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Heat Transfer and Pressure Drop Characteristics of Cross Stair Slit Fin

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ABSTRACT

The new type of slit fin "Cross Stair Slit Fin" for the outdoor fin-tube heat exchanger has been developed to enhance heat transfer on dry and wet surface condition and restrain heat transfer performance degradation on frost surface condition. The shape of cross stair slit fin was optimized using relationships between air side heat transfer and pressure drop by CFD. The air side heat transfer and pressure drop of 3 different fin shapes (ring, conventional slit, cross stair slit) were measured on dry, wet and frost surface condition. The air side heat transfer of cross stair slit fin on dry and wet surface condition was 10% larger than ring fin and 10% smaller than conventional slit fin. Also, heat transfer performance of cross stair slit fin on frost surface condition was the same as ring fin, and 40% larger than conventional slit fin.

1. INTRODUCTION

The slit fin has been studied in order to improve the performance of fin-and-tube heat exchanger for air conditioners. However, in case of the outdoor fin-tube heat exchanger, frost grows on the slit. Therefore air side pressure drop increases compared with flat fin without slit on the frost condition. And the heat transfer performance of slit fin is decreased as air flow rate decreases.

In this study, new type of slit fin "Cross Stair Slit Fin" has been developed to enhance heat transfer on dry and wet surface condition and prevent heat transfer performance degradation on frost condition. The shape parameters of cross stair slit fin which influences on air side heat transfer and pressure drop were optimized by CFD. The air side heat transfer and pressure drop of 3 different fin shapes (ring, conventional slit, cross stair slit) were measured on dry, wet and frost surface.

2. CONCEPT AND PERFORMANCE OF CROSS STAIR SLIT FIN

2.1 Concept of Cross Stair Slit Fin

The concept of cross stair slit fin is increasing heat transfer on dry and wet surface condition and preventing heat transfer performance degradation on frost condition. If the slits are blocked by the frost growth, the bypass air flow rate can be kept to restrain the increase of pressure drop. Figure 1 shows the shape of cross stair slit fin. The slit1 is divided into two parts and slit2 of the fin center is formed like 'crossing'. And the height of slit1 H1 is lower than the height of slit2 H2 like a 'stair'. Therefore the frost is decentralized, and bypass air flow rate is kept. In addition, the decrease of heat transfer performance on frost condition can be prevented. On dry and wet condition the heat transfer increases by dividing the boundary layer, because air passes through the slit.

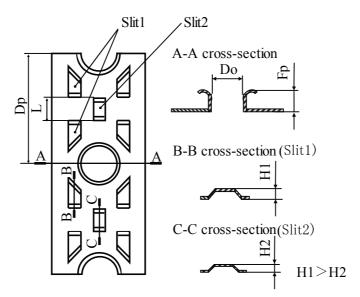


Figure 1: Cross stair slit pattern

2.2 Numerical Analysis Evaluation

2.2.1 Analysis condition

A representative parameter of cross stair slit fin is the width between two slit1 L. L is equal to the length of slit2. L divided by step pitch Dp is L/Dp. Divided width ratio L/Dp is the dominant parameter to the slit performance. By using CFD (FLUENT), the influence of L/Dp on the air side heat transfer coefficient α_o and air side pressure drop $\triangle P$ were calculated.

Figure 2 shows the boundary condition of numerical analysis. An analysis model is three-dimensional non-steady flow. The flow field is laminar. The pressure solution is SIMPLE method, and 1st-order implicit method is used for convective and diffusion term. The inlet boundary condition of the air is 1 m/s, 293 K (20°C). The outlet boundary condition is free flow, the fin surface is the wall boundary condition, and temperature conditions of the fin collar is 323 K (50°C). The periodic boundary condition is used for the other surface of the analysis area.

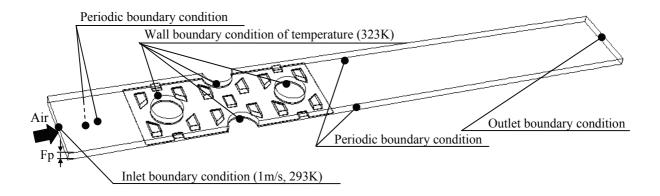


Figure 2: Boundary condition

2.2.2 Analysis result

Figure 3 shows the relationship between L/Dp and the air side heat transfer coefficient α_0 . Figure 4 shows the relationship between L/Dp and air side pressure drop $\triangle P$. As L/Dp increases, both the air side heat transfer

coefficient α_0 and pressure drop $\triangle P$ increase.

