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Experimental study of frost growth on a horizontal cold surface under forced convection[†]

Lingyan Huang, Zhongliang Liu[*], Yaomin Liu and Yujun Gou

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, 100124, China

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Abstract

Frost formation on a horizontal copper surface under low air temperature and forced convection conditions is investigated experimentally. Both the frost crystals pattern and the frost layer thickness formed on the cold plate are compared under different experimental conditions. The environmental variables considered in this study include the ambient temperature (T_∞), air relative humidity (ϕ), and velocity (v), as well as the cold surface temperature (T_w). The tested ranges are $-5 \le T_\infty \le 5$ °C, $50\% \le \phi \le 80\%$, $2.2 \le v \le 8.0$ m/s, $-16.8 \le T_w \le -25.5$ °C. The experimental results show the cold surface temperature and the air relative humidity have obvious effects on the frost growth: the frost layer thickness increases strongly with the decreasing cold surface temperature and increasing air relative humidity. The air temperature and air velocity or Reynolds number are also important factors affecting the frost crystals' growth and thickness. With the increase of the air temperature and velocity, the frost crystals become denser, and the frost layer thickness become thicker, but this trend becomes weaker under higher air temperature and velocity.

Keywords: Frost; Forced convection; Frost layer; Heat transfer; Mass transfer

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1. Introduction

Frost deposition occurs when water vapor in the surrounding air gets contacted with a cooled surface through heat and mass transfer; it is a well-known and undesirable phenomenon in cryogenics, refrigeration, air conditioning, and aerospace industry. The frost crystals deposited on the heat transfer surfaces initially act as fins and enhance the heat transfer process due to the increase in effective heat transfer area and surface roughness. However, the continuous frost layer that finally inevitably forms on the heat transfer surface will adversely affect the performance of the refrigeration system due to the additional pressure drop and thermal resistance. Thus, defrosting is required to remove the frost layer periodically in most applications. This of course will increase both operation cost and energy consumption.

Frost formation is a complicated transient phenomenon process in which a variety of heat and mass transfer mechanisms occur simultaneously, and many factors such as air temperature, air relative humidity, air velocity, cold surface temperature and surface characteristics influence frost deposition and growth process. As early as in 1960, Smith et al. [1] discussed the effects of ambient conditions and cold surface temperature on the frost growth rate. With the development of the refrigeration, cryogenics and aerospace industry, investigations concerning the frost formation have received great attention in recent years [2, 3]. Furthermore, Lee et al. [4] and Liu et al. [5] investigated the effect of surface energy on frost formation under free convection. They found that surface hydrophilicity is one of the more advanced and attractive methods to reduce frost formation on cold surfaces. A large number of models have also been proposed to clarify the effects of environmental parameters on frost formation and to predict the frost layer growth. Lee et al. [6] developed the correlations for the thickness, density and thermal conductivity of the frost layer in the cases of high inlet air temperature. Yun and Kim [7] proposed a physical model of frost layer growth and frost properties with airflow over a flat plate at subfreezing temperature; they also suggested an empirical correction for average frost roughness. Na and Webb [8] presented a new model for frost growth rate based on supersaturated air at the frost surface; it showed good ability to predict the frost growth rate. Gupta and Gopal [9] developed a comprehensive thermo-fluidic model for a domestic frost-free refrigerator, and the

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[*] Corresponding author. Tel.: +86 10 6739 1917, Fax: +86 10 6739 2774
E-mail address: liuzl@bjut.edu.cn

model is simulated by employing a finite volume method, with an unstructured meshing.

Although frost formation under free convection has been studied extensively, information on the fundamental researches of frost formation under forced convection conditions on a cold surface is still limited, especially at low ambient temperature, which would be the standard operation conditions for evaporator, and most of them have been focused on heat exchangers [10] and heat pump systems [11-13]. As mentioned above, the frost deposition on a cold surface is a complicated heat and mass transfer process with phase change and moving boundary, so the theoretic simulation still has some difficulty to predict frost formation and it is necessary to turn to experimental research.

The present study is aimed to investigate the effects of the ambient temperature (T_∞), relative humidity (ϕ), and velocity (v), as well as the cold surface temperature (T_w) on frost formation on a cold horizontal surface under relative lower ambient temperature; the ambient temperature is varied in the range of -5 °C to 5 °C. Observations on the frost crystals growth are performed by using a microscope image system. Both the frost crystals pattern and the frost layer thickness formed on the cold plate are provided under different experimental conditions.

