International Journal of Heat and Mass Transfer 120 (2018) 259–266

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The behavior of frost layer growth under conditions favorable for desublimation

Jaehwan Lee, Kwan-Soo Lee [*]

School of Mechanical Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

ARTICLE INFO

Article history:
Received 29 September 2017
Received in revised form 7 December 2017
Accepted 8 December 2017

Keywords:
Conditions favorable for desublimation
Initial frost crystal morphology
Frost layer growth behavior
Frost thickness
Frost density

ABSTRACT

The purpose of this study is to understand the behavior of frost layer growth under conditions favorable for desublimation. The frosting experiments were conducted on a horizontal cooling surface. Condensation did not occur at the initial stage of frosting, and feather-shaped frost crystals were formed on the cooling surface. These frost crystals grew one-dimensionally while maintaining their shapes. In addition, the effects of operating conditions (air temperature, air velocity, air absolute humidity, cooling surface temperature) on frost layer growth under the conditions favorable for desublimation were investigated. As the cooling surface temperature decreased, the increase in the amount of frost was insignificant. Additionally, an increase in air velocity increased the frost density but not the thickness of the frost layer.

1. Introduction

Frosting processes generally begin when supercooled condensate water is generated on a cooling surface. After this condensed water is formed, it changes to a solid state, and frost columns and branches grow on the frozen water [1]. When frosting occurs by freezing after condensation, the frost formation processes are divided into periods of crystal growth, frost layer growth, and frost layer full growth [2,3]. However, when the cooling surface temperature is very low, desublimation can occur instead of freezing after condensation. According to Pablo [4], the minimum temperature to which water can be supercooled under atmospheric pressure is approximately −42 °C. Nath and Boreyko [5] found that desublimation can occur depending on the cooling surface temperature and contact angle. If desublimation occurs, the growth behavior and physical properties of the frost layer can be significantly different from those of a frost layer formed by freezing after condensation. Therefore, it is necessary to study the growth behavior and physical properties of the frost layer under conditions favorable for desublimation.

A number of studies have been conducted to develop a fundamental understanding of frosting phenomena. Studies typically focus on frost layer growth behavior [6–8] and frost crystal morphologies [9–12]. Experimental correlations between the physical properties of the frost layer have also been proposed by various researchers [13–17]. However, these studies were conducted at cooling surface temperatures higher than −35 °C [6–17], and the cooling surface temperatures considered in each study are summarized in Table 1. Because frost formation occurs mainly in the form of freezing after condensation in such a cooling surface temperature range, it is difficult to understand the frosting phenomenon associated with desublimation from these research results. To fundamentally understand the frosting phenomenon caused by desublimation, various experimental studies at lower cooling surface temperatures are required. There are only a few studies on frosting at low cooling surface temperatures where desublimation can occur [18,19]. Biguria and Wenzel [18] conducted frosting experiments on a −96 °C to −29 °C horizontal plate under forced convection conditions, and they proposed a correlation between the thermal conductivity and density of the frost layer. Cremers and Mehra [19] conducted frosting experiments at −90 °C to −60 °C using vertical cylinders under natural convection, and they proposed a correlation of frost thickness and density. Both studies focused on the observation of the physical properties of the frost layer rather than a fundamental understanding of frosting phenomena. Moreover, there is a limitation in that those studies did not clarify the effects of the four main operating conditions (air temperature, air velocity, air absolute humidity, cooling surface temperature) on the growth of the frost layer.

The purpose of this study is to fundamentally understand frosting behavior occurring under conditions favorable for desublimation. For this purpose, frosting experiments were conducted on a horizontal plate at a temperature lower than −30 °C. In particular,

---

[*] Corresponding author.
E-mail address: ksleehy@hanyang.ac.kr (K.-S. Lee).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.039

Nomenclature

a	actual area per one pixel (m^2)
A	frost layer frontal area (m^2)
h	heat transfer coefficient ($W/m^2 \cdot °C$)
h_m	mass transfer coefficient ($kg/m^2\ s$)
L	horizontal length of frost layer (m)
m	mass (kg)
N	number of pixels in edge of frost layer
P	pressure (kPa)
T	temperature (°C)
u	velocity (m/s)
V	volume of frost layer (m^3)
w	width of test surface (m)
Δ	relative uncertainty
δ	average thickness (m)
ε	measurement error
ρ	density (kg/m^3)
ω	absolute humidity (kg/kg)

Subscript

a	air
atm	atmospheric
f	frost
s	saturation
w	test surface

Table 1
Cooling surface temperature in previous studies.