The relationship between the heat transfer coefficient α_o and the pressure drop $\triangle P$ were evaluated in terms of the coefficient of performance (COP) of the heat pump unit. The increase of the heat transfer of the fin means the increase of COP by the decrease of the input power of the compressor, and the increase of the air side pressure drop means the decrease of COP by the increase of the input power of the fan. So $\alpha_o/\triangle P$ was defined as the performance index of the heat exchanger from the relationship between the input power of the fan and the compressor. Figure 4 shows the influence of the L/Dp on $\alpha_o/\triangle P$. When L/Dp is 0.2, $\alpha_o/\triangle P$ showed the maximum value.

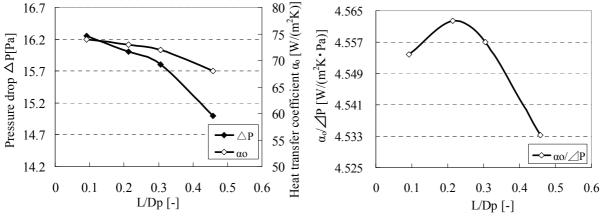


Figure 3: Influence of L/Dp on α_o and $\triangle P$

Figure 4: Influence of L/Dp on $\alpha_o/\triangle P$

3. EXPERIMENTAL APPARATUS AND METHOD

The prototype of heat exchanger with cross stair slit pattern picked out by CFD was produced. And, 2 different fin shapes (ring, conventional slit) were produced to compare with the cross stair slit. The air side heat transfer and pressure drop of 3 different fin shapes (ring, conventional slit, cross stair slit) were measured on the condition of dry, wet and frost surface. Experimental apparatus, test heat exchangers and experimental method are explained below.

3.1 Experimental Apparatus

Figure 6 shows the schematic view of experimental apparatus. Test heat exchangers are put into the wind tunnel, and the wind tunnel is in the constant temperature and humidity room. The wind tunnel is square shape with cross section area 300×300 mm. Along the air flow, the honeycomb, the thermocouple grid, the dew point meter, pressure taps, a test heat exchanger (Figure 5), and the fan are installed in the wind tunnel.

The fluid flowing in the test heat exchanger pipe is water or brine. The temperature of the fluid is measured by the sheathed resistance thermometer (Pt100, ClassA). The mass flow rate of the fluid is measured by the coriolis mass flow meter (Accuracy: $\pm 0.2\%$, R.D.).

The airside temperature is measured by the thermocouple grid (Accuracy: $\pm 0.1^{\circ}$ C). The dew-point temperature is measured by the mirror surface cooling type dew-point meter (Accuracy: ± 0.2 C). The air flow rate is measured by the ultrasonic volume flow meter (Accuracy: $\pm 0.03\%$, F.S.). The pressure drop is measured by the differential-pressure meter (Accuracy: ± 0.1 Pa)

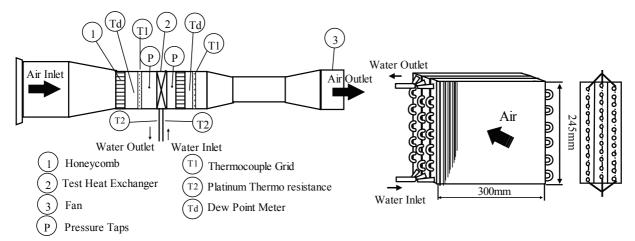


Figure 5: Experimental apparatus

Figure 6: Test heat exchanger

3.2 Test Heat Exchanger

Table 1 shows specifications of test heat exchangers. The specifications of fin patterns are ring, conventional slit and cross stair slit. The specification of ring fin is that tube diameter is ϕ 7.94mm, step pitch is 20.4mm, row pitch is 17.7mm, number of row is 3, fin pitch is 1.6mm, fin thickness is 0.09mm, and surface treatment is bare (no-hydrophilic coated). The specification of conventional slit fin and cross stair slit fin are that tube diameter is ϕ 7.94mm, step pitch is 20.4mm, row pitch is 17.7mm, number of row is 3, fin pitch is 1.8mm, fin thickness is 0.09mm, and surface treatment is bare (no –hydrophilic coated).

Table 1: Specifications of test heat exchangers

Fin pattern	Ring	Conventional slit	Cross stair slit	
Tube Diameter: Do[mm]	7.94	7.94	7.94	
Step pitch: Dp[mm]	20.4	20.4 20.4		
Row Pitch: Lp[mm]	17.7 17.7		17.7	
Number of Row: N[-]	3	3	3	
Fin pitch: Fp[mm]	1.6	1.8	1.8	
Fin Thickness: Tf[mm]	0.09	0.09	0.09	
Surface treatment	Bare	Bare	Bare	
	(no-hydrophilic coated)	(no-hydrophilic coated)	(no-hydrophilic coated)	
Fin shape	L.p Do			

3.3 Experimental Condition and Method

Table 2 shows experimental conditions. Air side heat transfer coefficient α_o and pressure drop $\triangle P$ are measured on dry, wet and frost surface condition. On the dry surface condition, the inlet temperature of air is 20°C, the fluid in the tube is water, and the inlet temperature of water is 50°C. By changing the air velocity and the water flow rate are changed, air side heat transfer coefficient α_o is measured by Wilson-Plot method.