2. Experimental apparatus and methods

The experimental setup to investigate the effects of the ambient temperature, relative humidity (ϕ), and velocity (v) on a cold horizontal surface was designed and constructed as illustrated in Fig. 1. This experimental setup is composed of five sections: a climate chamber maintaining the humidity and temperature of the inlet air, a refrigeration system regulating the cold surface temperature, a circulation wind tunnel, a data acquisition system, and a microscopic image system. The air temperature inside the climate chamber is monitored by using RTD sensors of Pt, and those are regulated by a PID controller, a heater, a condenser and an air cooling system. The uncertainty of the air temperature measurements is ±0.5 °C with in -15 °C to 15 °C. The air relative humidity inside the chamber is regulated by a humidifier; the uncertainty of the air relative humidity is ±3% as it ranges from 40% to 80%. The wind tunnel, which has a cross section of 150 mm×150 mm, is made of PVC. Air is forced through the wind tunnel and then the climate chamber by a blower. The air velocity can be varied in the range of 0 to 15 m/s by means of a frequency regulator connected to the blower. The test section of the wind tunnel is made of a movable plexiglas cover to permit easy access and clear observation by the microscope image system.

A copper plate with the dimension of 320 mm×110 mm×6 mm is aligned with the bottom surface of the test section; the bottom side of the copper plate is fixed tightly to the evaporator pipes in which the low temperature refrigerant is circulated. It can maintain the cold plate temperature from 0 °C to -30 °C. The lateral surfaces of the copper plate are insulated by a bakelite layer to prevent dew and frost formation on surfaces other than the test surface. The temperature of the copper plate is measured by six Pt electric resistance temperature sensors that are beneath the test surface through 6 holes of 2 mm in diameter and 15 mm in depth (in Fig. 1). The cold surface temperature is the average of the temperature readings of the six locations. The temperature sensors are calibrated in advance and the estimated uncertainty of the cold plate surface temperature is less than 0.5 °C, including those resulting from the location errors.

In addition, two thermocouples and humidity sensors are installed at the inlet and outlet of the test section to measure the air temperature and humidity. Air velocity is calculated from the air volume flow that is measured by a flow meter with an estimated uncertainty of 0.1 m/s. All measurements including temperature, humidity and velocity are logged and processed via a computer interfaced to a data acquisition system for further analysis.

The microscopic image system consists of a microscope, a CCD camera and a luminescence illuminator. The system is used for the micro and transient observations of the frost deposition process and the frost layer thickness measurement. The microscope and CCD camera with a maximum magnification of 135 are mounted by the side of the test section for taking photographs of the frost formation through the plexiglas cover. The illuminator provides luminescence light for observation, having no appreciable thermal radiation to the frost layer. A personal computer, equipped with image acquisition and process software, receives the images taken by the microscopic image system, and then the frost layer thickness can be measured with an accuracy of ±0.001 mm.

The copper plate is placed in the test section and its surface is cleaned and covered with a sheet of thin plastic film so that water vapor can get contacted with the test surface before test starts. The test is started by tearing off the thin plastic film and turning on the plate refrigeration system simultaneously when

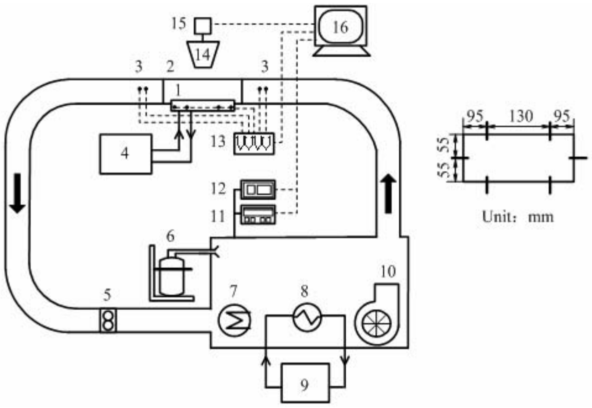

Fig. 1. Experimental system and apparatus: 1.copper plate; 2.plexiglas cover; 3.temperature and humidity sensor; 4.plate cooling system; 5.flow meter; 6.humidifier; 7.heater; 8.condenser; 9.air cooling system; 10.blower; 11.temperature and humidity controller; 12.frequency regulator; 13.data acquisition system; 14. microscope; 15.CCD; 16. PC.

the preset temperature, relative humidity and air velocity inside the climate chamber are attained. The air and the plate temperature, the air humidity and the velocity are recorded every 0.1 min, the image collection time interval is 0.5 min and the magnification time is 90. The observations of the frost crystals pattern and the frost layer thickness measurement on the cold plate are carried out at various combinations of these physical parameters. The standard duration of each test is 100 min.

