Experimental Study of Initial Process of Frost on Heat Exchanger Surface of Refrigerated Transport Vehicle

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Abstract

The frost on the surface of the heat exchanger deteriorates the effect of heat transfer, and the freezing of water droplets is the beginning of frost formation. In order to study the microscopic growth and freezing process of water droplets on aluminum surface under different temperature and humidity conditions during cold chain transport, this article introduces the construction of constant temperature and humidity frost microscopic imaging experimental table first, experimentally studied the frozen of water droplets on the horizontal surface of aluminum cooled by a semiconductor cooling device. The results show that the total frozen time decrease with the increase of temperature in the range of 10°C~13°C. When the humidity range between RH30% and RH70%, the frozen time of cold water droplets decreases with the increase of humidity. Finally, a theoretical analysis of the experimental results is conducted.

Keywords

Cold chain transport, temperature and humidity, frozen of water droplets, microscopic imaging.

1. Introduction

Since the frost layer has a certain heat transfer resistance, when the thickness of the frost layer increases to a certain extent, the heat exchange efficiency of the refrigeration system is greatly reduced, and at the same time, the existence of the frost layer itself will hinder the flow of air for heat exchange. For example, when using a refrigerated truck to transport goods, different goods such as precision electronic products, medical supplies, fresh foods, etc. often have different temperature and humidity requirements for the transportation environment, and the refrigeration unit of refrigerating truck will have the phenomenon of frost after running for a certain period of time. The appearance of the frost layer will lead to negative effects such as increased energy consumption in the refrigeration system and unstable temperature control inside the truck. Therefore, the microscopic level of the process of frost layer growth on the aluminum surface is studied, and the study of the influence of environmental factors on the frosting process is particularly important.

For the growth process of the frost layer, a large number of experimental studies have been carried out by the predecessors. Hayashi and others divide the growth process of frost into three processes through image recording: crystal growth period, frost layer growth period and frost layer complete growth period. [1]， Xu Wangfa and others divided the initial frost crystal into four categories according to the appearance and shape characteristics of frost crystal, pointing out that the relative humidity of air have a certain influence on the shape of frost crystal.[2] Wu Xiaomin et al. used continuous microscopic camera recording to divide the frost on the cold surface into water droplet formation, growth, freezing, initial frost crystal formation, frost crystal growth and melting. [3]Li Ruixia and others have found when it’s on the cold surface of the pre-cooling surface, super-cooled water droplets appear on the cold surface with a cold surface temperature of -29 °C, and direct frosting occurs on the cold surface of -38 °C. [4]

In the process of frosting, frost crystals grow on the frozen water droplets, so the influence of environmental factors on the freezing time of the water droplets is very important for studying the frosting process. At present, scholars have mainly divided into two methods for the research on the freezing process of water droplets. One method such as Wu Xiaomin uses is to titrate water droplets on a cold surface to study the effect of environmental factors on water droplet freezing. [5]However, in actual frosting, the water droplets formed by the cold surface come from the phase change of the wet air, rather than being directly titrated by the outside. The other way is to study the water droplets formed by the frosting process of the wet air on the cold surface. For example, Huang Lingyan observed the droplet freezing process on the horizontal copper surface in the low temperature environment, and found that under the experimental conditions, while the cold wall surface temperature is lower and the greater the humidity of the air, the freezing time is shorter, and the freezing time of the droplets has a critical point with the change of air temperature and flow rate. [6]However, the temperature range set in the existing research is not wide enough, and there are few studies on the freezing of water droplets in the range of 10 °C~15 °C for the air temperature during the cooling process.

