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FROSTING BEHAVIOR OF FIN-TUBE HEAT EXCHANGER ACCORDING TO REFRIGERANT FLOW TYPE

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ABSTRACT

In order to investigate characteristics of frost behavior according to refrigerant flow type, plate fin-tube heat exchanger was operated under both cross-counter flow and cross-parallel flow conditions. The cross-counter flow heat exchanger showed more uniform frost formation than the cross-parallel flow heat exchanger in each row. Also, under a parallel flow condition, the heat exchanger exhibited more non-uniform frost formation at lower refrigerant temperature condition (T_{ref} =-12.0°C). At higher refrigerant temperature condition (T_{ref}=-9.5°C), difference of overall heat transfer rate according to the refrigerant flow type was insignificant. However, at the lower refrigerant temperature condition, the counter flow type showed higher overall heat transfer rate than the parallel flow type.

INTRODUCTION

Because the heat pumps used for cooling and heating show higher energy effectiveness than other instrument, demands of the heat pump is still increasing. Additionally, because heat pumps are designed primarily for cooling, they are operated under counter flow conditions (which is more efficient for cooling), and operate in the reverse cycle for heating. Under parallel flow conditions, a frost layer forms on the outdoor unit of a heat exchanger, blocking the air passage and creating additional thermal resistance. As a result, the performance of the heat exchanger is degraded. Consequently, it is very important to investigate frosting behaviour on heat exchanger.

A number of studies have been conducted on frost formation according to refrigerant flow type. Aoki et al. [1] conducted frosting experiments on a flat plate under both counter flow and parallel flow conditions and compared the properties of the frost layer in upstream and downstream regions of the plate. Nelson et al. [2] used numerical calculations to design a liquid overfeed heat exchanger and investigated its performance under counter flow and parallel flow conditions. Aljuwayhel et al. [3] investigated the air-side and refrigerant-side temperatures of a liquid overfeed heat exchanger, using both numerical and experimental techniques. Also, the authors investigated performance of the heat exchanger under counter flow and parallel flow conditions with frosting. The authors of these studies reported that parallel flow type yielded better performance than counter flow type. However, Aoki et al [1] focused on flat plates rather than heat exchangers, and the studies [2,3] focused on heat exchangers used in liquid overfeed systems rather than air-source heat pumps. Liquid overfeed heat exchangers have different temperature characteristics between the air and refrigerant with respect to air flow direction, compared to the heat exchangers used for air-source heat pumps.

Therefore, the characteristics of frost formation on the heat exchanger which used for air-source heat pump according to refrigerant flow type are studied in the paper. Based on the investigation, variations of performance in heat exchangers under frosting conditions are discussed.

NOMENCLATURE

BR	[%]	Blocking ratio
Co	[-]	Cross-counter flow type
C_P	[kJ/kg·K]	Specific heat at constant pressure
L_H	[kJ/kg]	Latent heat of sublimation
$\dot{m}_a$	[kg/s]	Mass flow rate of air
Pa	[−]	Cross-parallel flow type
w_a	[kg/kg$_{DA}$]	Absolute humidity ratio
$\dot{Q}$	[kW]	Heat transfer rate
Q_a	[m^3/min]	Air flow rate

Subscripts

a	Air-side
ave	Average
f	Frosting
fat	Latent heat transfer
ref	Refrigerant-side
sen	Sensible heat transfer
t	Total heat transfer

EXPERIMENT

Figure 1 shows the experimental set-up for frosting and defrosting experiments of the plate fin-tube heat exchanger. The set-up is consisted of 5 parts [4,5]; a test section (where the heat exchanger was installed), a climate chamber (to maintain constant air temperature and humidity), a refrigeration section (to regulate the temperature and flow rate of the refrigerant for the frosting experiments), a defrosting section (to supply warm refrigerant to melt the frost layer), and a recirculation section (to connect the other components and act as an air pathway). Bypass valves were installed at the inlet and outlet of the test section to alternately supply cold refrigerant (frosting experiments) and warm refrigerant (defrosting experiments). The refrigerant used in the experiments was a solution of ethylene glycol as mass ratio of 1:1. Experimental data was recorded after given experimental conditions (air temperature, air humidity, air flow rate and refrigerant temperature) reached a steady-state, at which point the frosting experiments were started.