Reference	Cooling surface temperature, °C
Cheng and Shiu [6]	−18 to 0
Kandula [7]	−18 to −10
Wu et al. [8]	−19 to −10
Lee et al. [9]	−28.4 to −11.6
Wu et al. [10]	−20 to 0
Da Silva et al. [11]	−10 to −3
Wu et al. [12]	−16 to −10
Ostin and Andersson [13]	−20 to −7
Yang and Lee [14]	−35 to −15
Kim et al. [15]	−32 to −20
Negrelli and Hermes [16]	−30 to −4
Kim et al. [17]	−27 to −15

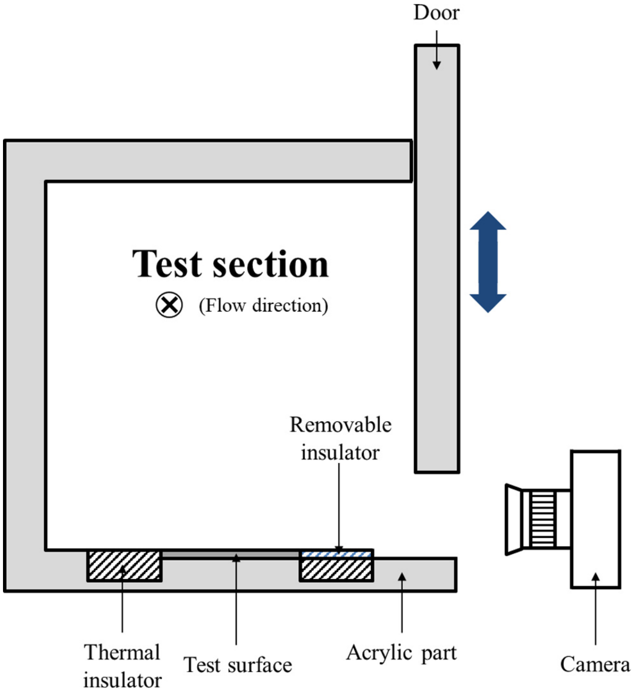

Fig. 1. Schematic diagram of the test section.

experiments were carried out with cooling surfaces at temperatures below −40 °C; only a few studies have addressed this temperature regime. The initial frost layer growth process was observed, and the effects of cooling surface temperature, air temperature, air velocity, and air absolute humidity on the physical properties of the frost layer were investigated.

2. Experiments

2.1. Experimental setup

The experimental apparatus was constructed in the same manner as has been done in previous studies [1,15], and the test section was constructed as shown in Fig. 1. As shown in the figure, each side of the test surface was insulated. Fig. 2 presents the test surface. In this experiment, a bare surface (Aluminum 6061, 5 × 5 cm) with a contact angle of 75 ± 1° was used, and the surface temperature was measured by an inserted type-T thermocouple. Both the refrigeration cycle and the thermoelectric cooler were used at the same time to control the temperature of the test surface. In the experiment, the temperature of the test surface was maintained by controlling the output of the thermoelectric cooler. The inlet temperature of the refrigerant was −30 °C, and the rated output of the thermoelectric cooler was 24 V, 350 W.

The average thickness of the frost layer was measured by image processing. High-resolution photographs were obtained with a Nikon D800E camera and an AF-S Micro Nikkor 60 mm f/2.8G ED lens. The actual area occupied by a pixel in photographs was very small, approximately 4×10^{-10} m^2. The frost layer frontal area was calculated using ImageJ software, based on the pixel information. A digital balance with an accuracy of 0.0001 g was used to measure the mass of the frost layer.

2.2. Experimental method

Experiments for measuring the average thickness δ_f and the density ρ_f of the frost layer were carried out by the following procedure.

Step 1. Cover the insulation on the top of the test surface to prevent heat and mass transfer between humid air and the test surface.
Step 2. After setting the operating conditions according to the experimental conditions, remove the insulation and start the frosting experiment.
Step 3. When the desired experiment time is reached, take a photograph.