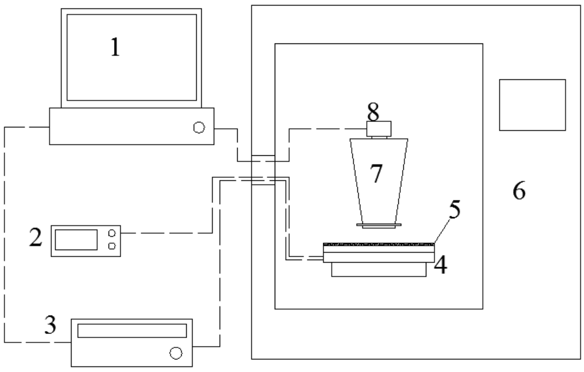
In this research, the experiment is to study the effect of ambient temperature and humidity on the freezing time of the water droplet during the frosting process. The result provide a reference for the establishment of the frosting model and the selection of the defrosting timing in the defrost system.

2. Experimental Device and Method

The main experimental devices used in this experiment are mainly divided into four parts: constant temperature and humidity chamber, semiconductor refrigeration module, temperature acquisition module and image acquisition module. As shown in Figure 1, the constant temperature and humidity chamber is responsible for providing stable ambient temperature and humidity, with a temperature control accuracy of ±0.5 °C and a relative humidity control accuracy of ±3%. The semiconductor refrigeration module consists of a smooth aluminum plate, a semiconductor refrigeration chip, a heat dissipation system and a temperature controller. It is responsible for providing a cold source in the experiment and lowering the surface temperature of the aluminum plate to the target temperature. Among them, the semiconductor cooling sheet power is 75w, and the cold surface temperature control precision is ±0.5°C. A temperature probe of a semiconductor refrigeration stage thermostat and a temperature acquisition system is arranged near the target observation area of the aluminum plate, and the temperature acquisition module is connected with a computer, and is responsible for collecting and recording the internal air temperature and the cold surface temperature. The image acquisition module is composed of a microscope and a CCD image acquisition module. The microscope is responsible for adjusting the optical magnification and the focal length. The CCD image acquisition module is responsible for transmitting the image information to the computer for storage.

During the experiment, the wire harness holes of the cabinet were closed with rubber stoppers to avoid heat leakage, the constant temperature and humidity chamber and the semiconductor refrigeration device were first set to the target temperature and humidity and the temperature acquisition system was turned on. Then the CCD image acquisition system was turned on, the image data was recorded, and then the water droplet freezing process was started.

In this experiment, the starting point of the experimental starting time in the collected video data is taken as the end of time for the first time the water surface loses permeability in the cold surface of the field of view, and the total time from the beginning to the end is counted as the freezing time τ of the water droplet. During the experiment, the relative position of the aluminum surface and the microscope did not change, and the same area of the aluminum plate was displayed in the microscope field of view.



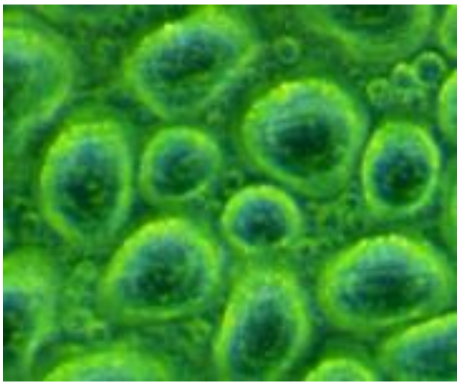
1:Computer; 2: Semiconductor refrigeration station thermostat; 3: Temperature collector; 4: Semiconductor refrigeration unit; 5: Aluminum sheet; 6: Constant temperature and humidity chamber; 7: Microscope; 8: CCD image collector

Fig. 1 Experimental device schematic

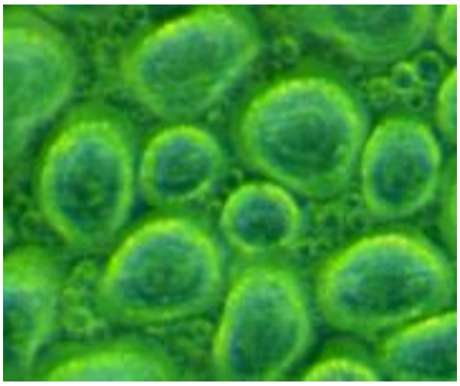
3. Experimental Results and Analysis

3.1 Judgment Flag of Droplet Frozen

As shown in Fig. 2, the cold surface is maintained at -5℃, and the water droplets are kept under super-cooled during the growth until the water droplets freeze. The permeability of the water droplets will change before and after freezing.