3. Results and discussion

3.1 Effect of the cold surface temperature on frost growth

Fig. 2 compares the photographs of the frost growth at different instants under different cold plate temperatures. In this study, the images of the frost growth are recorded per 0.5 min; however, only the photographs for every 10 or 15 minutes are displayed in order to save space. The ambient temperature, air relative humidity and velocity are held constant at T_∞=0.8 °C, ϕ =65%, and v=8.0 m/s. It can be seen from the pictures in Fig. 2 that decreasing the cold plate temperature from -16.8 °C to -20.4 °C results in significant changes in frost growth. The frost growth rate increases as the cold plate temperature decreases; the frost crystals pattern and growth directions change with the cold plate temperature. For the case of T_w=-16.8 °C, the frost crystals on the cold surface appear to be intersected randomly and denser; the growth of the frost crystals is inclined to the down stream direction. However, at T_w=-20.4 °C, the frost crystals on the cold surface are more of arborization, that is, more dendritic, and the growth of the frost crystals is mainly along the direction vertical to the cold surface. Fig. 3 presents the influences of the cold plate temperature on the frost layer growth. It can be seen from the figure that the frost layer thickness increases strongly with the decreasing of the cold plate temperature. For example, at t=30 min, the frost layer thickness is 0.844 mm for T_w=-16.8 °C, the thickness is as large as 1.287 mm for T_w=-25.5 °C. The frost layer thickness of T_w=-25.5 °C is 52.5% higher than that of T_w=-16.8 °C. The frost layer thicknesses after 100 min at the three cold plate temperatures of -16.8 °C, -20.4 °C and -25.5 °C are 1.712 mm, 2.230 mm and 2.523 mm, respectively, which again shows the strong influence of the cold plate temperature on the frost layer growth.

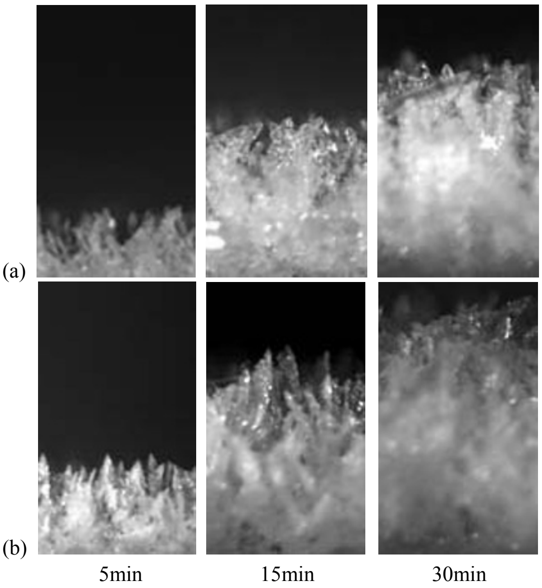

Fig. 2. Comparison of frost growth under different cold plate temperature: (a) T_w=-16.8 °C; (b) T_w=-20.4 °C.

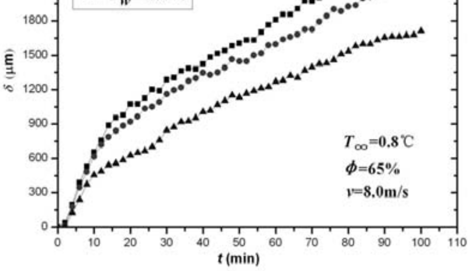

Fig. 3. Effect of the cold plate temperature on the frost thickness.