Figure 2 showed the plate fin-tube exchanger used in the experiments. The heat exchanger had 4 steps and 2 rows and height of the heat exchanger was 85 mm, width was 120 mm, and length was 36 mm. The aluminium fin surface was not coated (without condensation coating), fin pitch (collared fin length) was 1.81 mm, inner diameter of the tube was 7 mm, longitudinal pitch was 21 mm, and tube pitch was 18 mm. The measuring holes for observing the frost formation were drilled on the top of the test section, and the rigid-borescope which had 90º view direction and 4 mm inner diameter was inserted through the holes for capturing images of frost layer. Three points along the width and six points along the height of the heat exchanger were selected for the image capturing. The images of 18 points in 1st row (front row) were captured from the front side of the heat exchanger, and the images of 18 points in 2nd row (rear row) were captured from the rear side. The captured images were analyzed with NIS-element D software program. Uncertainties of the experiments were as follows [6]; average blocking ratio 3.6%, air-side pressure drop 3.3%, and heat transfer rate 3.9%.

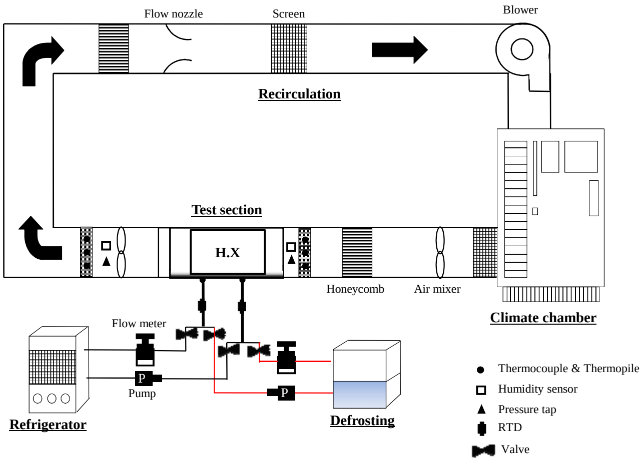


Figure 1 Experimental set-up

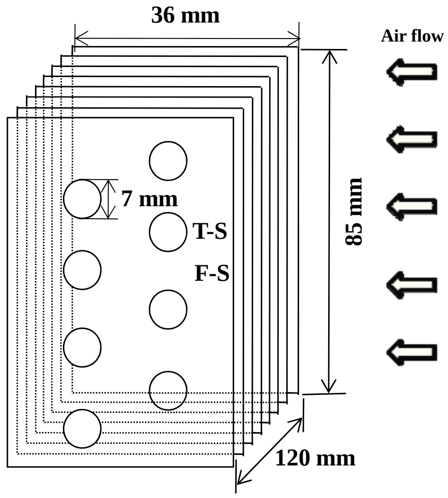


Figure 2 Tested fin-tube heat exchanger

Measured location	Front row (1st row)	Rear row (2nd row)
Tube Side [T-S]		
Fin Side [F-S]		

Figure 3 Characteristics of frost growth on a fin tube heat exchanger according to position (t_f=30 min)

RESULT AND DISCUSSIONS

To investigate the characteristics of frost formation on a heat exchanger according refrigerant flow type, heat exchanger was operated under both the cross-counter and cross-parallel flow conditions. The heat transfer rate was calculated using following equations:

$$\dot{Q}_t = (\dot{Q}_a + \dot{Q}_{ref})/2 \quad (1)$$

$$\dot{Q}_a = (\dot{Q}_{sen} + \dot{Q}_{lat})/2$$
$$= \dot{m}_a \cdot C_{p,a}(T_{a,in} - T_{a,out}) + \dot{m}_a \cdot L_h(w_{a,in} - w_{a,out}) \quad (2)$$

$$\dot{Q}_{ref} = \dot{m}_{ref} C_{p,ref}(T_{ref,out} - T_{ref,in}) \quad (3)$$

Figure 3 shows typical frost formation behaviour on a fin tube heat exchanger at given experimental condition (T_a=3.0°C,