τ=740s，T_{air}=13℃，RH50%

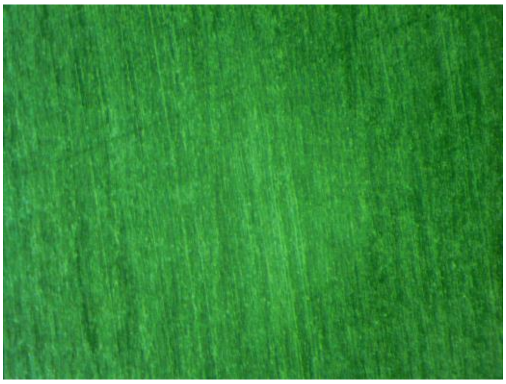


τ=746s，T_{air}=13℃，RH50%

Fig. 2 Before and after water droplets frozen

3.2 Water Condensation Process

Figure 3 shows the microscopic process of cold surface water droplet growth and freezing when the surface of the aluminum plate with a surface temperature of -5℃is exposed to a temperature of 13℃ and RH 50%. The experimental result shows that when the cold surface is exposed to the environment, the water vapor in the ambient air continuously aggregates with the liquid core on the cold surface with the air flow, and continuously merges and grows with time until the water droplets freeze.

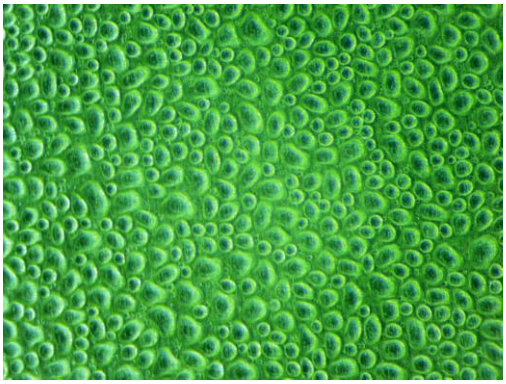


τ=1s

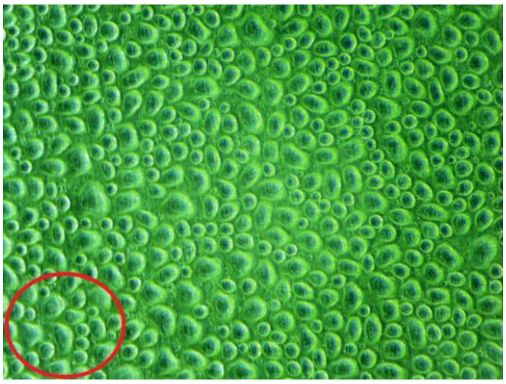
τ=360s

τ=480s

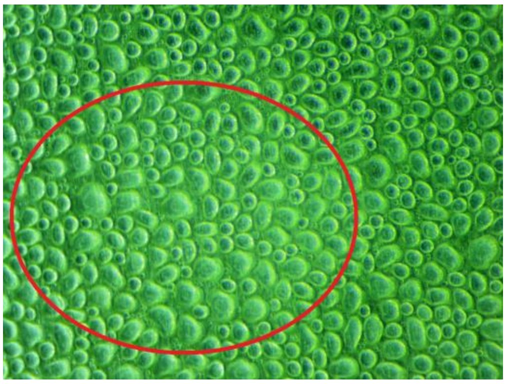
τ=600s



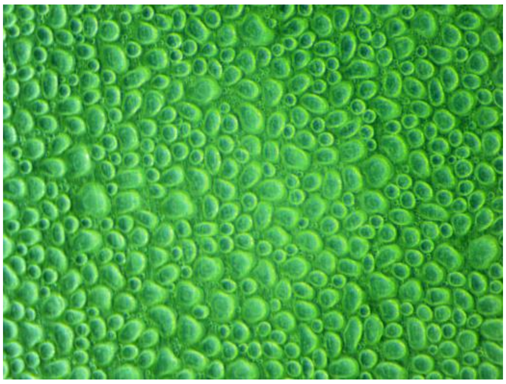
τ=714s



τ=716s



τ=738s



τ=747s

Fig. 3 Freezing process of water droplets T_{air}=13℃ RH50%

3.3 Effect of Ambient Temperature on Freezing Time

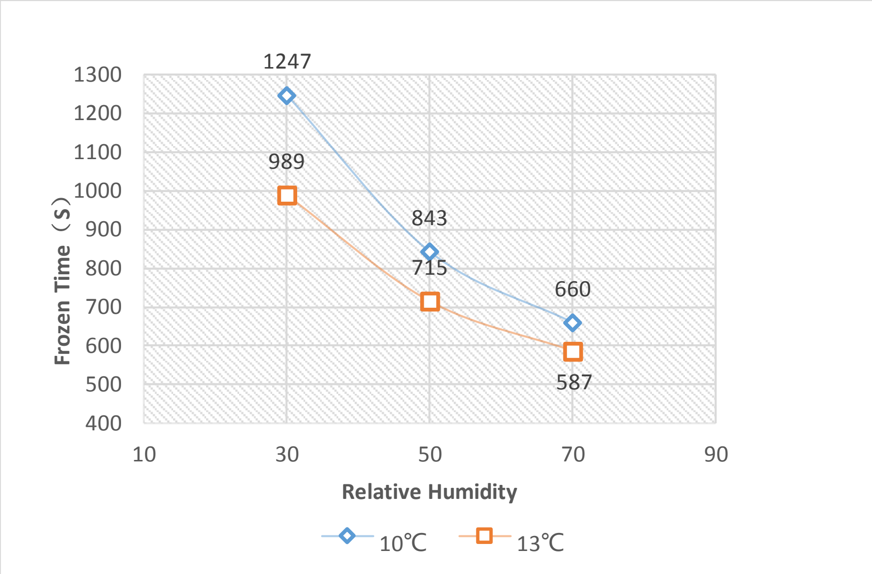


Fig. 4 Influence of environmental temperature and humidity on freezing time of water droplets

As shown in Fig. 4, when the cold surface temperature of the semiconductor refrigeration unit is set to -5 ° C, the influence of different air temperatures on the freezing time of the water droplets during the frosting process. The experimental results show that under the current experimental conditions, as the air temperature increases, the