ID 040101

A MICROSCOPIC OBSERVATION OF TRANSIENT FROST FORMATION PROCESSES AND THEIR ANALYSIS BY USE OF PHASE CHANGE DYNAMICS

WANG Hongyan, LIU Zhongliang*, MA Chongfang
Enhanced Heat Transfer and Energy Conservation, Key Laboratory of Ministry of Education,
Beijing University of Technology, Beijing100022, People's Republic of China
Tel.: 010-67391985, fax: 010-67392774, E-mail: lywanghongyan@emails.bjut.edu.cn

ABSTRACT

Frost formation is a common phenomenon under cryogenic conditions. Without effective control, frost deposition may result in serious malfunction of cryogenic equipment and systems. In this paper, an experimental study on the initial period of frost deposition and the crystal morphology and its variation with time of frost ice are carried out of frost formation on a vertical plate by microphotographics. The phase change, the initiation of frost formation and the different shapes of frost crystal at various time stages are described. It is proved from the present study that the main factors that affect frost formation in natural convection are plate temperature, air humidity and air temperature. In order to explain the frost thickness difference under various conditions, a frost thickness growth driving force is defined and compared with the experimental results. Hydrophobic surfaces are used to release frost formation on cold surfaces and the results show that these surfaces can retard the formation and growth of frost significantly.

INTRODUCTION

It is well known that when humid air is exposed to a surface that is colder than the dew-point temperature of air, condensation will take place, and the air will pass directly from the gaseous to the solid state of frost if the surface temperature is below 0℃. The frost crystals deposited on the surface initially act as fins and enhance the heat transfer process between the surface and air. However if a continuous layer is formed, the frost deposited will act as an insulation and thus the heat transfer is degenerated seriously. Furthermore if the frost deposited is not removed on time or without effective control, then as the thickness of the frost layer increases 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 maneuverability as well. So it is very important to find an effective defrosting method, and many scholars in the field of heat and mass transfer science have studied this problem since 1960's. There are many defrosting methods. But all these methods are based on frost-melting principles. Obviously, these methods are all energy consuming and accompanied by a

* Corresponding author, Email: Liuzhl@bjut.edu.cn

reduction in overall efficiency.

Most of the previous investigations so far were concerned with the frost formation phenomena after a porous layer of frost had grown to a certain thickness. Very little studies were carried out on the process of frost formation, especially the microstructure of nucleation of the initial stage. Recently, there were a few investigators studied the initial period of frost formation by photographic observation and some of them have found that the frost structure would change with changing the characteristics of frosting surfaces. The frost formation phenomena on a surface coated with hydrophilic material were further studied by Okoroafor[1], which showed that the hydrophilic surface could retard the growth of frost compared with an uncoated metallic surface, and he contributed this to the fact that the material of the coating possesses the ability of both absorbing water and suppressing freezing of the contained water even under very low temperatures. This method has a great economic value for optimizing systems and energy conservation. In this paper, an experimental system was set up to study the frost formation on a vertical plate. The phase change, the initiation of frost formation and the different shapes of frost crystal at various stages are described. It is proved from the present study that the main factors that affect frost formation in natural convection are cold plate temperature, air humidity and air temperature. Both hydrophobic and metallic surface were prepared and tested, results showed that the hydrophobic surfaces could retard the formation and growth of frost significantly.

1. EXPERIMENTAL APPARATUS

A thermoelectric cooler is used as a cooling source for the frosting surface，it can provide a temperature as low as –26℃. A copper plate of 150mm×52mm×6mm is mounted on the cooling unit and one of its surfaces which were polished by an 800# polish paper is used as the test sample surface. The surface temperature is measured by 4 Type-T thermocouples. Temperature data recorded by a 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 4 thermocouples. There is a microscopic image system that consists of a CCD camera, a microscope, and a capture card. The CCD camera and microscope with an maximum of 45× magnification, are mounted right over the cooled surface for taking photographs and observing the frost growth with the help of an optical fiber luminescence. The frost deposition process recorded by the microscopic image system as well as the frost thickness measured by the calibration in the ocular, are of an accuracy of ±0.05mm. A thermo-hygrometer is used to monitor environmental conditions, including temperature and relative humidity. Fig 1 shows the experimental system.

