Available online at www.sciencedirect.com
SCIENCE DIRECT®
International Communications in Heat and Mass Transfer 33 (2006) 819 – 826
International Communications in HEAT and MASS TRANSFER
www.elsevier.com/locate/ichmt

Experimental study on behavior of initial frost crystal formation under lower water vapor pressures☆

Kaiyang Qu [a,*], Xu Xu [a], Zhengwei Duan [b]

[a] *Department of Building Science, Tsinghua University, Beijing, 10084, China*
[b] *Real Estate Managing and Developing Center of Zhengzhou Railway Branch Bureau, Zhengzhou, 450052, China*

Available online 17 May 2006

Abstract

This paper studies the fashion in which the initial ice crystals form on the surface under lower water vapor pressures. The fashion affects greatly the ensuing frost growth. A unique fashion of ice crystal formation was observed. Some kind of unknown surface property, but not roughness and maybe more microscopic than roughness, determined the possibility of the surface to induce frosting. There were a limited number of sites with such kind of property on the surface. Improving the conditions of those sites is possible to avoid or delay the induction of deposition.

Keywords: Frost; Initial crystal formation fashion; Cold surface; Lower water vapor pressure

1. Introduction

When a cold surface is exposed to moist air, frosts may form on it. This phenomenon is frequently encountered with heat exchange services working in lower temperature air. It is usually undesirable for heat exchange services because it may cause a great decrease in heat transfer rate and increase in pressure drop. However, frost formation, especially the formation of small frost crystals, is definitely desirable in the process of freezing food products since a frost crust forming on the outer layer of a food product can help minimize dehydration of the food and seal in the juices and flavoring agents.

When moist air reaches a cold surface, water vapor in the air condenses on the cold surface in the form of supercooled liquid water droplets first. The water droplets grow and combine to form bigger water drops. Those bigger water drops freeze sometime and produce ice particles on the cold surface, which is usually regarded as the beginning the frost formation process. Frost then grows on the surface.

Generally, the entire frosting process can be divided into three stages: crystal growth period, frost layer growth period, and frost layer full growth period. In crystal growth period, frost crystals grow in a direction perpendicular to the surface at about the same rate. The frost formation in this period is best characterized by the crystal growth

☆ Communicated by P. Cheng and W.Q. Tao.

* Corresponding author.
E-mail address: qukaiyang@tsinghua.edu.cn (K. Qu).

0735-1933/$ - see front matter
doi:10.1016/j.icheatmasstransfer.2006.04.001

Nomenclature

T_s	Temperature of cold surface (°C)
t	Time (s)
T_a	Dry bulb temperature of air (°C)
N	Number of ice particles
h	Absolute roughness of the stripes on the cold surface (μm)
Greek symbols	
ϕ	Relative humidity of air

in linear dimension, such that the frost becomes like a forest of trees, without the growth of a homogeneous layer. Hayashi et al. [1] observed the morphologies of the frost forests and classified them into several types. Schneider [2] and Tao et al. [3] modeled the frost growth in this period. In frost layer growth period, the rough frost, which is a cluster of rod-type crystals, changes its shape by the generation of branches around the top of a crystal or by the interaction of each crystal and then grows gradually into a meshed and more uniform frost layer until the frost surface becomes nearly flat. In this period, frost density increases as well as frost layer thickness because of the three-dimensional growth of frost and the internal diffusion of water vapor in the frost layer. This period was extensively studied experimentally [4–14]. Frost properties, such as its height, deposition rate, density and effective thermal conductivity were measured in connection with surface temperature, air temperature, air humidity ratio and Reynolds number, etc.. A number of models were built to simulate the frost growth in this period, the representatives of which are those by Tao [3], Sahin [15], Lee et al. [16], and Ismail and Sailinas [17]. In frost layer full growth period, the frost layer does not change its shape significantly until the frost surface temperature comes to 0 °C due to an increase in frost thermal resistance. The frost surface then begins to melt. The resultant water soaks into the frost layer and freezes into an ice layer. The melting and freezing cause a sudden increase in the frost layer density and a sudden decrease in its thermal resistance, and frost deposition occurs again. Then a cycle process of melting, freezing and deposition continues periodically until the frost formation stops when the equilibrium condition of heat transfer is reached. This period was studied by Ostin and Andersson [10] and Aoki et al. [18].

In contrast to frost growth has drawn extensive attentions, in what fashion the dotted ice crystals initially form on the surface has been studied little, which, however, essentially determines the ensuing frost growth. Tao et al. [19] photographically observed frosting process in its initial period on an aluminum surface under various conditions. He measured the size distribution of the ice particles formed in the initial period. The variation of the time when the water droplets froze against various parameters was graphed. Xu et al. [20] studied the randomness of frost particle formation on the cold surface. Experiments of both Tao and Xu were conducted under relatively higher water vapor pressures. While, this paper is devoted to studying in what fashion frost crystals were initially formed on a cold surface under lower water vapor pressures.

2. Experimental apparatus

Fig. 1 schematically describes the experimental apparatus. There was an airtight vessel shaped like inverted "U". Water or aqueous solution with various temperatures and concentrations were contained in the vessel so that various vapor pressures were created in the vessel. At the other end of the vessel, a piece of aluminum plate was mounted, which could be cooled by a thermoelectronic cooler immediately attaching it. The heat released by the thermoelectronic cooler was brought away by water through the flow paths below the cooler. Sizes of the aluminum plate and the thermoelectronic cooler are exactly same, both in $6.2 \times 4.5\,cm^2$. The aluminum plate was 2 mm thick. Its top surface was well polished. One thermocouple was set at the bottom side of the aluminum plate, whose temperature was considered equivalent to the temperature of the aluminum plate top surface for the heat flux through the plate was rather low. Another thermocouple was set in water or aqueous solution. Water vapor pressure in the vessel could be deduced by temperature of water or by together temperature and concentration of aqueous solution. A CCD camera is employed to record the frosting process on the aluminum