for $T_\infty = 18.4$ ℃, the frost mass is only 2.51 g. The results reveal that the higher the ambient temperature, the denser the frost layer density, and therefore there will be more water entering frost layer, changing into frost, and increasing the frost layer density. This conclusion is in full agreement with that without electric field.

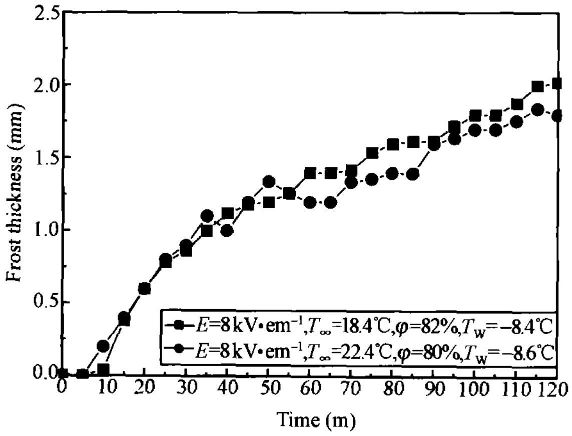

Fig. 6. The influence of ambient temperature on frost layer thickness with electric field.

3 Conclusions

The experimental results have revealed that the applied electric field can change the shape of frost crystals, decrease the frost layer thickness, and may also decrease the frost mass by up to 18.8% compared with that without electric field. When the external electric fields are applied, the cold plate surface temperature strongly affects the frost layer thickness growth, and the lower the cold plate temperature, the thicker the frost layer. However, the influence of cold plate temperature on frost mass is weak: the reduced cold plate surface temperature can only result in a relatively small increase in the frost mass, and in our experiments, the decrement is less than 4%. The ambient temperature has a very strong influence on the frost mass deposition, but its influence on the frost thickness growth is almost negligible when the external electric field is applied. The increase in the ambient temperature leads to a nearly doubled frost layer mass deposition in our experiments.

References

1 Swanson M. and Libbrecht K. G. Crystals grow quicker in E-fields. Caltech Undergraduate Research Journal, 2001, 1: 48—53.

2 Wang C. C., Huang R. T., Sheu W. J. et al. Some observations of the frost formation in free convection: with and without the presence of electric field. International Journal of Heat and Mass Transfer, 2004, 47: 3491—3505.

3 Schaefer V. J. Project cirrus. General Electric Research Laboratory, Schenectady, New York, Final Report 1953, 52—53.

4 Munakata T., Yabe A. and Tanasawa I. Effect of electric fields on frosting phenomenon. In: The 6th International Symposium on Transport Phenomena in Thermal Engineering, 1993, 381—386.

5 Meng F. J., Ma H. B. and Yue D. T. Forced phase change heat transfer in frost growth through sublimation under EHD. In: Academic Symposium for Celebration of the 80th Anniversary of Dalian Maritime College (in Chinese), Dalian, 1989, 38—44.

6 Liu Z. L. The frost layer growth rate equation of frost formation on a vertical cold plate under natural convection conditions and its numerical solution. Master Thesis (in Chinese), Dalian Maritime College, 1984.

7 Cheng C. H. Observations of early-stage frost formation on a cold plate in atmospheric air flow. Journal of Heat Transfer, 2003, 125: 95—102.

8 Wang H. Y. An experimental study of frost deposition on hydrophilic/hydrophobic cold surface under natural convection conditions. Master Thesis (in Chinese), Beijing University of Technology, 2004.