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Frosting behaviors and thermal performance of louvered fins with unequal louver pitch

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ABSTRACT

We created heat exchanger louvered fin designs in which the louver pitch successively increased or decreased by 20% from the air inlet region to the redirection region. The frost behavior and thermal performance of the unequal louver pitch design were compared with those of an equal louver pitch design, under both dry and frost conditions. When unequal louver pitch design was used, frost blocking of the spaces between louvers at the front side was delayed and the thermal performance was improved by 21%, compared with the equal louver pitch design. The frost blocking ratios of the two unequal louver pitch designs were compared; the design in which the louver pitch successively decreased from the air inlet region to the redirection region provided more uniform frost growth and improved thermal performance, compared to the design in which the louver pitch successively increased.

1. Introduction

Louvered fin heat exchangers, commonly used in heat pumps and automotive air conditioning systems, develop thin boundary layers owing to interruptive surfaces that break up and reform the boundary layers [1]. Louvered fin heat exchangers generally outperform flat-fin heat exchangers in dry conditions. However, when a louvered fin heat exchanger operates under frost-forming conditions, compared to a flat-fin heat exchanger [2–5], the spaces between the louvers can quickly become blocked by frost, and then the thermal performance of the louvered fin heat exchanger will decrease sharply, induced by a sharp drop in the air pressure due to the blockage. When the spaces between louvers at the front side of a louvered fin become blocked by frost, the louvered rear side of the fin becomes ineffective, even though the space between louvers at the rear side of the fin may not be totally blocked [1]. Thus, developing a new design is required for the louvered fin that can provide similar thermal performance with conventional louvered fin heat exchangers under dry conditions, while also slowing down frost blockage of the space between louvers.

Frost formation on louvered fin heat exchangers has been investigated in numerous studies. Kim et al. [6–8] examined the thermal performance of louvered fin heat exchangers and frost growth uniformity for various surface treatments and heat exchanger geometries. They reported that in frosting conditions, the thermal performance of a louvered fin heat exchanger with a hydrophobic surface treatment was better than that of a louvered fin heat exchanger with a hydrophilic surface treatment. Additionally, frost growth uniformity was improved at both the front and rear sides of the heat exchanger with decreasing depth of the heat exchanger, decreasing channel pitch, and increasing fin pitch. Xu et al. [9] analyzed the thermal performance and condensate retention of vertical- and horizontal-tube microchannel heat exchangers. They showed that the capacity and air pressure drop of the vertical tube heat exchanger varied little from its initial value during a cycle, with little water retention; however, the capacity of the horizontal-tube heat exchanger decreased by 27% relative to its initial value. Moallem et al. [10–13] studied the thermal performance of louvered fin heat exchangers in response to the variables of surface treatment, louvered fin heat exchanger geometry, and refrigerant temperature, and proposed empirical correlations for the frost thickness and air-face velocity degradation in microchannel heat exchangers. Hsieh and Jang [14] used a three-dimensional numerical analysis method to evaluate a louvered fin with variable louver angle under dry conditions; the louver angle was varied by ±2° or ±4°. They reported that the +4° variation in the louver angle was the maximum area reduction. Park et al. [1] investigated the frost behavior and thermal performance of louvered fin heat exchangers by using a scaled-up model. This study reported that the spaces between louvers in the redirection region were the first to become blocked by frost formation, followed by blockage at the

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Nomenclature

f	friction factor
j	Colburn factor
JF	JF factor
m	mass (kg)
Q	heat transfer rate (W)
RH	relative humidity at air side (%)
Δp	pressure drop (Pa)
t	time (min)
T	temperature (°C)
u	velocity (m/s)
w	absolute humidity (g/kg$_{DA}$)

Subscript

a	air
DA	dry air
fs	fin surface
i	inlet
out	outlet
r	refrigerant

air inlet region. The analysis showed that frost blockage of the spaces between louvers at the front side of the heat exchanger significantly reduced the thermal performance of louvered fin heat exchangers.