Before each experiment, the surface is cleaned, the microscope is adjusted to set the right focus, cooling water is turned on and the temperature set to the prescribed value.

2. RESULTS AND DISCUSSIONS

2.1 The process of frost formation

The mechanisms of frost formation are complicated due to the effects of many environmental parameters. Based on the experimental observations by Ahmet Z. Sahin et al [2], frost formation process was usually divided into three periods: 1) crystal growth period, 2) frost layer growth period, 3) frost layer full-growth period. In order to control frost formation, it is necessary to have a deep understanding of the phenomena, and thus the crystal growth period is very important because it is critical for controlling the whole frost formation process. Therefore we made a series of careful experimental observations on the frost formation process. The test surface is cooled down from room temperature to -14.7℃, this process took about 5 minutes. Fig. 2 presents the photographs of frost formation at T_∞= 23.2℃, φ=62% with a magnification of 35. Fig. 2(a) shows the clean smooth surface. And Fig. 2(b) gives the picture at150s, it was observed that many small dotted drops appeared on the test surface. At t=300s (Fig. 2(c)), the drops that appeared on the test surface grew bigger and united. At t=450s (Fig. 2(d)), observation shows that the drops were frozen into isolated ice crystal, and presented opacity. After that the frost crystals grow faster and faster. At t=600s (Fig. 2(e)), frost crystals began to grow perpendicularly to the surface on the top of the ice crystal at almost the same rate. And finally, at t=750s (Fig. 2(f)), a noticeable meshing of the crystals occurred, the frost crystal shapes changed from needles into hexagon. They looked like pine trees from profile, because many thin branches are formed around the top of the crystals. Then a rough frost layer appeared, which is a cluster of rod-type crystals. The structure of the frost layer is changing as the generation of sub-branches around the top of crystals and the interaction of crystals (Fig. 2(g, h)). After that, the frost density and thickness increased with time and the surface became flat, because of the filling of many thin crystals and the internal diffusion of water vapor into the frost layer.

