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An experimental study of frost formation on cryogenic surfaces under natural convection conditions

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ABSTRACT

An experimental system of frost deposition on cryogenic-temperature surfaces under natural convection conditions was set up and a series of frost formation experiments were conducted under various conditions, focusing on the frosting phenomena on horizontally- and vertically-placed cryogenic-temperature surfaces under natural convection conditions especially the early stage frost formation phenomena. The influences of surface temperature, air temperature and air relative humidity were also carefully studied of frost formation on vertical cryogenic surfaces. A very peculiar and important phenomenon for frost formation on cryogenic-temperature surfaces observed is that liquid air droplets were first formed on cryogenic-temperature surface if surface temperature is lower than −165 °C before frost crystals appeared. The liquid droplets on horizontally-placed surfaces may exist for a quite long time and even form a continuous film, and have significant influences on frost deposition. It was found that frost crystal clusters deposited on liquid air droplets are not static, they moves both as and relatively to the droplets. The frost layer growth on the vertical surfaces of cryogenic-temperature is highly non-uniform and exists a downward growth period during which the frost layer grows mainly along the downward direction of the vertical surfaces. It was also found that under very low surface temperature and natural convection conditions, as the surface temperature drops, the frost layer thickness decreases. This is completely different to the phenomenon observed on ordinary low-temperature cold surfaces.

1. Introduction

Frost deposition on cold surfaces is a well-known phenomenon in nature and is commonly observed in cryogenic, refrigeration, air-conditioning, and aerospace industries. Frost deposition is inevitable once moist air is exposed to a cold surface whose temperature is below water triple point and air dew point [1]. The frost crystals deposit on these heat transfer surfaces act as fins [2] and may improve the heat transfer between the surfaces and air during the early initial period of frost formation. However, after significant frost accumulation and a continuous frost layer formed, this frost layer will turn into an insulation and increase heat transfer resistance due to its porous characteristics and thus the heat transfer is degenerated seriously. Moreover, if the frost accumulation is not removed on time or without effective control, then as frost layer thickness increases, the frost formed on the fins of heat exchangers blocks the air flow passage, leads to COP (coefficient of performance) decrease and even system malfunction [3]. According to the report by Emery and Siegel [4], there is a 50–75% decrease in heat transfer and a substantial increase in pressure drop resulted from the frost deposition on a compact heat exchanger. In the field of aerospace, the phenomenon of frost deposition is also harmful [5]. For the planes that fly in night, due to low air temperature, frost may deposit on the wings. The frost deposition increases surface friction drag during taking off or navigating and thus affects safety. In launching rockets, there are similar problems. Frost may deposit on the rocket surface and lead to communication satellites failing to enter correct synchronous orbit [6]. Frosting has caused serious negative effects in many areas, therefore a good deal of theoretical and experimental studies (see, for example, [1–3] and [7–9]) have been made aiming at reducing or controlling frost formation on various cold surfaces.

As one may understand, since the harmful frosting phenomena mainly take place in various industry processes involving ordinary low-temperature conditions, therefore, up till now, most of theoretical and experimental researches on frost deposition have been focused on ordinary low temperature conditions [7–9]. However, this situation is changing, the frost formation on very low-temperature surface is of increasing concern. For example, as LNG (liquefied natural gas) production and application develop quickly,

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Nomenclature

t	time (min)	T_w	surface temperature (°C)
T_a	air temperature (°C)	δ	frost layer thickness (mm)
φ	relative humidity (%)		

