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An experimental study on the effects of frosting conditions on frost distribution and growth on finned tube heat exchangers

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ABSTRACT

Recently, the authors have published a paper which provided the frost distribution and growth along the airflow direction of finned tube heat exchangers (FTHXs), and demonstrated that some frost was accumulated on the edge of windward fins at a given frosting condition. As a follow-up to the work reported in the previous paper, in the current paper, the effects of frosting conditions on frost distribution and growth characteristics of FTHXs with different fin pitches were experimentally investigated. The results showed that the protruded thickness of frost on the edge of windward fins and the ratio of the frost mass on the edge of windward fins to that on the entire FTHX were both increased with the increases in air temperature (T_a) and relative humidity (RH_a), but decreased with an increase in initial air face velocity (v_a). In addition, the effects of RH_a on the mass ratio were more significant than those of T_a and v_a. Furthermore, the averaged frost density on the edge of windward fins was increased with an increase in RH_a; and that on the surfaces of fins and tubes was increased with an increase in v_a, but decreased with an increase in RH_a.

1. Introduction

Finned tube heat exchangers (FTHXs) are commonly used as evaporators in air source heat pump (ASHP) units. However, when the evaporating temperature in an ASHP unit is lower than 0 °C and the dew-point temperature of the inlet air, frost may appear on the surfaces of the evaporator, which can significantly decrease its air side performances, hence the efficiency of the ASHP unit [1,2]. To mitigate the negative impacts of frosting on the operation of ASHP units, it is necessary to better understand the frosting mechanism and characteristics on FTHXs, which have been extensively investigated using experimental and numerical approaches. The details of related previous studies including research method, fin type, fin pitch, cold source type, cold source temperature, air velocity, air relative humidity, and air temperature are given in Table 1.

As seen, the majority of the related studies focused on the air side performances and frost growth of FTHXs under various frosting conditions. For example, in 1988, Kondepudi [3] experimentally and numerically investigated the effects of frost growth on the air side performances of FTHXs with five types of fins under laminar air flow conditions. It was shown that air humidity impacted more significantly on the air side performances than air temperature, velocity and fin pitch. Wang et al. [4] carried out an experimental study on frosting performances of FTHXs with surface treatment. The results showed that surface treatment significantly impacted the frosting rate and hence the air side performances of the FTHXs. Compared to an FTHX without any surface treatment, an FTHX with superhydrophobic surface treatment can reduce the frost thickness and mass by 17.1% and 28.8%, respectively. In addition, the FTHX with superhydrophobic surface treatment had the lowest air side pressure drop and highest heat transfer rate in comparison with the FTHXs with bare and hydrophilic surface treatment under the same frosting condition.

On the other hand, there were much fewer studies focusing on the frost distribution on FTHXs. Generally, these studies can be divided into two groups. One studied frost distribution on the windward side along refrigerant flow direction or among different circuits of an FTHX. Padhmanabhan et al. [5] developed a mathematical model to predict uneven frost growth on the windward side of an FTHX based on air redistribution which was caused by uneven frosting. The numerical results showed that the use of the model with air redistribution can increase the prediction accuracy of frost thickness and air side performances by 20–50% and 42%, respectively, in comparison with using a model without air redistribution. Song et al. [6,7] defined a frosting evenness value (FEV) as the ratio of the minimum mass of frost accumulated on

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Nomenclature

ASHP	air source heat pump
COP	coefficient of performance
EEV	electronic expansion valve
FEV	frosting evenness value
FTHX	finned tube heat exchanger
LFT	leeward fins along the height or outside diameter of six tubes
LFR	leeward fins remained except LFT
M	mass [kg]
RH	relative humidity [%]
T	temperature [K]
t	frosting time [s]
v	initial face velocity [m/s]
δ	thickness [m]
$\delta_{f,pe}$	protruded thickness of frost on the edge of windward fins [m]
$\delta_{f,ee}$	expanded thickness of frost on the edge of windward fins [m]
ρ	density [kg/m^3]

Subscripts

a	air
e	evaporating
f	frost
f,s	frost accumulated on the surfaces of fins and tubes
f,l	frost accumulated at the exit from LFR
f,e	frost accumulated on the edge of windward fins
f,w	frost accumulated at the entrance to windward fins

the surface area of a circuit to the maximum one among a total of three circuits. The experimental results demonstrated that the system COP could be increased from 4.10 to 4.26 when FEV was increased from 75.7 to 90.5% for an ASHP with a three-circuit outdoor coil during a 60-min frosting period. In addition, the defrosting duration could also be shortened by 11.2% and defrosting efficiency increased by 5.7% as FEV was increased from 79.4% to 96.6%.