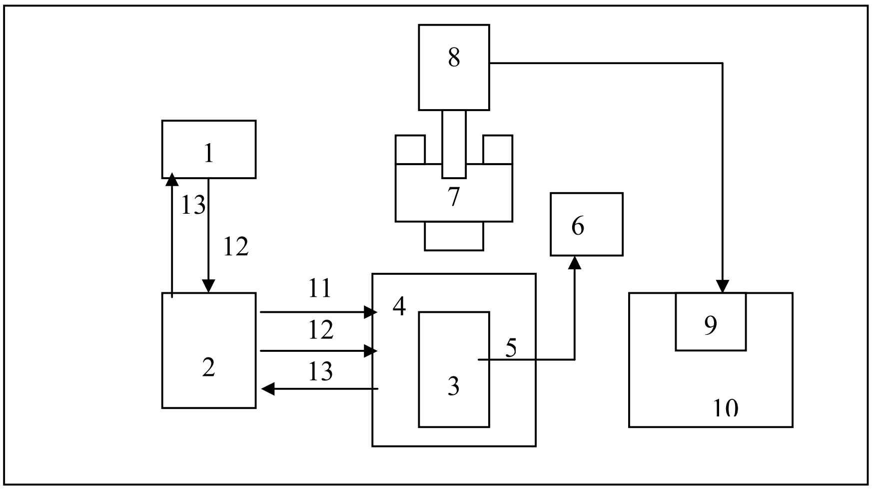


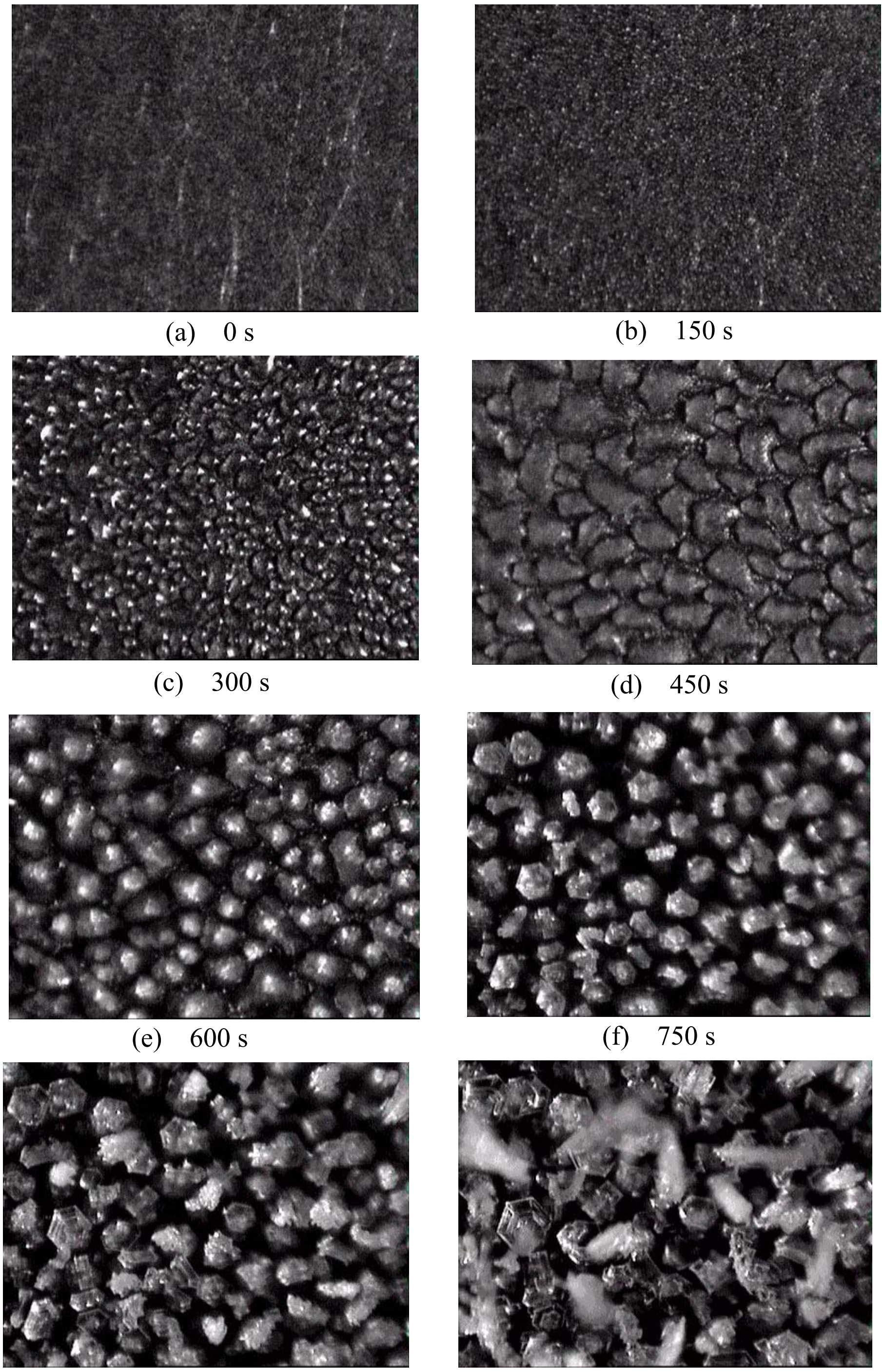
Fig.1. Experimental setup

1. cooling water 2. heat exchanger 3. cold plate 4. thermoelectric cooler 5. T-thermocouple 6. HP data acquisition 7. microscope 8. CCD camera 9. capture card 10. computer 11.cable 12. inlet pipe 13.outlet pipe

In frost crystal growth process, their shapes vary with time: from needles to columns, trees and denser slices, they grow gradually into a mixture of water vapor, ice and air. The shapes are also different with the different cold surface temperatures.