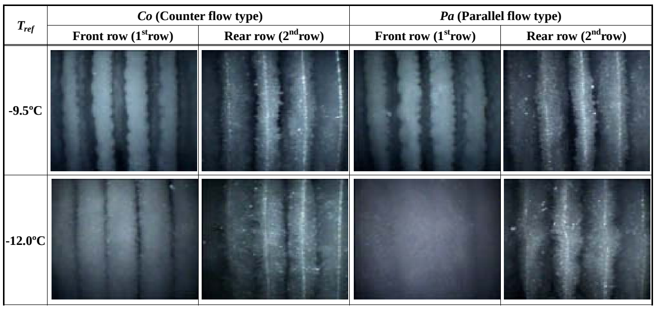


Figure 4 Frost formation according to refrigerant flow type and refrigerant temperature (t_f=40 min).

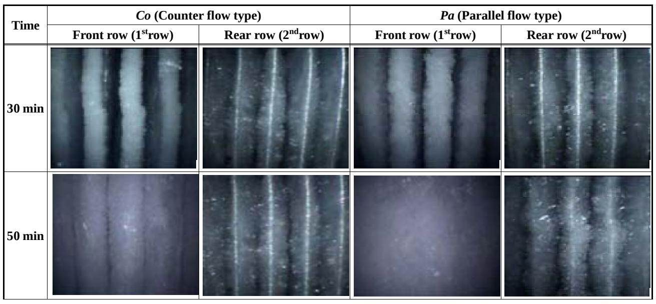
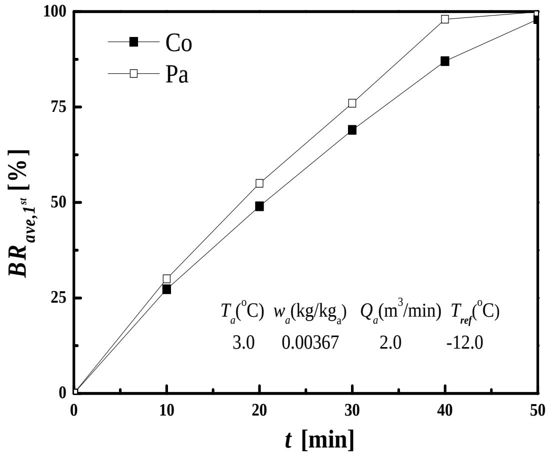
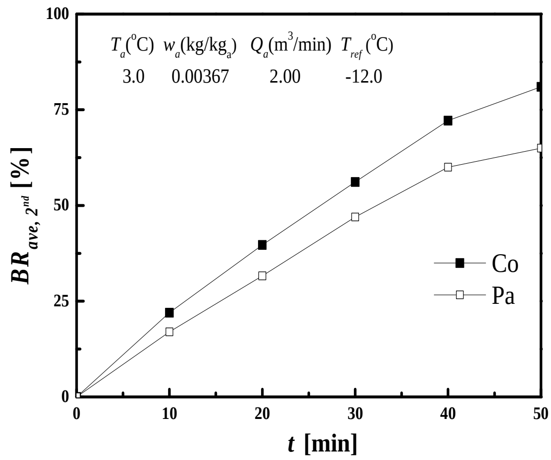


Figure 5 Frost formation according to refrigerant flow type and elapsed time (T_{ref}=-12.0°C).