freezing time of the cold surface water droplets decreases, but the decreasing trend is slowed down. And while the humidity changes by 30%, 50%, 70%, the trend is the same. According to the theory of thermodynamic phase transition, the nucleation barrier to be overcome in forming the critical nucleus on the cold wall is related to the critical radius and surface tension. [6]

$$\Delta G = \left[\frac{4\pi {r_c}^3}{3\Omega_s}\Delta g + 4\pi {r_c}^2\sigma_{lv}\right]\frac{(2+\cos\theta)(1-\cos\theta)^2}{4} \quad (1)$$

$$r_c = \frac{2\sigma_{lv}V}{\Delta g} \quad (2)$$

In the formula, ΔG is the nucleation barrier of the critical nucleus, r_c is the critical radius, Ω_s is the volume of a single molecule, Δg is the reduced Gibbs free energy during the phase transition, V is the water vapor specific volume, σ_{lv} is the gas phase and The surface tension between the ice cores, θ is the contact angle between the water droplets and the surface of the aluminum plate. As the ambient temperature increases, the critical radius r_c of the droplet phase change increases, but its surface tension σ_{lv} decreases as the temperature increases. In the results of this experiment, as the ambient temperature increases, the freezing time of water droplets decreases. It can be seen that under the current experimental conditions, the barrier increase due to the increase of the critical radius increases, and the reduction of the barrier caused by the reduction of surface tension plays a leading role.

