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Research paper

Experimental study on frost formation on a cold surface in low atmospheric pressure

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HIGHLIGHTS

- Frost formation process under natural convection is investigated experimentally.
- Morphology evolution of frost formation in low atmospheric pressure are presented.
- The atmospheric pressure plays a significant role in whole frost formation process.
- The irregular, columnar and dendritic frost crystal is observed on cold surface.
- The frost layer is thinner and sparser in a lower atmospheric pressure.

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ABSTRACT

The role of atmospheric pressure on the frost formation process including the droplet growth, freezing process and frost growth process on the cold surface under natural convection condition is investigated experimentally via a visualization system. The visualization system, configured with the enclosed tank, observation window, microscopy setup and vacuum unit, is used to observe the frost formation process on the cold surface in low atmospheric pressure. The results indicate that the atmospheric pressure plays a significant role in the whole frost formation process. Decreases in atmospheric pressure lead to a smaller phase transition driving force and hence results in a longer time for the process of droplet growth and freezing. The frost crystal shape transforms from irregular to a columnar type and then to a dendritic type when the atmospheric pressure increases from 0.1 bar to 0.5 bar and then to 1 bar. In particular, the frost layer turns to be thinner and sparser in a lower atmospheric pressure.

1. Introduction

Frost deposition is an important phenomenon in nature and industry, such as refrigerator, aeronautics, cryogenics and polar instruments [1–4]. The frost grows up on a cold surface having a temperature below the freezing point of water. The frost formation under low atmospheric pressure condition is usually encountered in the engineering application, taking the airfoil surface of plane and mirror of astronomical telescope at high plateau as an example. This phenomenon may cause catastrophic harm. In the context, understanding the frost formation, especially how the atmospheric pressure plays the role, has been becoming a crucial imperative motivated by the technical development in aviation industry and polar exploration.

The understanding of frost nucleation and growth on a cold surface is the premise to reveal the mechanisms of frost formation. One way in which can be accomplished is through a set of experimental observation. The observation taken by Wu et al. [5] suggests that the transition from water vapor to frost experiences the droplet condensation, droplet growth with coalescence of supercooled droplets, droplet freezing, formation of frost crystals on the frozen droplets, and crystal growth with simultaneous collapsing. According to whether the frost appears on the cold surface, the frost formation could be divided into droplet growth and freezing stage as well as frost growth stage. The frost nucleation is generated on the frozen droplet and is the

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origination of the frost growth. After the appearance of frost on frozen droplet, there exists the crystal growth, frost layer growth and frost layer full growth [4] on the cold surface. From the viewpoint of phase change, the frost formation may go through the processes of vapor-liquid-solid, direct vapor-solid or occurring simultaneously [6].

In the past decades several experimental and theoretical attempts have been conducted to investigate the frost formation process as affected by several factors, including the cold surface temperature, surface wettability and ambient conditions, etc. Jones and Parker [7] developed a theoretical model of frost growth based on molecular diffusion of water vapour at the frost surface and used the energy and mass balances to predict the frost formation with varying parameters. Wu et al. [8] found that the surface temperature is the primary factor affecting the frost crystal shape, and the relative humidity has less effect on the frost crystal shape. Piucco et al. [9] found that nucleation is guaranteed when the supercooling degree is higher than 5 °C. Liu et al. [10,11] and Huang et al. [12] investigate the effect of surface wettability on frost formation. Their results indicates that, for the surface with larger contact angle, the freezing time is longer, and the frost crystal is a weaker, sparser, thinner structure and is easier to be removed. Results taken by Shin et al. [13] indicate that the surface with a lower contact angle shows a higher frost density and thermal conductivity during a two-hour test, but minor differences have been observed after two hours of frost generation. However, the nucleation limit is practically independent on the contact angle when it higher than 140° [9], and the frosting can be delayed by coating the hydrophilic material over fin surfaces of the air cooler. Lee and Ro [14] presented models to analyze the frost growth on a flat plate, and found that the initial porosity of the frost layer plays an important role in determining the frost layer growth characteristic. Yang et al. [15] developed a model to investigate the influence of air flow on frosting. And it appears that increase in air velocity has little effect on mass transfer under turbulent flow, while frost growth under laminar flow is influenced by the air velocity. Na and Webb [16] presented a theoretical analysis of the fundamental factors affecting frost nucleation and pointed out that a lower energy surface requires a much higher supersaturating degree for frost nucleation. The experimental results obtained by Rahman and Jacobi [17] indicated that the microgrooves on a cold surface significantly affect the frost structure at the early stages. Wu et al. [18] observed the uneven distribution of frost on non-uniform temperature distribution surface through the experiment on a parallel flow evaporator. Qin et al. [19] observed that the frost growth rate increases with relative humidity of air, but the increasing tendency slows down when the relative humidity is larger than 80%.

