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Frost behavior of a louvered fin heat exchanger with vortex-generating fins

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ABSTRACT

A heat exchanger with vortex-generating fins at the center of each louver was manufactured. Through 3D computational analysis, we analyzed the air flow characteristics and the fin temperature in the heat exchanger under dry conditions. In addition, we conducted an experiment for observing frost behavior and variation in thermal performance of the louvered fin heat exchanger. The fins generated vortexes and increased the length of air flow, which improved the dry condition thermal performance by 12%. The vortex-generating fins reduced the blockage ratio of frost at the louvers of the head part and improved the frost uniformity of the front and rear sides of the heat exchanger, increasing the usability of the rear louver. Therefore, the decrease in the heat transfer rate of the heat exchanger with vortex-generating fins over time by frost formation was smaller than that of the conventional heat exchanger, and the heat transfer performance was improved by at least 28%.

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1. Introduction

Louvered fin heat exchangers are used in many fields, for instance, heat pump systems and automotive air conditioners. Their thermal performance is superior to the conventional heat exchanger's performance because the boundary layers repeatedly grow and disappear. However, when the surface temperature of the heat exchanger is lower than a freezing point during heating operation the heat exchanger suffers from the frost formation on its surface [1]. Frost growth not only increases the heat resistance inside the heat exchanger, but also blocks the gaps in the louvers and decreases the air flow rate in the heat exchanger, thereby considerably decreasing its performance [2,3].

To solve these problems arising from the development of frost in heat exchangers, a number of researchers have proposed various heat exchanger shapes and methods to enhance their thermal performance. Park et al. [2,3] manufactured a heat exchanger with a non-uniform louver pitch based on a scaled-up model, and then investigated its frost growth uniformity and temperature variation. They reported that the frost growth between the louvers was delayed, thus improving its performance compared to conventional heat exchangers. Xu et al. [4,5] compared the thermal performance of heat exchangers in which the tube directions were either vertical or horizontal with respect to the ground. They reported that the drainage performance of the heat exchanger with vertical tubes was superior to that with horizontal tubes, improving the thermal performance of the former. Moallem et al. [6–8] investigated the variation of temperature of the louvered fin heat exchanger per shape, its surface treatment, and the temperature of the cold surface. Kim et al. [9] fabricated a heat exchanger with a removed louver at the front side, and investigated its drainage performance and improved thermal performance. Although these works have contributed to improvements in thermal performance, further study is needed regarding the methods of delaying frost formation that blocks the spaces between louvers, which adversely affects the thermal efficiency of the heat exchanger.

Recently, vortex generators have been added to heat exchangers to enhance their thermal performance by changing air flow. Many studies have been conducted on such heat exchangers in terms of the shape, arrangement, and attack angle of vortex generators under dry conditions [10–13]. In the heat exchanger, delta wing type vortices generating fins have been installed on the louvered-fin side area to study the change in air flow and thermal performance according to the attack angle [14–16]. However, such studies have been conducted only under dry conditions; therefore, they were unable to predict the effect of vortex generators when frost is formed on the fin surface of a louvered fin heat exchanger.

We studied the heat transfer performance of a heat exchanger and the frost behavior including vortex-generating fins (vortex

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Nomenclature

BR	blockage ratio
f	friction factor
j	Colburn factor
JF	JF factor
L	louvered fin length [m]
L_p	louvered pitch [m]
m	mass [kg]
$\dot{Q}$	heat transfer rate [W]
Re	Reynolds number
RH	relative humidity [%]
t	time [min]
T	temperature [°C]
u	velocity [m/s]
w	absolute humidity [g/kg$_{DA}$]
x	length [m]

Greek symbols

θ	nondimensional temperature

Subscripts

a	air
err	error
f	fin
in	inlet
r	refrigerant
exp	experiment
sim	simulation

generators) at the middle of each louver fin surface. We manufactured the louvered fins including the vortex generators and conducted experiments under dry and frosting conditions. Moreover, we investigated the air flow characteristics and the variations in fin temperature using 3D computational analysis. We analyzed the frost formation delay and thermal performance characteristics by comparing a louvered fin heat exchanger equipped with vortex generating fins to a conventional louvered fin heat exchanger.

2. Experiments

The present experiments were conducted, following the method described in the works of Park et al. [2,3]. For the observation of frost behavior, we used a 10-times scaled-up model; the louvered fins including the vortex generators are shown in Fig. 1. Each fin-shaped vortex generator with a width of 0.8 mm, a height of 1.3 mm, and a length of 12 mm was located 1.3 mm from the midpoint of the louver. The vortex generators were welded to the louvers to minimize contact thermal resistance and to secure durability. A total of 32 vortex generators were installed on each louvered fin, and there were 320 vortex generators on the louvered fin heat exchanger of 10 louvered fins.

3. Analytical model

In this study, we conducted a 3D computational analysis to study the effect of the vortex generators upon the air flow characteristics and the fin temperature. As shown in Fig. 2, the inlet and outlet regions were 30 times longer than the louver pitch, considering the convergence of the air field, since the most influential parameter is the louver pitch [17,18]. The upper and lower boundary conditions were periodic.

This numerical analysis was based on the following assumptions:

(1) The flow is 3D and turbulent.
(2) Air is the working fluid with constant properties.
(3) Radiation heat transfer and natural convection are neglected.

Because the size of the louvered fin was small and the Reynolds number was rather high, a realizable k–ε model of the turbulence model was selected to investigate the air flow characteristics and the fin temperature, as in previous studies [17–19]. To verify the validity of the selected turbulence model, the analysis results were compared with the experimental results under dry conditions (T_a = 20 °C, T_r = 4.5 °C, 1000 < Re_{Lp} < 5000) using the heat exchanger with vortex generating fins; this comparison was carried out using the j and f factors. Table 1 lists the mean errors in terms of Reynolds number for the analytical models.

$$j_{err} = \frac{|j_{\exp} - j_{\sim}|}{j_{\exp}} \times 100\ (\%)$$
$$f_{err} = \frac{|f_{\exp} - f_{\sim}|}{f_{\exp}} \times 100\ (\%) \quad (1)$$

where j_{err} and f_{err} are the mean errors of the j and f factors of the analytical results in terms of Reynolds number respectively.

As described in the table, the mean errors of factors j and f of the realizable k–ε model were 5.8% and 9.7%, respectively; these were the lowest errors among all the turbulence models we investigated, confirming that the results from the selected model were reasonable.

The results of the 3D steady and unsteady state analyses were compared with the experimental results regarding the flow vibrations inside the louvered fin heat exchanger. As listed in Table 1, there was almost no difference between the errors of the steady and unsteady state analyses. Therefore, we conducted a 3D computational analysis using a 3D steady-state model (realizable k–ε model).

4. Results and discussion

4.1. The air flow characteristics of the louvered fin heat exchanger with vortex generators under dry conditions

To compare the thermal performance of the louvered fin heat exchanger with and without vortex generators under dry conditions, the factors j and f were calculated for both conditions using experimental results. The values of the factors j and f were 15% and 8%, respectively, being higher for the exchanger including the vortex generators (Fig. 3). To compare the thermal performance, we used the JF factor proposed by Yun and Lee [20].

$$JF = \frac{(j/j_{ref})}{(f/f_{ref})^{1/3}} \quad (2)$$

Here, j_{ref} and f_{ref} are the j and f factors of the conventional louvered fin heat exchanger (without vortex generators), respectively. The JF factor as a function of the Reynolds number was calculated to be 1.12, and the performance of the temperature distribution of

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