According to the vapor crystal growth theory, the crystal growth rate depends on the water vapor supersaturation degree that is defined [14] as:

$$S \equiv (p_v - P_{vs})/P_{vs} \tag{1}$$

where P_v and P_{vs} denote the actual local vapor pressure and the local saturation vapor pressure, respectively. The supersaturation degree at the frost surface is very important for the mass transfer during frost growth because it determines the driving potential for the mass transfer. A larger supersaturation degree means a larger supercooling degree and thus a lower surface temperature. Therefore, lowering the surface temperature will result in more serious dendritical growth of frost crystals. From the dynamics theory of phase transition, Liu [15] proposed a conception of 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, a low cold plate temperature accelerates the frost thickness increase.

$$\Delta g_{\mathrm{t}} = \left(\frac{\Delta T}{T_{\mathrm{s}}}\right)\Delta g = R\Delta T \ln\left(\frac{p}{p_{\mathrm{vs}}}\right) = R(T_{\mathrm{m}} - T_{\mathrm{s}})\ln\left(\frac{p}{p_{\mathrm{vs}}}\right) \tag{2}$$

Where Δg_t is the frost thickness growth driving force, ΔT is the supercooling degree, T_m is the water vapor triple point temperature, T_s is the frost surface temperature, Δg is phase change driving force, R is the water vapor gas constant, p is the vapor pressure away from the phase transition interface.

This equation states that the frost thickness growth driving force Δg_t increases as the cold plate temperature decreases and thus the surface temperature. This explains why a cold plate temperature has a stronger influence on frost layer thickness growth.

3.2 Effect of the cold ambient temperature on frost growth

Cheng and Wu [16] observed only a very weak effect of the ambient temperature on the frost layer growth as the air temperature changes from T_∞=23.3 °C to T_∞=28.4 °C. However, Lee and Ro [17] found that the frost layer thickness increases significantly with the ambient temperature as the air temperature varies in the range of 9.9 °C to 20.3 °C. To clarify the ambiguous results on the influences of the ambient temperature, we carried out a series of the experiments under the lower ambient temperature from T_∞=-5.2 °C to T_∞=4.8 °C.

Fig. 4 and Fig. 5 depict the effects of the ambient temperature on the frost layer growth under the condition of T_w=-20.4 °C, ϕ =65%, and v=8.0 m/s. Fig. 4 compares the frost growth pattern under two different ambient temperatures: T_∞=-5.2 °C and T_∞=0.8 °C. From these photographs we can find that, under the lower ambient temperature, the frost layer formed is relatively loose and the frost crystals are sparse. While under the higher ambient temperature conditions, the distribution of the frost crystals is dense and continuous, and the frost layer formed looks denser. Fig. 5 shows the effects of the ambient temperature on the frost layer thickness. It is noted that as the ambient temperature increases from -5.2 °C to 0.8 °C, there is an obvious increase in the frost layer thickness: the frost layer thickness increases from 1.35 mm to 2.55 mm. The present experiment results support the conclusions of Lee and Ro [17], other than that of Cheng and Wu [16].

From Eq. (2) we can see that the supercooling degree ΔT will directly change the driving force for the frost layer thickness increase and ΔT is fully determined by the frost surface temperature. Therefore, the frost surface temperature, and thus the cold plate temperature and ambient temperature, will affect the driving force; hence the cold plate temperature and ambient temperature influence the frost layer thickness.

For given cold plate temperature and air relative humidity, an increase in the ambient temperature will certainly result in a higher frost surface temperature and of course an increase in the absolute moisture content of the air. Hence, the frost layer thickness will increase with the ambient temperature if only no melting of the frost crystals at the frost layer surface occurs, due to the fact that frost deposition is a mass transfer controlled process. However, a relative lower ambient temperature leads to a lower frost surface temperature and the melting of frost crystals is not easy to occur. In this aspect, increasing the ambient temperature will increase the frost layer thickness. It can be speculated from our experiment results that there exists a critical ambient temperature: below this value, the frost crystals are not easy to melt; increasing the ambient temperature also increases the frost surface temperature, and thus the driving force for the frost growth rate, and hence the frost layer thickness will increase with the increasing ambient temperature. Above this value, increasing the ambient temperature results in a much higher frost surface temperature (T_s), which could cause the frost crystals to melt and increase the frost layer density. When the frost surface temperature (T_s) is higher than the water vapor triple point temperature (T_m), the supercooling degree (ΔT) and the driving force for the frost layer thickness increase (Δg_t) is less than zero; therefore, the frost layer thickness does not increase and even becomes thinner. This can explain the phenomenon that some researchers have found that the air temperature has almost no effect on the frost layer growth.