On the wet surface condition, the inlet temperature of air is 27°C, the inlet absolute humidity of air is 10.5 g/kg, the fluid in the tube is water, and the inlet temperature of water is 10°C.

On the frost surface condition, the inlet temperature of air is 2° C, the inlet absolute humidity of air is 3.7 g/kg, the air velocity is 1.5m/s, the fluid in the tube is brine, the inlet temperature of brine is -5° C, and the brine flow rate is 6 l/m.

Surface State of Fin	Dry	Wet	Frost
Inlet Temperature of Air [°C]	20	27	2
Inlet Absolute Humidity of Air [g/kg]		10.5	3.7
(Inlet Relative Humidity[%])	-	(47)	(84)
Air Velocity[m/s]	1,1.5,2	1,1.5,2	1.5
Fluid	Water	Water	Brine
Flow Rate[l/min]	7,9,11,13	7,9,11,13	6
Inlet Temperature of fluid[°C]	50	10	-5

Table 2: Experimental condition

4. EXPERIMENTAL RESULTS

4.1 Dry Surface Condition

Figure 7,8 shows the experimental result of the air side heat transfer coefficient α_o and pressure drop $\triangle P$ to the air velocity on dry surface condition. The calculation result of cross stair slit fin is shown in the same figure. The deviation between the calculation and experimental results of the air side heat transfer coefficient α_o is within 6%. The deviation of the air side pressure drop $\triangle P$ is within 10%. When the air velocity is 1.5m/s, the air side heat transfer coefficient of conventional slit fin is highest, and α_o of cross stair slit fin is higher than ring. The same tendency is shown in case of pressure drop. The air side heat transfer coefficient α_o of conventional slit fin is 23% larger than ring fin, and pressure drop $\triangle P$ is 27% larger. On the other hand, the air side heat transfer coefficient α_o of cross stair slit fin is 12% larger than ring fin, and pressure drop $\triangle P$ is 2% larger.

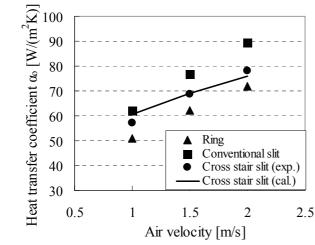


Figure 7: Air side heat transfer coefficient α_o (on dry surface condition)

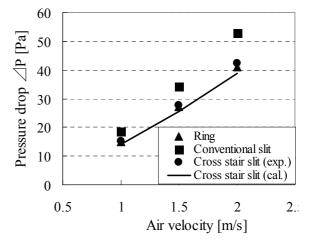
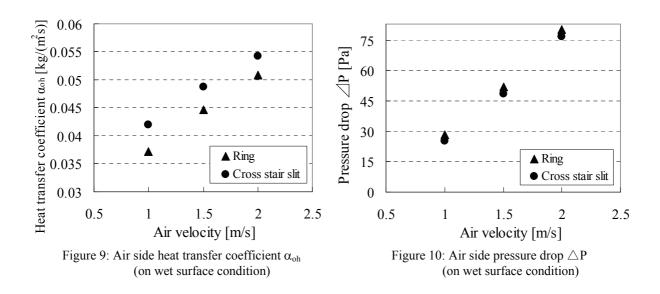


Figure 8: Air side pressure drop $\triangle P$ (on dry surface condition)

4.2 Wet Surface Condition

Figure 9,10 shows the experimental result of the air side heat transfer coefficient α_{oh} and pressure drop $\triangle P$ to the air velocity on wet surface condition. α_{oh} is calculated based on air enthalpy. When the air velocity is 1.5m/s, the air side heat transfer coefficient α_{oh} of cross stair slit fin is 10% larger than ring fin. But the air side pressure drop $\triangle P$ is 7% smaller than ring fin. The increasing ratio of pressure drop $\triangle P_{wet}/\triangle P_{dry}$ is defined as the ratio of the wet pressure drop to dry pressure drop. Figure 11 shows $\triangle P_{wet}/\triangle P_{dry}$ to the air velocity. When the air velocity is 1.5m/s, $\triangle P_{wet}/\triangle P_{dry}$ of cross stair slit fin is 10% smaller than ring fin. Figure 12, 13 shows the photograph of real surface states on the wet condition. The condensed water is hold between fins, because the surface treatment of the both fins are bare (no-hydrophilic coated). The hold area of cross stair slit fin is smaller than that of ring fin. The condensed water is moved to the silts and drained, because the gravity force of the condensed water and the shear stress of the air are larger than the surface tension. In the result, the drainage performance of the cross stair slit fin is improved, and the increase ratio of pressure drop of cross stair slit fin is smaller than ring fin.