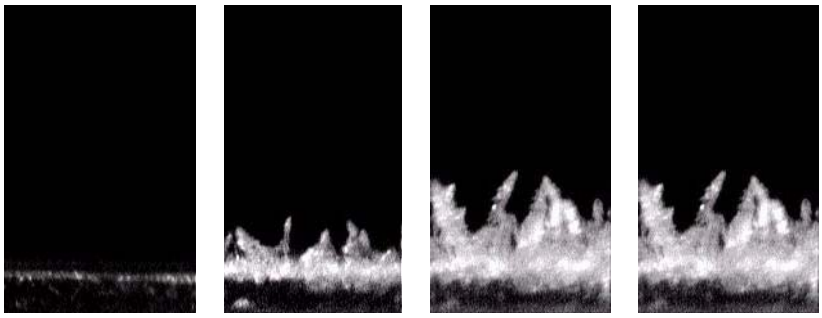
2.2 The main factors that affect frost formation in natural convection

The main factors that affect frost formation in natural convection are plate temperature, air humidity and air temperature. In order to prove this conclusion, we carried out two sets of the experiments. The surface was first cleaned and then covered with a sheet of clean plastic film. When the cold surface is cooled down to the prescribed temperature, the plastic film is taken away and frost deposition is started. Fig. 3 gives a series of pictures of frost crystals at different times under the two different cold plate temperatures. One can conclude by comparison of these pictures that the lower the plate temperature the faster the growth of frost crystals is. Figure 4 depicts the frost layer thickness variation with time under different humidity conditions. One can see clearly from the figure that under the same conditions a higher relative humidity of air results in faster growth of frost layer, which indicts that air humidity strongly affects the frost deposition rate.

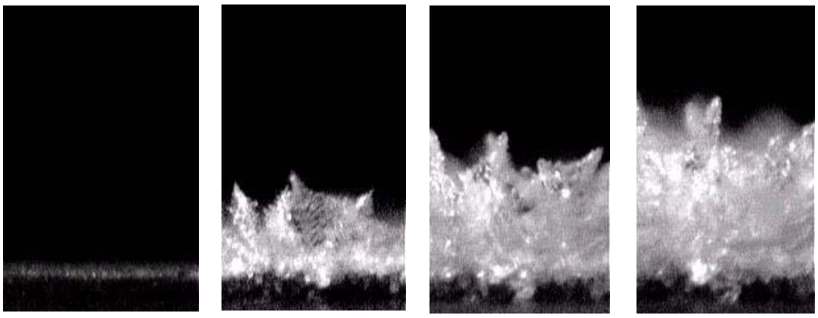


(a) 0 s (b) 150 s (c) 300 s (d) 450 s (e) 600 s (f) 750 s (g) 900 s (h) 1200 s

Fig. 2 Frost growth on a vertical plate under natural convection conditions



a) T_w=-13.5℃



t=0s *t*=80s *t*=160s *t*=240s

b) T_w=-18.7℃

Fig. 3 Growth of frost crystals at different T_w (T_∞=19.8℃ φ=50%)