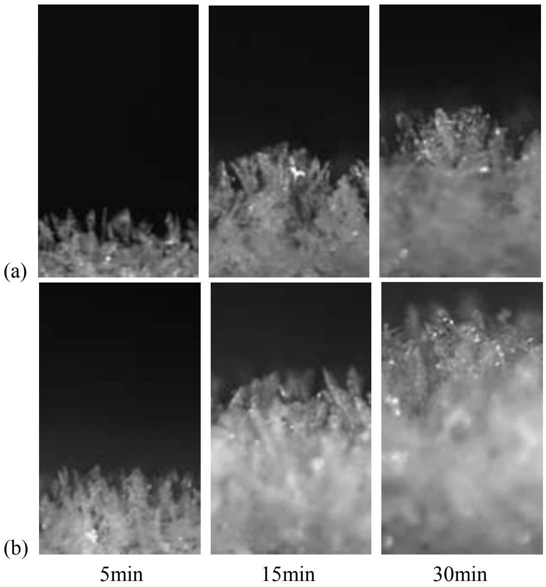

Fig. 4. Comparison of frost growth under different ambient temperature: (a) T_∞=-5.2 °C; (b) T_∞=0.8 °C.

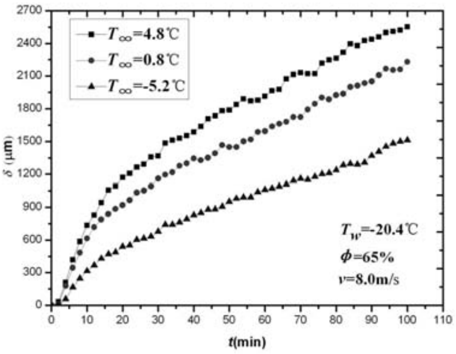

Fig. 5. Effect of the ambient temperature on the frost thickness.

3.3 Effect of the relative humidity on frost growth

To study effect of the air relative humidity on frost layer thickness, the controlled parameters include T_w=-20.4 °C, T_∞=0.8 °C and v=8.0 m/s. The results are plotted in Fig. 6. It can be found that the frost layer thickness increases significantly with the air relative humidity, though the influence becomes weaker at high relative humidity. For example, at 100 min, the frost layer thickness increases 1.011 mm as the relative humidity increases from 50% to 65%, while the frost layer thickness increases only 0.855 mm as the relative humidity increases from 65% to 80%. This is because a higher relative humidity leads to a higher water vapor supersaturation; the nucleation rate decreases and so does the frost growth rate. This result again shows that the frost deposition is basically a mass transfer controlled process.

3.4 Effect of the air velocity on frost growth

Most of the previous researches on the influences of the cold plate temperature and the air relative humidity disclosed that a lower cold surface temperature and higher air humidity result in a thicker frost layer. However, as far as the influences of air velocity or Reynolds number on the frost layer growth are concerned, so far there are no generally accepted conclusions. Actually, the contradictory results are almost everywhere in the literature. For example, Schneider [18] found that the frost layer growth is independent of Reynolds number when it varied from 4000 to 32000 at air temperature of 5.0 °C. Sahin [19] observed that the effect of Reynolds number on frost thickness is not significant as it changed from 2400 to 4500 at air temperature of 13.0 °C. In contrast, O'Neal and Tree [20] found that there exists a critical Reynolds number in the frost growth trends for flow through a parallel plate heat exchanger (they set it as Re=15900 at T_w=-5.2 °C and T_∞=6.5 °C). Figs 7-8 show the mean frost thickness on the plate versus time for Reynolds number less than 15900 and greater than 15900, respectively. Below 15900, increasing the Reynolds number also increased the rate of frost growth. However, above 15900, the Reynolds number appeared to have little effect on frost growth. In fact, there was actually a slight decrease in frost thickness as the Reynolds number increased. It is possible that the critical Reynolds number could vary with the environmental conditions and plate geometry. So, more data would need to be taken at different temperatures to fully support this hypothesis.

