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Research Paper

Experimental study of frost formation on cold surfaces with various fin layouts

Xiaomin Wu [a,*], Shan Hu [b], Fuqiang Chu [a]

[a] *Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Beijing Key Laboratory of CO_2 Utilization and Reduction Technology, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China*

[b] *Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China*

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ABSTRACT

Frost formation significantly increases the heat transfer resistance on heat exchangers and the flow resistance in the channels, so there is great interest in understanding the frost formation mechanism on a finned surface. Frost formation was experimentally investigated on several complex finned surfaces, including a single aligned fin, a single angled fin, a single row of aligned fins, a single column of angled fins and five columns of angled fins. The experimental conditions were –2 to 7 °C air temperatures, 80% air relative humidity, 0.3 to 1.1 m/s air velocities and –19 to –10 °C cold surface temperatures. The results show for all the investigated pieces, the frost weight per unit area in the fin region is greater than in the base region at a lower temperature, more frost was observed near the edges than in the middle of the fins, the fins angled with the airflow had more frost than the aligned fins and the multiple lines and columns of fins had the most frost on the frontal fins. A dimensionless empirical correlation for the frost weight in the fin area was developed with 85% of predictions within ±30% of the experimental data.

1. Introduction

When humid air flows over a cold surface, frost may form on the surface if the surface temperature is below the freezing point and the dew point of the humid air. In air conditioning systems, frosting on the evaporator surface would reduce the performance due to both the additional thermal resistance on the evaporator and the increased airside pressure drop, with some severe cases even resulting in system failure. Sanders [1] showed up to 35% cooling capacity reductions for an air conditioning system with frosting. Therefore, a comprehensive understanding of the frost mechanism and frosting patterns is necessary to improve heat exchanger performance.

Frosting has always been one of the most difficult problems in the refrigeration and cryogenic fields and has attracted a large number of researchers. Many researchers have focused on the simple geometries using experimental and numerical approaches, such as flat plates and cylinders, with empirical correlations developed for the frost thickness, density and thermal conductivity [2–5]. Yun et al. [2] experimentally studied frosting on a horizontal flat plate and developed a model for the frost layer growth, with the predicted frost layer thicknesses and thermal conductivities agreeing well with experimental data. Hermes and Piucco [3] investigated the frost layer thickness and density variations with time on a flat plate for different experimental conditions and compared the measurements with a theoretical model. Kim et al. [4] performed frosting experiments on a cylindrical surface and proposed dimensionless correlations for the frost layer thickness, density, surface temperature and heat transfer coefficient. Sengupta et al. [5] also performed similar frosting experiments on a cylindrical surface with empirical correlations presented for the frost layer thickness and heat transfer coefficient variations with time. However, all of these used only simple geometries like flat or cylindrical surfaces, with few empirical correlations for the frost weight.

Other researchers have concentrated on direct experimental studies of entire heat exchangers to analyze the effects of the fin type and arrangement on the frost formation and thus the heat exchanger characteristics [6–10]. Seker et al. [6] compared experimental data for the airside pressure drop and the overall heat transfer coefficient with an analytical model of a finned-tube heat exchanger. Kondepudi and O'Neal [7] experimentally studied louvered finned tube heat exchangers and estimated the frost accumulation using the air flow velocity and the difference in the measured absolute humidity before and after the test coil. Kondepudi et al. [8] also experimentally studied the effects of flat, wavy, and louvered fin configurations on the performance of finned-tube heat exchangers in the presence of frost. Xia et al. [9] experimentally investigated the effects of a louvered fin heat exchanger of the frost, defrost, and refrost processes and their impact on the air-side thermal-hydraulic performance. Silva and Hermes [10] carried out tests on three wavy

* Corresponding author. Tel.: +86 10 6277 0558; fax: +86 10 6277 0558.
E-mail address: wuxiaomin@mail.tsinghua.edu.cn (X.M. Wu).

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fin and one louvered fin evaporators to observe the frosting morphology and summarized the frost weight variations with time and super-cooling degree. Those studies mostly studied heat exchangers but ignored the effects of the detailed fin layout and orientation.

Only a few studies have used fins or fin bundles for experimental investigations. Koyama et al. [11] experimentally studied frosting on a rectangular staggered fin bundle and measured the frost weight, pressure drop and sensible and latent heat flux variations with time. Kim et al. [12] measured the local temperature distribution and the frost thickness on a two-dimensional fin surface parallel and perpendicular to the air flow for various conditions and proposed several empirical correlations. Most of these studies have simply used enlarged fin structures.

Thus, most frosting studies have focused on either simple geometries such as flat plates or entire heat exchangers. Only a few studies have focused on surfaces with fins that complicate the frosting pattern and the key aspects of finned surfaces like the fin layouts. The frosting experimental studies have mostly been conducted at room temperature and rarely at lower temperatures. However, in real frosting process, such as in refrigeration systems and heat pumps in the winter, the air temperature is always below room temperature. The ISO Standard 5151 points out that the standard test environment temperature for heat pump evaporators in the winter should be 0 °C (for 50% load) [13]. Therefore, the present study uses surfaces with louvered fins as the study subject to investigate frosting, especially in winter conditions, focusing on the factors influencing the frost weight and the effect of the morphology of the fin layout, the fin orientation, the entrance effect and the experimental conditions with comparisons of the frost formation in the fin region and the base region. The data are used to create a dimensionless correlation for the frost weight on complex finned geometries.