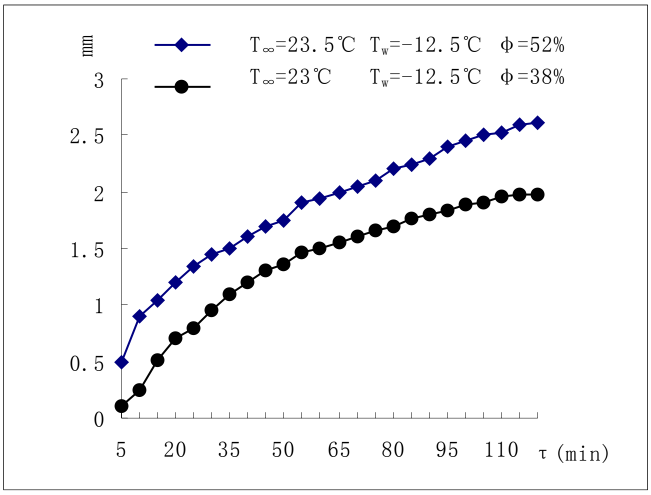


Fig. 4 Effects of relative humidity on frost layer thickness

2.3The effects of hydrophobic surfaces on frost formation

Observations by microscope conducted in this paper reveal that as the test surface cooled down, the liquid 'droplets' will first appear on the cold surface at the beginning of the experiment. The shape of these droplets is strongly dependent on the surface properties. If the surface is a hydrophobic one, then drop-wise condensation will occur, which is quite different from that of an ordinary metallic surface. Since the interface area between droplets and the hydrophobic surface is smaller than that of the plain metallic surfaces, this will certainly slow down the heat transfer between the cold surface and the droplets and therefore these droplets are difficult to be frozen. Therefore hydrophobic surfaces can retard the formation of initial frost crystal. In this experiment, we used silicon oil to form a hydrophobic coating of the cold plate. Fig. 5 and 6 show the comparison of frost growth on two different surfaces. The cold plate surface is copper and its right half is coated with a thin silicon oil film (20μm). Fig. 5 gives a picture at 110s under the condition of T_{∞}=23℃, T_w=-14.5℃, φ=50%. One can see from this picture clearly that though there is no water drops appeared on the coated surface (the right half), there are many droplets observed on the uncoated part (the left half). Fig. 6 shows a picture at t=360s for the case T_{∞}=19.8℃, T_w=-19.1℃, φ=22%. This picture reveals the influences of hydrophobicity of the test surface on frost layer structure. The frost crystals formed on the coated part look like needles and are loose, but on the opposite side the frost crystals are short and dense. This can be explained by the fact that the contact angles of initial droplets that deposited on the hydrophobic surface are larger than that on the metallic surface and therefore large droplets instead of a homogeneous film of condensed water appear on the hydrophobic surface. Therefore when these large droplets are frozen, a much more coarse frost layer will be formed. During the whole frost growth process, the frost layer grew slower on the coated part than on the uncoated metallic part. This proves that hydrophobicity can not only retard the frost formation on a cold surface but also enhance the dendritical growth of frost crystals which results in a loose frost layer that can be more easily removed. Liu[3] reported similar phenomena. They found out that the small droplets appeared first on a metallic surface and then these droplets formed a continuous water film, the film is frozen and became an ice layer. However, on a hydrophobic surface the droplets would not form a water film and on the further cooling these droplets are frozen into ice beads.

3. THEORETICAL ANALYSIS

According to phase change theory, the Gibbs free energy of a metastable phase are higher than that of a stable phase, and it is this difference of Gibbs free energy that makes a metastable phase transform into a stable phase. And therefore the Gibbs free energy difference is usually referred to as the phase change driving force[4]. In the frost growth process, the water vapor that approaches to the cold plate is turned into supersaturated state, and is thus a metastable phase, while the frost crystal is the stable phase. With the cooling of the cold plate the water vapor in metastable phase that contacts the cold surface is turned into frost crystals continuously under the effects of this phase change driving force. The bigger the phase change driving force is, the faster and easier the frost growth.

The following formula is the definition of phase change driving force in phase change dynamics:

$$\Delta g = RT_S \ln(p/p_s) \tag{1}$$

Where Δg is the phase change driving force, T_S is the frost surface temperature, R is the water vapor gas constant, p is the vapor pressure that is far away from phase interface, p_s is the saturated vapor pressure corresponding to the frost surface temperature T_S..