especially the so-called passive-evaporation technology using air as heat source, frost may deposit on very low temperature surfaces of LNG evaporators. Another example is in aerospace applications. For liquid-fueled rockets, frost may deposit on the surface of cryogenic oxidizer tanks of very low temperature as rockets fly through atmosphere. The frost deposition may change both the shape and weight of the oxidizer tanks and thus influence rocket aviation performance. Still another example is also in aerospace. As aircrafts propelled by gas turbines fly through atmosphere which can be of heavy moisture at a very high speed, then due to the adiabatic stagnation effect, the air that enters the compressors of gas turbine can be of a very high temperature. The high temperature may reduce the air intake efficiency of compressors and thus reduce the efficiency of gas turbine. So the air has to be cooled through a pre-cooler by cryogenic fluids before it enters the compressors. The surface temperature of the pre-cooler can be very low and frost deposition may take place and block air flow passage. Due to the increased practical an engineering applications, the frost formation on very low temperature surfaces is receiving more and more attentions from both industries and scientific researches. A group of researchers led by Chen seemed one of the earliest paying attentions to frost deposition phenomena on cryogenic surfaces. They designed a test rig for measuring the frost deposition and heat transfer characteristics of a finned tube and carried out a series of experimental and theoretical studies [10–12]. The low surface temperature was obtained by evaporating liquid argon or nitrogen, the declared lowest surface temperature is −190 °C, but the reported experimental results are that of −120 °C. Although some of the measured results of the frost layer thickness were reported, no detailed experimental phenomenon description and even no specific conditions were given. Kim et al. [13] investigated the heat transfer characteristics and frost layer formation on the surface of a cryogenic oxidizer tank for a liquid propulsion rocket numerically taking forced and natural convection, frost deposition, and solar radiation into consideration. The lowest surface temperature on which frost layer grew is 90 K (−183.15 °C) and both frost-layer growth and heat transfer characteristics were obtained. However, these results are merely numerical. No cryogenic frost deposition experimental data were provided and used to validate their mathematical models. Actually, the experimental data of frost formation on very low-temperature surfaces are rare. Ferrick et al. [14] reported their experimental study results of ice release coatings at cryogenic temperature, the surface temperature studied was fixed at −122 °C of the liquid oxygen feed line brackets on which frost deposition may appear during the prelaunch period following fuel loading of space shuttle. However, no frost layer growth data were given in their report and their research focused on the effectiveness of ice release coatings only. Another research concerning low-temperature surface frost deposition is that by Kuang et al. [15].They presented a mathematical model for predicting frost deposition behavior and thermal performance of a direct-contact ambient air vaporizer of LNG. The LNG inlet temperature of the ambient air vaporizer is 113 K, the frost deposition is taken into consideration in their model. Although the surface temperature is not given, however, it can be deduced that this temperature can be very low at least at the entrance section.

From above introduction one can see, although the frost deposition phenomena on cryogenic-temperature surfaces are becoming more and more important, there are little experimental data reported in literature on the frost formation on cryogenic-temperature surfaces. And the frost layer can be of completely different properties to that formed on ordinary low temperature (> -30 °C) surfaces. Therefore, in this paper, experiments were made of frost deposition phenomena on cryogenic surfaces whose temperature was as low as -190 °C under natural convection conditions. The frost deposition processes were closely observed of the initial period through a CCD camera and microscope system and the influences of cold surface temperature, air temperature and air relative humidity on frost layer growth were carried out. The most impressive finding of this study is that under very low surface temperature (< -165 °C), it is the liquefied air which is rich in oxygen, not frost crystal that appears first on the cryogenic surface, and this phenomenon produces significant influences on frost deposition process. These phenomena have not been reported before, as far as the present authors could know.

2. Experimental apparatus and methods

2.1. Test rig

Fig. 1 shows the experimental apparatus. The whole experimental device mainly consists of a cryogenic system, microscopic image system, data acquisition system, optical fiber luminescence and air-conditioning system. The cryogenic system uses liquid nitrogen as coolant that experiences a throttling process to maintain the cold plate temperature from −191.3 °C to room temperature. Liquid nitrogen is stored in a liquid nitrogen tank and a pressurized nitrogen gas bottle is used to provide proper pressure needed for driving liquid nitrogen flow. The temperature of the cold plate on which frost deposition takes place is changed by regulating the flow rate of the liquid nitrogen. The cold plate (the test section) is made of two pieces of copper blocks. One block (the base black) is manufactured with a group of serpentine channels whose depth is 3.0 mm and width 4.0 mm allowing liquid nitrogen flow and be evaporated to produce cooling demand for maintaining the low temperature. Another one serves as the cover of the cold plate which is of the same size as the base block whose width, length and thickness is 52 mm, 150 mm and 6 mm, respectively. The two copper blocks are fixed together by 6 countersunk head screws. In order to minimize heat transfer between cold plate and surrounding air, the bottom and the side surfaces of the cold plate are buried in a polyurethane plastic block that serves as insulation. Then the cold plate and the polyurethane block are placed in a large box that is filled with glass fibers, leaving only the upper surface (frost deposition surface) of the cold plate exposed to air. The surface temperature of the cold plate is measured by 4 T-type thermocouples that are buried inside the cover copper block through 4 holes of 2 mm in diameter, the locations of these thermocouples are shown in Fig. 2. The temperature data are recorded by Agilent 34970A HP data acquisition system, and transferred to a personal computer for further analysis. The cold surface temperature is the average of the temperature readings of these 4