The other group studied frost distribution between the windward and leeward sides along the airflow direction of an FTHX. A number of related studies in this group have suggested that there was a significant difference on the frost distribution between the two sides according to their experimental observations, without actually providing any data on the observed difference [5,8–11]. In 2004, Yao et al. [12] developed a mathematical model to predicate frost growth on an FTHX with four tube rows. The numerical results showed that the frosting rate was decreased from the first tube row (the closest to windward side) to the last tube row, and the percentage of frost mass on the last row was less than 3.7%, but that on the first row more than 39.5% of the total frost mass on the FTHX. Kim et al. [13] studied the effects of refrigerant flow direction and surface treatment on the local frosting behavior for an FTHX. The results provided pictures of windward and leeward sides of the frosted FTHX, and they believed that the difference on frost distribution between windward and leeward sides was mainly caused by the leading edge effect. Particularly, they demonstrated that the difference was more significant when the refrigerant temperature was lower. Thereafter, Kim and Lee [14] and Kim et al. [15] carried out similar experimental studies on surface-treated louvered-fin heat exchangers and microchannel heat exchangers, respectively. They also presented pictures of windward and leeward sides of frosted FTHXs, showing significant difference on frost distribution between the windward and leeward sides. However, all the three experimental studies [13–15] did not present quantitative analysis on the difference.

It can be seen that, therefore, quantitative studies focusing on the frost distribution between the windward and leeward sides along the airflow direction of an FTHX are still inadequate, except a previous study to quantitatively and qualitatively investigate the frost distribution and growth on FTHXs experimentally [16]. The previous study not only provided the frost distribution characteristics along the airflow direction of FTHXs, but also demonstrated that some frost was accumulated on the edge of windward fins, accounting for more than 10% of the total frost mass accumulated on the entire FTHXs. However, the results of the study were only obtained at a fixed frosting condition. Considering that the frost growth on an FTHX was a very complicated heat and mass transfer process, the effects of frosting conditions on frost growth on a simple surface were different from those on an FTHX. Besides, there were no published studies that could quantitatively reveal the law of the changes in the frost distribution and growth characteristics along the air flow direction for an FTHX under various frosting conditions, since most of the published studies did not distinguish the frost on the edge of windward fins from that on the surfaces of fins and tubes, and did not consider the difference in frost thickness between windward and leeward sides. To get a better understanding of frosting mechanism and characteristics on an FTHX, as a follow-up to the previous study [16], an experimental study to quantitatively investigate the frost distribution and growth on FTHXs with different fin pitches under various frosting conditions was carried out, and the study results are reported in this paper. Firstly, a brief description of the experimental setup, procedures, conditions and data reductions is reported. Then the experimental results and related discussions are presented. Finally, conclusions are given. The experimental results can help design efficient defrosting or frosting suppression strategies for units where FTHXs are used for evaporators, such as refrigeration and ASHP units.

2. Experimentations

2.1. Experimental setup

Fig. 1 shows the schematics of the experimental setup which comprised three parts: an environmental chamber, a wind box and a refrigerant supply system. To achieve a uniform surface temperature distribution along the tube, direct expansion FTHXs were used and R410A as the refrigerant. The specifications of the experimental setup are shown in Table 2. Fig. 2 shows the schematics of a visualization system, which can help quantitatively and qualitatively analyze the frost distribution and growth on an experimental FTHX by photographing its frosted surfaces at an interval of 5 min. To facilitate data analysis, as seen from Fig. 2, an experimental FTHX was divided into three parts: windward fins, leeward fins and tubes. Furthermore, leeward fins were further divided into those along the height of six tubes (LFT) and those except LFT (LFR). In addition, as demonstrated in the previous related study [16], the frost on the entire FTHX can be divided into that on the edge of windward fins and that on the surfaces of fins and tubes. Fig. 3 shows the detailed frost distribution on an FTHX. In this study, two flat-fin heat exchangers were selected as the experimental FTHXs (FTHX 1 with fin pitch of 2 mm and FTHX 2 with