2. Experimental apparatus and test conditions

2.1. Experimental system

Fig. 1 shows the experimental apparatus, including the humid air supply and regulating system, the semiconductor thermoelectric cooler system and the data acquisition system. The humid air supply and regulating system consisted of a humidifier, a voltage regulator, an air fan, a heat exchanger, a low temperature circulating pump, a rectification section and Plexiglas channels. The inlet humid air temperature was regulated by the low temperature circulating pump with the humidity controlled by the humidifier and the voltage regulator. The air velocity was set by the flow control valve in the air fan and the bypass in the Plexiglas channel. The test section was $50 \times 50 \times 16$ ($L \times W \times H$) mm with removable connections to the other parts of the channel for easy cleaning and change.

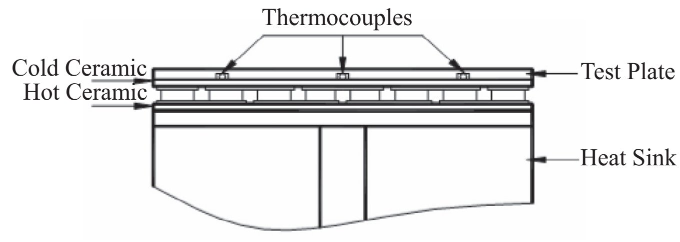

Fig. 2. Test section layout.

The semiconductor thermoelectric cooler system is shown in Fig. 2. The thermoelectric cooler cooled the frosting surface; it is a small heat pump which operates on direct current and can be used for either cooling or heating by reversing the current flow direction [14]. The cold side of the thermoelectric cooler was horizontal and attached to a 1 mm thick, 50 mm square aluminum test plate with fins. The hot side of the thermoelectric cooler was mounted on a heat sink with thermal grease. A Plexiglas duct allowed cooling water to flow through the heat sink to remove heat from the hot side of the thermoelectric cooler.

The data acquisition system included an image acquisition system and an electrical signal acquisition system. The image acquisition had a zoom stereo microscope (OLYMPUS B061) equipped with a CCD camera (OLYMPUS DP25), a single lens reflex camera (Canon EOS5D with EF 24–105 mm lens) and a digital camera (Canon IXUS 80IS) which are set on the left side, the back and the top of the test section to observe the fin frosting process. The signal acquisition system consisted of several thermocouples to measure the cold surface temperature, a temperature and humidity sensor for the inlet humid air temperature and relative humidity, an anemoscope to measure the air velocity and an electronic balance to measure the frost weight. The cold surface temperature, T_w, was the average of three T-type thermocouples buried in grooves on the backside of the plate, which are all calibrated by a standard thermometer with an accuracy of ±0.1 °C. The inlet air temperature, T_a, and the relative humidity, *RH*, were measured using a temperature and humidity sensor (Model HF532) with accuracies of ±0.1 °C and ±0.8%. The inlet humid air velocity, u_a, was measured using a hot bulb anemoscope with an accuracy of ±0.05 m/s. The frost weight was measured using a group of cotton to collect the melted frost for weighting on the electronic balance (1 mg/100 g) [15]. The data acquisition procedure was to zero the electronic balance with the cotton before the experiment; to use the cotton to blot up the frost on the cold surface right after melting at each frosting time interval and immediately weighing the wet cotton on the electronic balance to get the frost weight for each frosting time interval. Repeated tests gave an average

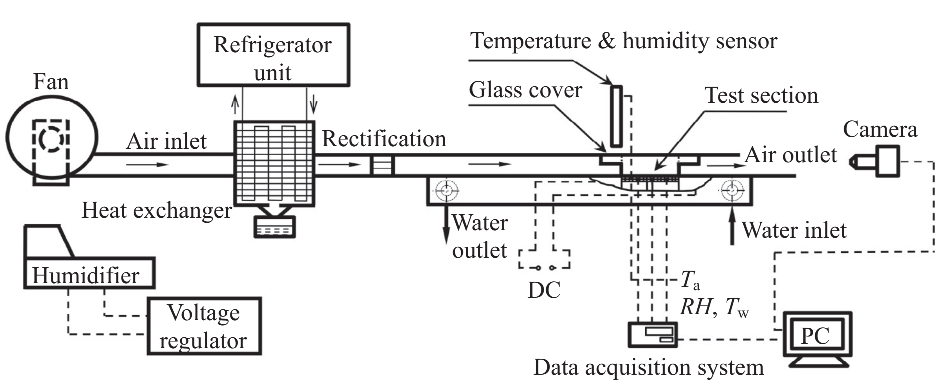

Fig. 1. Schematic diagram of the experimental apparatus.