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Frost deposition on a horizontal cryogenic surface in free convection

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ABSTRACT

A series of experiments were carried out to investigate the influences of cold surface temperature, air relative humidity and air temperature on frost deposition on a horizontal flat copper plate in free convection. The plate was cooled by liquid nitrogen. The results show that the cold surface temperature has an essential influence on frost deposition mechanism. The frost deposition mechanism is different for different cold surface temperature levels. For ultra-low cold surface temperatures, the frost layer growth is outer boundary layer mechanism controlled. Under this mechanism, the frost layer is formed mainly by heavy phase drift that is formed in the vicinity of the cold surface and the frost layer growth rate is significantly smaller than that under ordinary-low temperature conditions. What is more important is that there is a tendency that the frost layer thickness decreases as the cold surface temperature decreases, which is totally different to the frost growth on the cold surfaces of ordinary-low temperature. The results also show that there is a transition temperature. For a cold surface whose temperature is lower than this transition temperature, the frost formation is outer boundary layer mechanism controlled. And this transition temperature is affected by air relative humidity and air temperature. Increasing air relative humidity for a given air temperature or air temperature for a given air relative humidity will accelerate the frost formation mechanism transition.

1. Introduction

Once moist air get contacted with a cold surface whose temperature is lower than 0 °C and the air dew point, then frost will inevitably form on the cold surface. The nucleation or start of frost formation can be roughly divided into two different ways. One is by condensation, *i.e.*, if the cold surface temperature is low enough but not very low, then the water vapor in the moist air will diffuse to and condense on the cold surface forming water droplets. Then these water droplets freeze later on to form initial ice embryos. The second is by desublimation, *i.e.*, if the cold surface temperature is well below the water triple point, then the water vapor in the very vicinity of the cold surface will undergo a gas-to-solid phase change (desublimation) directly to form the initial ice embryos [1,2]. Once the initial ice embryos formed or the nucleation process finished, frost crystals will build up on the cold surface. This phenomenon is common in the fields of refrigeration, air-conditioning, cryogenic engineering, chemical industry and aerospace. It has a harmful effect on heat transfer and pressure loss, and reduces system efficiency. In some cases, frost deposition even damages the devices and threatens system safety [3,4]. Because of the detrimental effects on engineering applications, frost formation has been extensively studied both theoretically and experimentally [5–10]. However, these studies mainly focused on the ordinary-low temperature conditions, the temperature usually ranged from −40 °C to 0 °C, for the application scopes are usually within this temperature range. However, as aerospace technology develops quickly, and more exact demands of cryogenic liquid storage, evaporation and transportation technology, frost formation on cold surfaces under ultra-low temperature conditions could be found in many occasions. Therefore, frost formation on cold surfaces of ultra-low temperatures gained more attention than before [11,12]. As important as it might be, the studies in this aspect were rare, what follows is a brief summary of the important studies on frost formation on cryogenic surfaces in the literature.

The experimental studies and theoretical analyses made by Ruccia et al. [13], Holden [14] and Barron et al. [15] revealed that frost deposition on cryogenic surfaces had a distinct mechanism and could result in different mass transfer amounts compared with the theoretical predictions. Ruccia et al. [13] studied the frost formation on the wall of a cylindrical stainless steel vessel contained liquid oxygen. Heat flux and mass transfer was measured and calculated. They observed that only a portion of the solidified water

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Nomenclature

T_w	Cold surface temperature (°C)	t	Time (min)
T_a	Air temperature (°C)	δ	frost layer thickness (mm)
φ	Air relative humidity (%)		

