International Journal of Heat and Mass Transfer 87 (2015) 491–496

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental investigation of frost retardation for superhydrophobic surface using a luminance meter

Donghee Kim, Hisuk Kim, Sun Woo Kim, Dong Rip Kim, Kwan-Soo Lee *

School of Mechanical Engineering, Hanyang University, Wangsimni-ro 220, Seoul 133-791, South Korea

A R T I C L E I N F O

Article history:
Received 4 March 2015
Received in revised form 15 April 2015
Accepted 15 April 2015
Available online 27 April 2015

Keywords:
Surface treatment
Superhydrophobic
Frost stage
Contact angle
Frost retardation

A B S T R A C T

We experimentally investigated the phenomena of frost retardation in terms of the heat exchanger fins with various water contact angles under normal air-source heat-pump operating conditions. We first introduced a new experimental method using a luminance meter, which measured the light intensity from the surface, and determined the phase-change time, for quantitatively defining the frost stages. The phenomena of frost retardation was analyzed for 10 samples with different water contact angles (75°–160°) at different refrigerant temperatures. When the refrigerant temperature was −10 °C or −12 °C, the effect of frost retardation increased remarkably with superhydrophobic surfaces. However, when the refrigerant temperature was −8 °C, the effect of superhydrophobicity diminished at water contact angles greater than 150°.

1. Introduction

Heat-pump systems have the outstanding advantage that they can be used with high efficiency, both for heating and cooling. However, there coefficient of performance (COP) significantly decreases in the heating processes when the frost forms on the fin surfaces of the heat exchanger. One way to address this phenomenon that has proven effective is to delay the frosting time by treating the fin surfaces. The fin surface treatment and the corresponding effects on the heat exchanger have been widely studied in attempts to delay the frosting time, which is strongly dependent on the contact angle between the cold fin surface and the water droplets. However, once the fin surface becomes frosted, the surface treatment does not have an effect on the frost formation any more before the defrosting takes place. Therefore, the understanding of the frosting seed behavior of the early frosting stage depending on the fin surface treatment is crucial to enhance the frost retardation, thereby increasing the efficiency of heat pumps under normal operating conditions.

Tao et al. [1,2] and Hayashi et al. [3] defined three stages of the frosting process: the early stage, the crystal growth period, and the fully developed frost-layer growth period. Most researchers, such as Tao et al. [1], Lee et al. [4,5] and Yang and Lee [6], have sought to establish numerical models, especially of the fully developed frost-layer growth period. Tao et al. [1] also developed a mathematical model of the crystal-growth period. However, there has been a lack of research for both the early stage when the seeds are forming and the crystal growth period, and the processes are not clearly defined. Thus, there needs the quantitative definition of the early stage.

Much research has been carried out to delay frosting on heat exchangers using surface treatments. Jhee et al. [7] compared the frost density, residual water, and blocking ratio in a fin–tube heat exchanger. Kim and Lee [8–10] investigated the thermal performance of a treated-surface louvered-fin heat exchanger experimentally; they showed that the performance of a hydrophilic heat exchanger was enhanced under wet conditions, while that of a hydrophobic heat exchanger was improved under frosting conditions. Although many other researchers have investigated the thermal performance of heat exchangers with the treated fin surfaces [11–15], there is few report on the research regarding the early stage of frosting.

Here, we examined the frosting seed behavior of the early frosting stage under normal air-source heat-pump operating conditions. To understand this period, we defined the early stage of frosting, and investigated how different fin surface treatments delayed the frosting time in terms of the water contact angles between the surface and the water droplets. To quantitatively define the early stage, we proposed a new experimental method based on a luminance meter. Additionally, we investigated the effect of the refrigerant temperature on the frosting time as a function of the water contact angles.