(a) 1st row



(b) 2nd row

Figure 6 Average blocking ratio in each row according to refrigerant flow type.

w_a=0.00367 Kg/Kg$_{DA}$, T_{ref}=-9.0°C, Q_a=2.0 m^3/min). As indicated in Figured 2, the tube side (T-S) is located where the fin intersects the step-three tube, and the fin side (F-S) is located between the step-two and step- three tubes. Because the tube obstructed the air flow, thereby generating a flow disturbance, the boundary layer was thin around the tube side in the 1st row of the heat exchanger. Also, because the temperature of the fin was lower as close to the tube, frost thickness was slightly higher at the tube side than at the fin side in the 1st row. However, in the 2nd row of the heat exchanger, air flow separation occurred when air passed the tube, and frost growth in the 2nd row was less active at the tube side than at the fin side. In view of this non-uniform frost growth, an average blocking ratio (BR_{ave}) was introduced. Original definition of blocking ratio [7] was a parameter indicating the extent of the blockage of the air flow passage between the fins of a heat exchanger by frost layer. In this paper, the average blocking ratio was calculated as the average value of the 18 measured values in each row.

Figure 4 presents captured images of the frost layer according to refrigerant flow type (t_f=40 min). These images were captured at the middle observation points relative to width, at the second step of the heat exchanger, in both the front and rear rows. To observe frost growth according to refrigerant temperature, the refrigerant temperature (T_{ref}) was set at -9.5ºC and -12.0ºC. At the relatively higher refrigerant temperature condition (T_{ref}=-9.5ºC), the counter flow (*Co*) type heat exchanger exhibited insignificant difference of blocking ratio in each row, because the temperature differences between the air side and refrigerant side in the 1st and 2nd rows were insignificant. However, the parallel flow (*Pa*) unit exhibited more active heat and mass transfer in the 1st row than the 2nd row, because the refrigerant entered at the 1st row distributor and exited at the 2nd row distributor, so the 1st row had a lower fin surface temperature. Also, due to the leading edge effect [8] of the heat exchanger, the blocking ratio was slightly higher in the 1st row than in the 2nd row.

At the lower refrigerant temperature (T_{ref}=-12.0ºC), the counter flow type also exhibited insignificant difference in frost growth between the 1st and 2nd rows. However, on the parallel flow type, the air passage in the 1st row was completely blocked by the frost layer, while an air passage still remained in the 2nd row. The parallel flow type heat exchanger exhibited more non-uniform frost growth, especially at the lower refrigerant temperature (-12.0ºC), for the following reason: at the refrigerant temperature of -9.5ºC, the relative humidity was decreased due to frost growth, and the water in the air was condensed onto the fin surface, but the reduction in humidity was insufficient to affect frost growth in the 2nd row. So, the

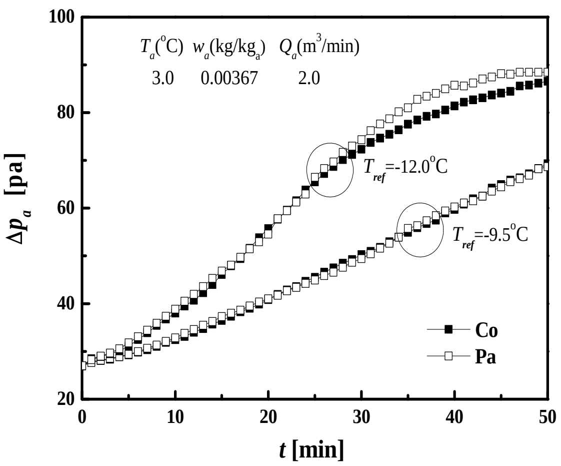


Figure 7 Air-side pressure drop due to frost growth with different refrigerant temperatures.

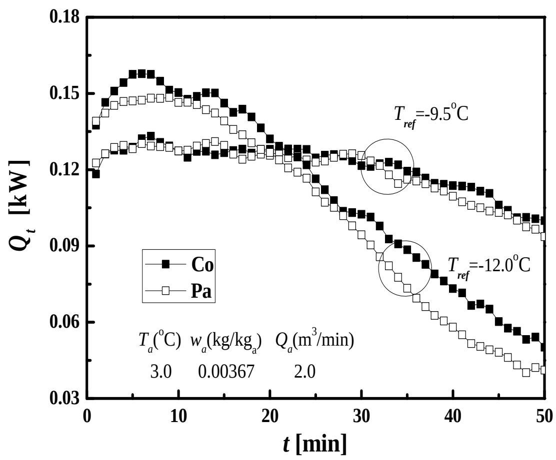


Figure 8 Variation of heat transfer rate with different refrigerant temperatures.