3.4 Effect of Air Humidity on Freezing Time

As shown in Fig. 5, the humidity in the experiment was set to three groups of RH30%, RH50%, and RH70%. The experimental results show that with the increase of ambient air humidity, the freezing time of water droplets during frosting decreases. And in the same three sets of humidity, the experimental ambient temperature was changed and the experimental results were compared, and the change trend was the same. According to the phase transition kinetics, during the phase transition, the phase change driving force is [7]:

$$F = kT\ln\frac{P}{P_s}/\Omega_s \quad (2)$$

Where k is the Boltzmann constant, T is the gas phase temperature, P_s is the saturated vapor pressure at the current gas phase temperature, and P is the vapor pressure. When the water vapor in the air reaches the vicinity of the cold surface, since the cold surface temperature is lower than the ambient temperature, the saturation pressure P_s near the cold surface sharply decreases, so that the water vapor in the air near the cold surface is supersaturated. When the cold surface temperature is constant, the saturation pressure near the cold surface is constant, and if the humidity of the ambient air is increased at this time, the vapor pressure P of the humid air near the cold surface is also increased, and the phase change driving force F is increased, thereby under the current experimental conditions, the higher the air humidity, the shorter the freezing time of the cold surface water bead.

4. Conclusion

By establishing a constant temperature and humidity platform, combined with microscopic observation to observe the frosting process and using a semiconductor refrigeration station to keep a stable cold surface temperature, the influence of ambient air temperature and humidity on frozen time of the water droplets during the frosting on the horizontal aluminum surface were studied. The experimental results show that under current experimental conditions, for the freezing time of cold surface water droplets, when the temperature changes between 10 °C and 13 °C, the reduction of surface tension caused by the decrease of surface tension plays a leading role, and the freezing time of cold surface water droplets decreases. When the humidity changes to RH30%, RH50%, and RH70%, the phase change driving potential becomes larger, and the freezing time of the cold surface water droplets decreases.

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References

[1] HAYASHIY, AOKIA, ADACHIS, HORIK. Study of frost properties correlating with frost formation types, Journal of Heat Transfer, 1977, 99(2): 239-245.
[2] Xu Wangfa. Frost crystallography on a horizontal cold surface length Lengthal realistic research, CRYOGENICS, 2003, (06): 41-46.
[3] WU Xiaomin, SHAN Xiaofeng, WANG Weicheng, et al. Meso-scale visual observation of frost formation on cold surfaces, J Tsinghua Univ (Sci & Tech), 2003, (10): 1437-1440.
[4] Li Ruixia, Wu Xiaomin, Wang Weicheng. Experimental study on frosting on aluminum surface, Journal of Thermal Science and Technology, 2005, 4(4): 315-318.
[5] WU Xiaomin, Xu Wangfa, WANG Weicheng, et al. Experimental Study on Super-cooled Drop Freezing on Cold Surfaces, Journal of Engineering Thermophysics, 2005, 26(1): 104-106.
[6] Huang Lingyan, Liu Zhongliang, Liu Yaomin, et al. Experimental Study of Droplet Frozen on Horizontal Copper Surface Under Low Ambient Temperature, Journal of Engineering Thermophysics, 2010, 31(4): 647-650.
[7] Yan naiben. Physical basis of crystal growth (Shanghai Science and Technology Press, China, 1982). (In Chinese)
[8] Chin-Hsiang Cheng，Chiuan-Che Shiu. Frost formation and frost crystal growth on a cold plate in atmospheric air flow, International Journal of Heat and Mass Transfer 2002, (45): 4289–4303.