vapor contributed to the frost deposition on the cryogenic surface. So the calculated amount of mass transfer was more than the measured value. Holden [14] did a study on frost formation on the out wall of two spherically shaped aluminum containers filled with liquid oxygen. He found that the analytical calculation results of mass transfer were significantly higher than the quantity actually deposited on the cold surface. And the condensation of water vapor in the outer boundary layer has a predominant effect on heat and mass transfer to a cryogenic surface. Though he failed to explain it reasonably, the "outer boundary layer mechanism" did give the later researchers some enlightenment. Barron et al. [15] conducted a series experiments on two vertical flat aluminum plates cooled by liquid nitrogen and built a boundary layer model for frost deposition system. Through the comparison between experiment and calculation results, they found the calculated mass transfer rate was about one order of magnitude greater than the measured data. They contributed this to the fact that there were frost particles in boundary layer near the frost-air interface, and these frost particles offer a greater resistance to the diffusion of water vapor. Later, a model contained fog layer was built by Epstein et al. [16]. In laminar convection the deposition of the water vapor was assumed to occur via ordinary Fick diffusion of water vapor plus thermophoretic fog particles drift. When low value of thermophoretic transport coefficient was employed, good agreement was gained between the calculated deposition rate and the Barron et al.'s experimental data. Although this agreement was far from satisfactory and more experimental data were needed to validate the model, this model did reflect the basic characteristics of the frost formation on ultra-low temperature cold surfaces. It might be supposed that the fog or fume particles formation in boundary layer near the frost surface influences the frost deposition mechanism substantially. To differentiate the frost formation mechanisms of different cold surface temperature levels, in this paper, the frost growth mechanism under ordinary-low temperature conditions is called vapor diffusion mechanism, and that under ultra-low temperature conditions is called outer boundary layer mechanism. The later was first proposed by Holden in his work [14]. It should be stressed that the vapor diffusion mechanism describes the frost deposition as a result of the vapor diffusion from the main stream air to the cold surface or the frost layer surface either by free or forced convection and the outer boundary layer mechanism explains the frost deposition as a result of the drift of the heavy phases of water vapor formed in the vicinity of the cold surface or the frost layer surface. So the frost deposition by the outer boundary layer mechanism can be taken as a result of snowing or raining. Brian et al. [17] studied the frost formation phenomena experimentally on a horizontal flat copper plate cooled by liquid nitrogen in forced convection. They found the boundary layer fogging phenomenon but took it for granted that this phenomenon could only last for a very short period of time, and therefore they paid little attention to it. In developing his frost growth model, Derenberger et al. [4] considered the boundary layer fogging phenomenon and Brian's experiments data were used to validate their model when the cold surface temperature was very low. The modified mass transfer coefficient was used to take the fog layer influence into consideration. Although the general trend of the numerical predictions were in good agreement with the Brain's data, the data points distributed in the time range during which the fog layer should exist were quite limited, more experiments data are therefore needed to validate the model. From then on, few studies paid attention to the special features of frost formation on ultra-low temperature cold surfaces for a long time. In 2016, Liu et al. reported their latest experimental results on frost deposition on a vertical flat copper plate [3], liquid nitrogen was used as coolant. Some new phenomena of frost formation under ultra-low temperature conditions were found in their studies, and these phenomena still needed further theoretical analysis.

The exact mechanism of frost formation phenomena under ultra-low temperature conditions is far from clear, and the literature on this topic is quite limited, especially when one compare it with the frost formation phenomena on ordinary-low temperature cold surfaces. In this work, a series of experiments were carried out on frost formation on a horizontal flat cold surface of ultra-low temperatures under free convection to examine the influences of cold surface temperature, air relative humidity and air temperature on frost formation for a better understanding of the frost formation mechanism under ultra-low cold surface temperature conditions. The range of the experimental parameters are: cold surface temperature varied from −190 °C to −30 °C, air relative humidity from 30.2% to 60.7%, air temperature from 15.1 °C to 24.8 °C. The phenomena observed in experiments and measured results were discussed and analyzed.

2. Experiment apparatus and methods

The schematic of experiment system is shown in Fig. 1. The test plate of pure copper is put in an insulation box filled with mineral wool, only the upper surface (R_a = 0.307 μm, measured by TSK SU FCOM 480A) is exposed to the ambient air. Another plate with serpentine channels is fixed together with the test plate by 6 countersunk head screws. The liquid nitrogen flows and evaporates in these channels. The flow and regulating of liquid nitrogen are control by high pressure nitrogen gas. The temperature of the test plate is measured by 4 T-type thermocouples. The thermocouples are all pre-calibrated with an uncertainty of 0.1 °C, the temperature data are collected by Agilent data acquisition system. The frost formation is observed by a microscope. The image information is collected by a CCD camera and a capture card. Temperature and image data are recorded in a personal computer. The air temperature is regulated by an air-conditioning system with an accuracy of 1.0 °C and measured by a T-type thermocouple. Air humidity is regulated and controlled by a humidifier (Goldmedalee GELM 2) with an accuracy of 2.0%. The air relative humidity is measured by a temperature-humidity meter (OMEGA RH511).

As a formal preparation step of the experiments, the test surface is first cleaned by fine sandpaper and then by acetone solution and de-ionized water, and finally is covered by a clean plastic film after the surface becomes dry. After the surface temperature reaches the pre-set value and remains basically a constant, the plastic film is removed to start frost formation test. The temperature data are recorded by 10 s, the image information is captured every 5 min in the first hour and every 10 min in the second hour. Frost thickness is measured every 10 min by a micro measurement system