To verify the effects of air velocity or Reynolds number on the frost layer growth under lower air temperature, we performed a group of tests for Reynolds numbers varying from 16400 to 59800. Fig. 9 depicts the effects of the air velocity on the frost crystal growth at T_w=-20.4 °C, T_∞=0.8 °C, and ϕ =65%. In this figure, the frost layer structures taken at different times for the air velocity of 2.2 m/s [Fig. 9(a)] and for 8.0 m/s [Fig.9(b)] are compared. It is found that at v=2.2 m/s, dispersed needle-like frost crystals form on the cold plate at 5 min. After that, these isolated crystals begin to grow at both the horizontal and vertical directions; however, the increase in the frost layer thickness is not obvious, and large air interstices may well exist among the frost layers even after 30 min. For air velocity 8.0 m/s, a different pattern of the frost layer is observed as shown in Fig. 9(b). Compared with the frost layer of 2.2 m/s, the frost layer formed at the air velocity of 8.0 m/s is denser and grows with a larger rate. Fig. 9 shows clearly that both the thickness and the density of the frost layer increase with time. To provide further insight into the effects of air velocity on frost layer growth, Fig. 10 presents the frost layer thickness growth at various air velocities. It can be seen that the air velocity or Reynolds number has a significant effect on the frost growth. And it is also clearly shown in this figure that the velocity effect on the frost layer growth becomes weaker as the air velocity increases. For example, at 100 min, the frost layer thickness increases from 1.236 mm to 2.028 mm as the velocity increases from 2.2 m/s to 5.0 m/s, which means an increase of 177% in air velocity results in an increase of 64% in the frost layer thickness; however, as the velocity increases from 5.0 m/s to 8.0 m/s, the frost layer thickness only increases from 2.028 mm to 2.223 mm, which means an increase of 60% in air velocity results in an increase

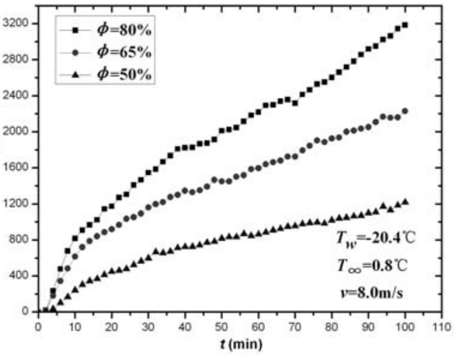

Fig. 6. Effect of the relative humidity on the frost thickness.

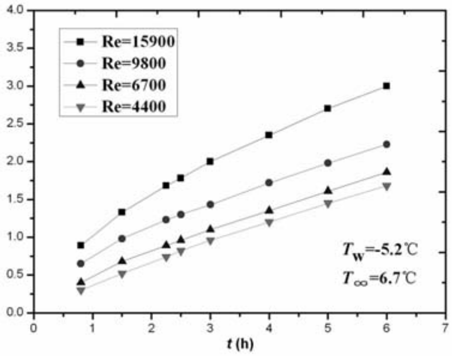

Fig. 7. Variation in frost growth for Reynolds number less than 15900 (O'Neal and Tree).

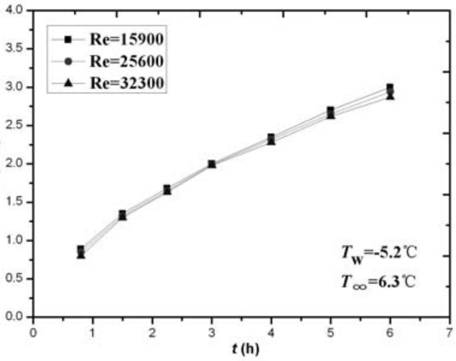

Fig. 8. Variation in frost growth for Reynolds number greater than 15900 (O'Neal and Tree).

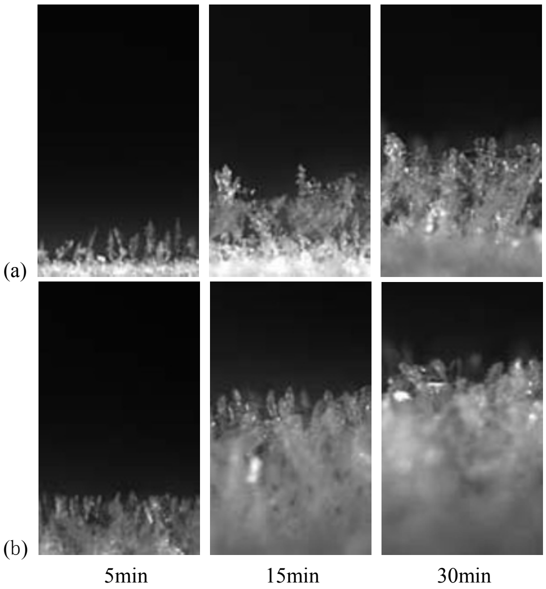

Fig. 9. Comparison of frost growth under different air velocity: (a) v=2.2 m/s; (b) v=8.0 m/s.