All of these studies considered louvered fins with equal louver pitch; frost growth uniformity and blockage of the louvers were not focused on in their studies. In this study, we analyzed the frost behavior and thermal performance of a louvered fin with unequal louver pitch. We created a louvered fin with successively increased or decreased louver pitch by 20% from the air inlet region to the redirection region. Experiments using the proposed louvered fin design were conducted to evaluate the delay time for frost formation between louvers. Then we compared the thermal performance of the variable-louver-pitch heat exchanger with that of a conventional louvered fin heat exchanger with equal louver pitch.

2. Experiments

In this study, experiments were conducted using a scaled-up model. The experimental set up [15], method, conditions and scaled-up model were the same as those cited by Park et al. [1]. The louvered fins proposed in this study were manufactured such that the louvers at front- and rear-side were symmetry with respect to the redirection region, following the symmetric design of conventional louvered fins. Each louvered fin heat exchanger was assembled by stacking ten louvered fins. Fig. 1 shows configuration and geometries of louvered fins with equal and unequal louver pitch. Two types of unequal louver pitch were tested: in Type 1, the interval successively decreased by 20% from air inlet region to the redirection region (Fig. 1b) and in Type 2, it successively increased by 20% (Fig. 1c).

Louvered flow has a remarkable influence on the thermal performance and operation time of louvered fin heat exchangers [1]. Conventional louvered fins use equal louver pitch. However, in the equal louver pitch configuration, the spaces between louvers in the redirection region are first blocked by frost formation due to high mass transfer rate, which limits the louvered flow [1]; thus, the redirection region has been identified as a weak region for frosting in the louvered flow (Fig. 2). In contrast, the air inlet region in the equal louver pitch configuration is considered to be a strong region for frosting, because the spaces between the louvers in this region are blocked by frost last. In this study, we created a louvered fin with an unequal louver pitch; this design was inspired by the principles of asymmetry and continuity of useful action in the theory of inventive problem solving [16]. The two types of louvered fins with unequal louver pitch defined above were constructed to highlight the strong point and complement the weak point in louvered flow.

3. Results and discussion

3.1. JF factor of a louvered fin with unequal louver pitch under dry conditions

Unequal louver pitch provides comparable thermal performance to that of conventional louvered fin heat exchangers under dry conditions. Fig. 3 shows the Colburn factor j and the friction factor f for fins of various Reynolds numbers and pitch types. As shown in the Fig. 3, the j and f factors of the louvered fin with equal louver pitch were respectively 6.3% and 5.4% higher on average than that with an unequal louver pitch. The JF factor proposed by Yun and Lee [17] was used to compare the thermal performance of a louvered fin with equal louver pitch to that with unequal louver pitch:

$$JF = \frac{(j/j_{ref})}{(f/f_{ref})^{1/3}} \quad (1)$$

where j_{ref} and f_{ref} respectively correspond to the j and f factors of the louvered fin with equal louver pitch. The calculated JF factor had an average value of 0.96. Therefore, the difference between the thermal performance of louvered fins with equal and unequal louver pitch was negligible with respect to operation under dry conditions.

3.2. Comparison of the thermal performance of louvered fins with equal and unequal louver pitch under frosting conditions

Fig. 4 shows the heat transfer rate as a function of time, according to the type of louvered fin, under base condition (T_a = 5.5 °C, u_a = 0.95 m/s, RH = 72%, and T_r = −20 °C). The extent of the decrease over time in the heat transfer rate of the louvered fin heat exchanger with unequal louver pitch was smaller than that with equal louver pitch. The heat transfer rate of the louvered fin heat exchanger with equal louver pitch became same as that of a flat fin heat exchanger at 160 min in operating time, while that of the louvered fin with unequal louver pitch became identical to that of a flat fin heat exchanger at 200 min for Type 1 and at 180 min for Type 2. Here we defined the time difference between the louvered fin heat exchanger with equal louver pitch and with unequal louver pitch as delay time. The delay time for Type 1 and Type 2 was 40 min and 20 min under base condition, respectively. During the delaying time, total heat transfer of louvered fin with unequal louver pitch increased at least 21% than that with equal louver pitch, given the experimental conditions used in this study [1].

To better understand the differences in the fin designs, the spaces between louvers were photographed after 160 min of operation to evaluate frost formation (Fig. 5). The blocking ratio, defined as the degree of blockage in the flow area due to the frost