relative humidity of the air in the 2nd row was still adequate for frost growth, the effect of refrigerant flow type was insignificant. However, at the refrigerant temperature of -12.0ºC, due to the more active frost growth in the 1st row, the reduction in humidity while passing through the 1st row was considerable. Thus, the relative humidity of the air in the 2nd row was inadequate for frosting, compared to the higher refrigerant temperature case (-9.5ºC). Accordingly, the difference in frost growth between the 1st and 2nd rows was more significant at the lower refrigerant temperature condition.

Figure 5 shows the counter flow (*Co*) and parallel flow (*Pa*) type units at refrigerant temperature -12.0ºC, according to elapsed time. The counter flow type exhibited relatively uniform frost growth in each row, regardless of the time. The parallel flow type exhibited more active frost growth in the 1st row, and a corresponding earlier complete blockage of the air passage. Consequently, flow resistance was increased, and air momentum was decreased due to the decreased air flow rate. In particular, after an experimental time of around 40 min, the air passage in the 1st row was completely blocked, and frost growth in the 2nd row had almost stopped. This finding indicates that the rapid air passage blockage in the 1st row of the parallel flow type was another cause of non-uniform frost growth in each row.

Figure 6 shows the average blocking ratio (BR_{ave}) for the 1st and 2nd rows when the refrigerant temperature was -12.0ºC. The parallel flow heat exchangers (*Pa*) had slightly higher average blocking ratio than the counter flow heat exchanger in the 1st row. As explained above, this can be attributed to the fact that the parallel type heat exchanger had greater temperature differences between the air side and the refrigerant side in the 1st row, and the fin surface temperature was lower in the 1st row than in the 2nd row. In contrast, the counter flow heat exchanger (*Co*) had higher average blocking ratios in the 2nd row.

Figure 7 shows the air-side pressure drop due to frost growth for different refrigerant temperatures. When the refrigerant temperature was -9.5ºC, the difference in air-side pressure according to the refrigerant flow type was insignificant. When the refrigerant temperature was -12.0ºC, the parallel flow type, which exhibited more active frost growth in the 1st row, had a higher air-side pressure drop than the counter flow type, because the parallel flow type showed faster frost growth, and had earlier air passage blockage by the frost layer.

Figure 8 shows the heat transfer rate for the tested heat exchangers at different refrigerant temperatures. First, in terms of the refrigerant temperature, and irrespective of refrigerant flow type, the lower temperature condition (T_{ref}=-12.0ºC) yielded a higher heat and mass transfer rate than the higher temperature condition (T_{ref}=-9.5ºC), in the early stage. However, as time elapsed, reduction of the heat transfer rate was more rapid at the lower temperature, due to the faster frost growth. After an experimental time of 25 min, the higher refrigerant temperature yielded a more active heat transfer rate, and the average heat transfer rate for the overall experiment (50 min) was 10% higher at -9.5ºC condition than at -12.0ºC condition, under the counter flow type.

Next, in terms of refrigerant flow type, the refrigerant temperature of -9.5ºC yielded insignificant differences according to refrigerant flow type. When the refrigerant temperature was -12.0ºC, the counter flow type (which exhibited more uniform frost growth in each row) had 8% higher heat transfer rate than the parallel flow type for the overall experiment. This finding indicates that uniform frost growth in heat exchanger yield higher heat transfer.

CONCLUSION

This study focused on frost formation on a heat exchanger according to refrigerant flow type. We investigated the air-side pressure drop and heat transfer rate due to frosting under both counter flow and parallel flow conditions. The difference of blocking ratio between the 1st and 2nd row was higher at cross-parallel flow condition with lower refrigerant temperature. The cross-counter flow type showed the more uniform frost growth and higher heat transfer rate than the parallel flow type.

ACKNOWLEDGMENTS

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