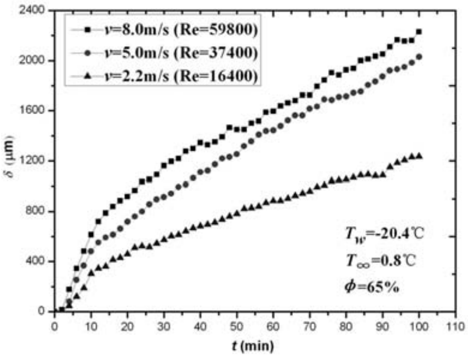

Fig. 10. Effect of the air velocity on the frost thickness.

of only 9.6% in the frost layer thickness.

This can be explained as follows. As was mentioned earlier in this paper, the frost formation on a cold surface occurs by the mass and heat transfer of the water vapor from the air flow to the cold surface or the frost surface. Some of the water vapor transferred from the air flow to the layer deposits on the frost surface, making the frost layer thicker. The rest of the water vapor moves into the frost layer by molecular diffusion, resulting in the frost layer becoming denser. As one can understand, an increase in air velocity may greatly enhance the mass and heat transfer process between the main air flow and the frost layer surface at lower air velocities, which therefore results in a large increase in the frost layer growth rate. At higher velocities, increasing the air velocity is less effective for enhancing the mass and heat transfer process, because the concentration of the water vapor decreased under higher velocities ; thus the water vapor transferred from the air flow to the frost surface is reduced. Therefore, a large increase in the air velocity at higher velocities can only result in a minor increase in the frost thickness growth rate. Furthermore, if the air velocity is large enough, the shear stress that acts on the isolated crystals of the frost layer may lead these frost crystals to collapse and be broken off. This effect is usually results in a frost density increase. Therefore, our experimental results extend the conclusions of O'Neal and Tree [20] to the lower air temperature conditions.

4. Conclusions

The frost formation on a cold horizontal surface under forced convection has been experimentally investigated. Different from previous researches that mainly presented experimental and computational results for normal air temperature, this study carried out experiments for relative lower ambient temperature which would be the standard operation conditions for evaporator. Our experimental results showed the frost layer thickness increases strongly with the decreasing cold surface temperature and increasing relative humidity. Furthermore, it can be speculated from our experiment results that there exists a critical ambient temperature; below this value, increasing the ambient temperature also increases the frost surface temperature, and thus the frost layer thickness. Above this value, increasing the ambient temperature results in a much higher frost surface temperature which causes the frost crystals to melt, ; thus the frost layer thickness does not increase and even becomes thinner. The air velocity or Reynolds number also has an obvious effect on frost formation. The present results showed that at lower air velocity, the frost crystals are dispersed and the frost density is small; at higher air velocity, the frost layer becomes denser and the frost crystals collapse and break off more easily. Our experimental results also indicate a critical Reynolds number between 16400 and 37400; at a Reynolds number higher than this value, the effect of air velocity on the frost growth seems to be weak. Certainly, further research including more experiments and observations needs to be carried out to confirm this hypothesis.

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Nomenclature

t : Time, min
T_∞ : Ambient temperature, °C
T_w : Cold plate temperature, °C
v : Air velocity, m/s
S : Supersaturation degree as defined by Eq. (1), dimensionless
P_v : Vapor pressure, kPa
P_{vs} : Saturated vapor pressure, kPa
Δg_t : Frost thickness growth driving force, J/kg
ΔT : Supercooling degree, K

T_m : Water vapor triple point temperature, K
T_s : Frost surface temperature, K
Δg : Phase change driving force, J/kg
R : Water vapor gas constant, J/kg·K
p : Vapor pressure away from the phase transition interface, kPa
Re : Reynolds number
ϕ : Air relative humidity, %
δ : Frost layer thickness, μm

References

[1] R. V. Smith, D. K. Edmonds and E. G. F Bernard, Analysis of frost phenomena on cry-surface, *Advances in Cryogenic Engineering*, 9 (1963) 88-97.

[2] M. Fossa and G. Tanda, Study of free convection frost formation on a vertical plate, *Experimental Thermal and Fluid Science*, 26 (2002) 661-668.