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

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.04.042
0017-9310/

Nomenclature

I	light intensity [cd/m^2]
m_w	absolute humidity [kg/kg$_{DA}$]
N	normalized intensity in Eq. (1) [–]
t	time [min]
T	temperature [°C]
u	velocity [m/s]

Greek symbols

τ	dimensionless freezing time in Eq. (2)
θ	water contact angle [°]

Subscripts

a	air
bare	bare sample
delay	frost retardation
e	end time
I	intensity
in	inlet
max	maximum
r	refrigerant
s	starting time
0	initial time ($t = 0$)
②	second stage in Eq. (2)

2. Experiments

2.1. Experimental apparatus and sample preparation

Fig. 1 shows a schematic diagram of the experimental set-up used in the present study [16,17]. The apparatus consisted of a climate chamber to control the operating conditions, a recirculation section to connect the parts and recirculate the air, a refrigeration section to maintain the cold plate temperature, and a test section to perform the frosting experiments. A type T thermocouple and HTB 120 (Edge Tech) humidity sensor were installed to measure temperature and humidity. The refrigerant-side temperature was measured using a resistance thermometer (RTD) inserted in the refrigerant pipe. To circulate the air, a honeycomb, an air mixer fan of diameter 150 mm, and a screen were installed at the front of the test section. A solution of ethylene glycol and distilled water, mixed at a mass ratio of 1:1, was used as the refrigerant.

Fig. 2 shows the test section ($L \times W \times H = 500 \times 300 \times 300$ mm). The test section was made of transparent acrylic plastic to allow the observation of frosting behaviors with a high-resolution camera, which captured the frosting behavior upon cooling the plate (Fig. 2). The luminance meter was placed at the top of the test section to measure the exact time when the condensate water transformed to frost.

In this study, 10 samples were prepared to analyze the early stage of frosting at contact angles varying from bare (75°) to superhydrophobic (160°) surfaces. The aluminum samples (5×5 cm) were first cleaned with acetone and distilled water for 10 min, and then etched for 10 min in aqueous 1 M NaOH before etching with 3.7 wt% HCl. Finally, they were washed thoroughly with distilled water and dried at 180 °C for 2 h in a vacuum environment [18]. Fig. 3 shows six representative samples with various water contact angles; the highest angle was 160°. The water contact angle of each sample was measured by a drop shape analysis system (Phonix 300, SEO Co.) at ambient temperature using a 4-μL water droplet. The average water contact angle calculated at five different points on the sample was regarded as the water contact angle of the sample.

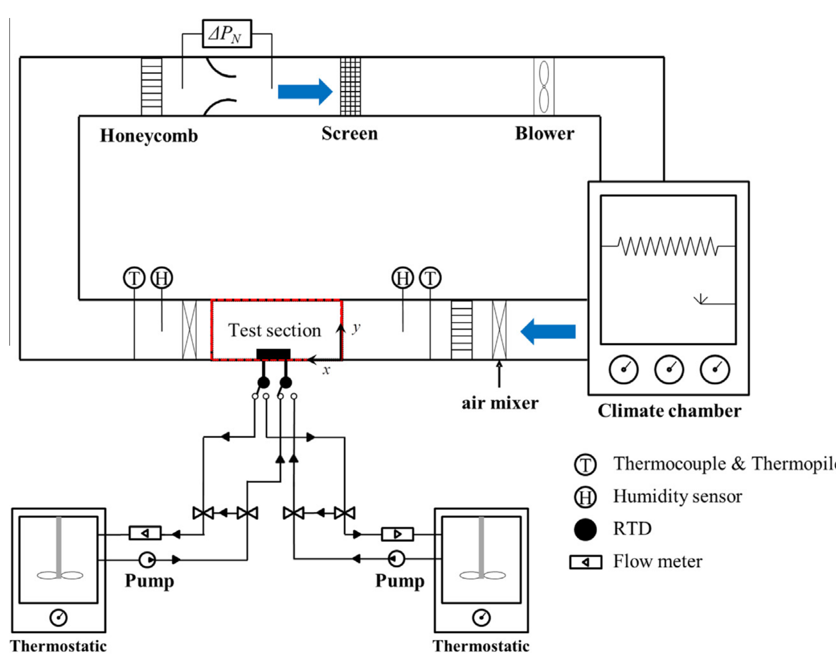

Fig. 1. Schematic layout of the experimental set-up.