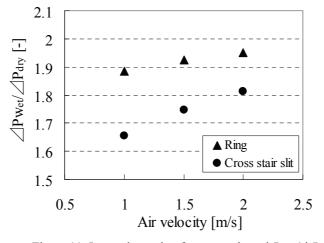


Figure 11: Increasing ratio of pressure drop $\triangle P_{wet}/\triangle P_{dry}$



Figure 12: The surface state of ring fin (on wet surface condition)



Figure 13: The surface state of cross stair slit fin (on wet surface condition)

4.3 Frost Surface Condition

The time changes of air side pressure drop $\triangle P$ are shown in Figure 14. On the same time condition, the air side pressure drop $\triangle P$ of conventional slit fin is highest, and that of cross stair slit fin is approximately the same as ring fin. In order to compare the heat transfer performance on frost surface condition, the amount of frost weight M is calculated below.

At first, the frost weight on a time interval ($\triangle t$) $\triangle M$ is given by equation (1). G_a is the air mass flow rate, (X_{a1} - X_{a2}) is the absolute humidity difference between the inlet and the outlet. And, the total amount of frost weight M is calculated by equation (2). Here n is total number which the air pressure drop reaches 200Pa.

$$\Delta M = G_a \cdot \left(X_{a1} - X_{a2} \right) \cdot \Delta t \tag{1}$$

$$M = \sum_{i=1}^{n(P=200)} \Delta M \tag{2}$$

Figure 15 shows M to each fin shape. The total amount of frost weight of cross stair slit fin is approximately 40% larger than that of conventional slit, and approximately the same as ring fin.

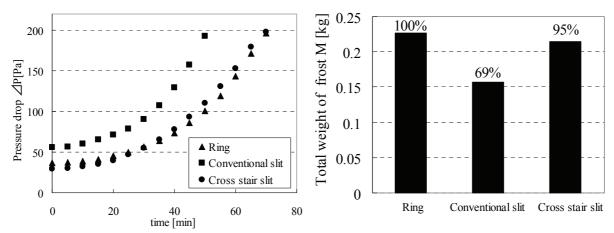


Figure 14: The time changes of air side pressure drop $\triangle P$ (on frost surface condition)

Figure 15: Total amount of frost weight M

5. CONCLUSIONS

Cross stair slit fin for the outdoor fin-tube heat exchanger has been developed to increase heat transfer on dry and wet surface condition and restrain heat transfer performance degradation on frost surface condition. The shape of cross stair slit fin was optimized using relationship between air side heat transfer and pressure drop by CFD. The air side heat transfer and pressure drop of test heat exchangers with 3 different fin shapes (ring, conventional slit, cross stair slit) were measured on dry, wet and frost surface conditions. Conclusions are shown as follows.

- The air side heat transfer coefficient α_o of cross slit fin is 12% larger, and pressure drop $\triangle P$ is 2% larger compared with ring fin on dry surface condition.
- Increasing ratio of pressure drop of cross stair slit fin is 10% smaller than ring fin, because the condensed water on the slits is well drained.
- The heat transfer performance of cross stair slit fin was the same as ring fin and 40% larger than
 conventional slit fin on frost condition.
- The deviation between the calculation and experimental results of the air side heat transfer coefficient α_o of cross stair slit fin is within 6% on the dry condition. The deviation of the air side pressure drop $\triangle P$ is within 10%

NOMENCLATURE

COP	coefficient of performance of heat pump unit	[-]
Do	tube outer diameter	[mm]
Dp	step pitch	[mm]
G_a	air mass flow rate	[kg/s]
H1	height of slit1	[mm]
H2	height of slit2	[mm]
L/Dp	divided width ratio	[-]
L	width between two slit1	[mm]
M	total weight of frost	[kg]
X_{a1}	inlet absolute humidity of air	[kg/kg]
X_{a2}	outlet absolute humidity of air	[kg/kg]
$\triangle P$	air side pressure drop	[Pa]
α_{o}	air side heat transfer coefficient	$[W/(m^2K)]$
$\alpha_{ m oh}$	air side heat transfer coefficient based on enthalpy	$[kg/(m^2s)]$

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