[3] C. H. Cheng and C. C. Shiu, Frost formation and frost crystal growth on a cold plate in atmospheric air flow, *International Journal of Heat and Mass Transfer*, 45 (2002) 4289-4303.

[4] H. Lee, J. Shin, S. Ha, B. Choi and J. Lee, Frost formation on a plate with different surface hydrophilicity, *International Journal of Heat and Mass Transfer*, 47 (2004) 4881-4893.

[5] Z. L. Liu, X. H. Zhang, H. Y. Wang, S. Meng and S. Y. Cheng, Influences of surface hydrophilicity on frost formation on a vertical cold plate under natural convection conditions, *Experimental Thermal and Fluid Science*, 31 (2007) 789-794.

[6] K. S. Lee, Y. C. Kim and S. Jhee, Correlation of frost properties considering the environmental parameters over a cold flat plate, *Transactions of KSME*, 25 (8) (2001) 1046-1052.

[7] R. Yun and Y. C. Kim, Modeling of frost growth and frost properties with airflow over a flat plate, *International Journal of Refrigeration*, 25 (2002) 362-371.

[8] B. Na and R. L. Webb, New model for frost growth rate, *International Journal of Heat and Mass Transfer*, 47 (2004) 925-936.

[9] J. K. Gupta and M. R. Gopal, Modeling of a domestic frost–free refrigerator, *International Journal of refrigeration*, 30 (2007) 311-322.

[10] Y. Xia, Y. Zhong, P.S. Hrnjak and A. M. Jacobi, Frost, defrost, and refrost and its impact on the air-side thermal-hydraulic performance of louvered-fin, flat-tube heat exchangers, *International Journal of Refrigeration*, 29 (2006) 1066-1079.

[11] X. M. Guo, Y. G. Chen, W. H. Wang and C. Z. Chen, Experimental study on frost growth and dynamic performance of air source heat pump system, *Applied Thermal Engineering*, 28 (2008) 2267-2278.

[12] D. Huang, Z. L. He and X. L.Yuan, Dynamic characteristics of an air-to-water heat pump under frosting/defrosting conditions, *Applied Thermal Engineering*, 27 (2007) 1996-2002.

[13] N. Hewitt and M. J. Huang, Defrost cycle performance for a circular shape evaporator air source heat pump, *International Journal of Refrigeration*, 31 (2008) 444-452.

[14] B. Na and R. L. Webb, Mass transfer on and within a frost layer, *International Journal of Heat and Mass Transfer*, 47 (2004) 899-911.

[15] Z. L. Liu, A physical and mathematical model of frost formation on a vertical cooled plate under free convection conditions, *Journal of Dalian Marine College*, 11 (2) (1985) 35-45.

[16] C. H. Cheng and K. H. Wu, Observations of early-stage frost formation on a cold plate in atmospheric air flow, *Journal of Heat Transfer*, 125 (2003) 95-102.

[17] Y. B. Lee and S. T. Ro, An experimental study of frost formation on a horizontal cylinder under cross flow, *International Journal of Refrigeration*, 24 (2001) 468-474.

[18] H. W. Schneider, Equation of the growth rate of frost forming on cooled surfaces, *Int. J. Heat Mass Transfer*, 21 (1978) 1019-1024.

[19] A. Z. Sahin, An experimental study on the initiation and growth of frost formation on a horizontal plate, *Exp. Heat Mass Transfer*, 7 (1994) 101-119.

[20] D. L. O'Neal and D. R. Tree, A review of frost formation in simple geometries, *ASHRAE Trans*, 91 (1985) 267-281.

Zhongliang Liu received his B.S. degree from Huadong Petroleum Institute, China, in 1982. He then received his M.S. degree from Dalian Marine College, China, in 1984. From 1987 to 1988, he worked in the Mechanical Engineering Department of Birmingham University as a visiting scholar. In 1996, he received his Ph.D. degree from the Power Engineering Department of Southeast University, China. He is currently a Professor and the dean of Environmental and Energy Engineering College of Beijing University of Technology, China. His research interests include numerical methods in heat and fluid flow, thermal energy storage theory and technology.

Lingyan Huang received her B.S. in Architectural Environment and Equipment Engineering from Shandong Agriculture University, China, in 2006. She is currently studying for her M.S. and Ph.D. in Environmental and Energy Engineering College of Beijing University of Technology. Her research interests include phase transition, heat and mass transfer and frost formation on low-energy surfaces.