In the context of reducing frost damage, the challenge consists in developing versatile methods to restrain the frost growth. For the moment, the utilization of ultrasound and electric field are the significant promising alternative to prevent the frost growth on a cold surface. According to the experimental study by Li et al. [20], the ultrasound is capable to remarkably restrain the frost formation process. Maybank and Barthakur [21] experimentally studied the effect of electric field on the ice crystal growth. Their results showed a rapid growth of ice crystals when the applied electric field strength is above 200 V/cm, and the observed crystals are thinner and more fragile when compared with those without electric field. Experimental results by Ma and Peterson [22] indicate that both the saturation pressure at the needle frost surface and the critical radius of ice nucleation decrease with the increase of electric field strength. Some observation made by Wang et al. [23] shows that, with the presence of electric field, the frost crystal is pulled up towards the electrode.

In summary, there have been a majority of available investigations on frost formation and prevention on a cold surface in the condition of ordinary pressure. However, in some real applications, the frost also generates on the equipment surface which is located in a low-pressure condition, such as the airfoil surface of planes and the mirror of astronomical telescope at high plateau for the astronomical research. Until now, few works have been conducted to study the impact of atmospheric pressure on frost formation. In order to provide a detailed understanding of frost formation under low atmospheric pressure, a visualization experiment is conducted to observe the frost formation process under different levels of atmospheric pressure. The morphology evolution of droplet growth and freezing process as well as the frost growth process are analyzed and discussed. In addition, the role of atmospheric pressure on the frost formation process is presented and examined.

2. Experimental apparatus and procedure

In order to analyze the role of atmospheric pressure on the frost formation, a visualization experiment is performed to observe the frost growth process on a cold surface under natural convection condition at different levels of atmospheric pressure. Fig. 1 shows the experimental apparatus of frost formation on a cold surface under natural convection condition in low atmospheric pressure, which mainly consists of the test section, data acquisition system, microscopic image acquisition system and low pressure system.

As shown in Fig. 2(a), the test section is made up of an aluminum plate (length: 40 mm, width: 40 mm, thickness: 5 mm) cooled by a semiconductor chilling plate (C1206 type with the highest power of 72 W) with heat dissipation to cooling water. The Aluminum plate has the hydrophilic surface with contact angle of $\theta = 76°$ (see Fig. 2(b)). Before the start of experiment, the sample surface is cleaned by the acetone and DI water so as to ensure that the sample surface is not contaminated. The cold side of the chilling plate contacts with the aluminum plate, on which the frost will grow. The hot side of the chilling plate contacts with the heat sink to release the heat to the cooling fluid supplied by the refrigeration unit. In the experiment, the whole test section, expect the aluminum plate surface on which the frost forms, is cover by the thermal insulation materials. The K type thermocouples, which are inserted in the aluminum plate and connected with a data acquisition, are used to measure the cooled surface temperature. A humidity sensor is applied to measure the relative humidity, and the accuracy of the humidity sensor is 2%. The dimensions of aluminum plate and temperature measurement point distribution are illustrated in Fig. 2(c).

In the experiment, the test section is inside the enclosed tank. A vacuum unit is connected to the enclosed tank to achieve the low

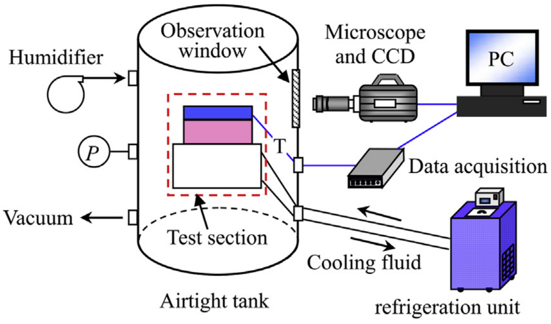

Fig. 1. Schematic of the experimental apparatus.