Phase change driving force can only describe the amount of total frost deposition, it cannot explain the growth of frost thickness, that is, the large total frost deposition mass does not necessarily always means a large frost thickness. The growth of frost thickness depends not only on the amount of frost crystals, but also on the density of frost layer, i.e. the structure of frost layer. If the frost deposition mass is equal per unit time, then the more dendritical the frost crystals are, the more loose the frost layer and thus the faster the frost thickness will increase with time. In vapor growth system, the large degree of supersaturation is the main reason that causes the drndritical growth of frost crystals. Furthermore, as supersaturation of air increases and the plate temperature (and so the frost surface temperature) decreases, the frost dendrites grow more easily. Therefore a frost thickness growth driving force is defined[5],

$$\Delta g_t = (\Delta T / T_S)\Delta g = R\Delta T \ln(P/P_S) \tag{2}$$

This equation simply states that the frost thickness growth rate increase with the frost thickness growth driving force. Where Δg_t is frost thickness growth driving force, T_m is water triple point temperature, ΔT is equal to T_m-T_S, and is the supercooling of the frost surface.

In order to prove the above theory, the data in Fig.4 and the data from [5] are used to calculate Δg_t and the results are listed in Table 1.One can see that the frost thickness is proportional to the initial value of the frost thickness growth driving force, which is in the full agreement with [5].

Table 1. The frost thickness and the frost thickness growth driving force

serial number	Experiment condition			At the beginning of frost formation	After 2 hours
	φ(%)	T_w(℃)	T_∞(℃)	Δg_t (462J/kg)	Frost thickness (mm)
1	52	-12.5	23.5	24.8	2.61
2	38	-12.5	23	20.5	1.98
3*	60	-13.7	16.5	25.2	2.81
4*	71	-13.7	16.5	27.6	3.18
5*	63	-18.6	16.7	52.8	3.55

* These data are from Reference [5].

The hydrophobic surface can lower the frost formation rate and reduce the density of the deposited frost layer. This can be explained as follows: the formation of the initial frost crystals are retarded significantly on hydrophobic surface according to our observation results, and accordingly the average growth rate of frost formation is thus slowed down. The same statement was also made by Wu et. al.[6]. On the other hand, the contact angle is larger on a hydrophobic surface and the contact area of liquid droplets is small, so the droplets can remain un-frozen even the surface temperature is well below the triple point. According to the thermodynamics theory of phase transition, the surface free enthalpy increase due to the frost deposition on an ice crystal is much smaller than that on the metallic surface and therefore the frost deposition is faster on the frost crystals than on the metallic surface. Accordingly, hydrophobic surface can promote the dendritical growth of frost crystals and thus results in a very loose frost layer.

4. CONCLUSION

Frost formation is a very complex process. Frost crystal shapes are dependent on many factors that may include could surface temperature, environmental temperature, relative humidity and the other surface characteristics. Frost formation process includes water vapor condensation, growth, coalescence and freezing of droplets and the initial crystal formation and growth. The frost deposition growth rate increases with the increase of phase change driving force, and the frost layer thickness growth rate increases with the so called frost thickness growth driving force. The contact angle is larger on a hydrophobic surface, and thus the droplets are more difficult to be frozen than on a ordinary metallic surface. The initial frost crystals occur later and the frost layer is looser on a hydrophobic surface than on a metallic surface. And we can conclude that the hydrophobic surfaces can be used to control the frost deposition on could surfaces.

5. REFERENCES

1. E.U. Okoroafor, M. Newborough, 2000, Minimizing frost growth on cold surface exposed to humid air by means of crosslinked hydrophilic polymeric coatings, Applied Thermal Engineering, Vol. 20, p.737-758.
2. Ahmet Z. Sahin, 1994, An experimental study on the initiation and growth of frost formation on a horizontal plate, Experimental Heat Transfer, vol.7, p.101-119.
3. LIU Fengzhen, CHEN Huanxin, 2000, Research on decreasing frost formation rate, Journal of Changsha Railway University, Vol. 3, p. 48-51.
4. MIN Naiben, 1982, Physics of Crystal Growth-Basic Theory, Shanghai Science and Technology Publisher.
5. LIU Zhongliang, 1984, The mathematical model and its numerical simulation of frost formation on a vertical cold plate under free convection conditions, Master degree thesis, Dalian Marine College
6. WU Xiaomin, 2002, The microcosmic process of frost formation and the effects of surface wettability on it, National Heat And Mass Transfer Conference, Chinese Society of Engineering Thermophysics, Shanghai