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A Study of the Defrosting Behavior according to Surface Characteristics of a Fin-Tube Heat Exchanger

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Key words : Defrosting, Fin-tube heat exchanger, Contact angle, Hydrophilic surface, Hydrophobic surface

Abstract

In this study, the defrosting behavior according to the surface characteristics of a fin-tube heat exchanger is experimentally examined. It has been found that the draining rates of the hydrophilic and hydrophobic heat exchangers are evenly dispersed during defrosting, compared with that of the bare one. This is due to the high density frost of the hydrophilic heat exchanger, and the surface characteristics of the hydrophobic heat exchanger. The rest periods of the hydrophilic and hydrophobic heat exchangers are shorter, and their weight of residual water is also smaller than that of the bare heat exchanger. The hydrophobic heat exchanger is the most efficient in terms of the defrosting efficiency.

Nomenclature

L : Latent heat of sublimation [J/g]
$M_{w,res}$: Weight of residual water [g]
m_f : Frost mass [g]
q_{heater} : Power supply for defrosting [W]
T : Temperature [℃]
t : Time [min]
t_p : Melting preparation period [min]
t_m : Frost melting period [min]
t_r : Moisture removal period [min]
t_{rest} : Rest period [min]
$\dot{W}$: Water draining rate [g/s]

Greek Symbols

η_m : Melting efficiency [%]
η_d : Defrosting efficiency [%]
τ_m : Melting time [min]
τ_d : Defrosting time [min]
θ : Contact angle [°]

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1. Introduction

Water vapor in the surrounding air forms a porous layer of frost on the cooling surface of a low temperature heat exchanger by the heat and mass transfer occurring between them. As the frost grows, it acts as a thermal resistance and increases the flow resistance, blocking the flow channel between the air and the heat exchanger. As a result, defrosting has to be activated periodically at appropriate times to remove the frost. However, during defrosting, the operation of the heat exchanger is paused so that refrigeration and cooling cannot be conducted constantly and additional defrosting heat has to be supplied to the system. All of this results in degradation of the efficiency, performance, credibility and life span of the refrigerating system. Therefore, it is necessary to improve not only the efficiency of the frosting but also that of defrosting to ensure the increment of system efficiency.

Until now, there has been much research related to the frosting and defrosting behavior of heat exchangers, but there are few works available on the defrosting behavior with respect to surface characteristics. As shown in Fig. 1, a water droplet formed on a solid surface holds a certain angle with the surface, according to the properties and state of the surface and the type of liquid. This is a contact angle representing the surface characteristic of the material. A hydrophilic surface develops an affinity for water, so that it has a large contact area with the water, making an acute angle. However, a hydrophobic surface repels the water, so that it has a small contact area with the water droplet, making an obtuse angle. The droplet is easily detached from the surface by gravity. O'Neal et al.(1) presented that the defrosting period of the hydrophilic and hydrophobic surface heat exchangers is shorter than that of the bare one, and the amount of residual water is the smallest in the hydrophobic one. Saito et al.(2-4) showed that the force attaching snow and ice to a surface is weakened in a hydrophobic surface. Tsuda et al.(5) investigated that a super hydrophobic surface heat exchanger shows an expanded successive operation time. Most of the previous investigations are concerned with only the characteristics of the surfaces but several works have an application to the heat exchanger. There is also little work available on the study of defrosting.

In the present study, experiments on frosting and defrosting have been conducted to investigate the effects of surface characteristics on the defrosting behavior of the bare, hydrophilic and hydrophobic heat exchangers. The purpose of this study is to provide basic data for designing a high performance heat exchangers under frosting conditions.

2. Experiment

2.1 Experimental apparatus

The experimental setup in this study consists of a test, circulation, cooling and heat supply section and a climate chamber, which is a closed-circuit system with a wind tunnel. Each

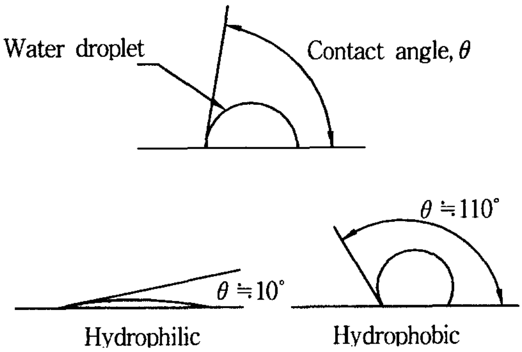

Fig. 1 The contact angle of water droplet.

respective section is controlled individually.(6)

Figure 2 shows the schematic of a fin-tube heat exchanger used in this study. The 2 columns and 2 rows heat exchanger is made of Al. The length of its tube is 310 mm excluding the bending section and its fin pitch is 7 mm. An electric heater is attached to the fins staggered between the tubes and consumes 32W at an input of 220 V. The hydrophilic and hydrophobic heat exchangers are coated with a chrome-based and a teflon-based substance on the aluminium substrates, respectively. The contact angle of the bare heat exchanger is about 72° and those of the hydrophilic and hydrophobic heat exchangers are 12° and 124° , respectively.

2.2 Experimental method

In this study, both frosting and defrosting tests were conducted to reveal the defrosting behavior of a heat exchanger with respective surface characteristics. As the conditions of the standard frosting test, the temperature, relative humidity and initial velocity of the inlet air are 10℃, 70 % RH and 2 m/s, respectively. The temperature and flow rate of the refrigerant are -27 ℃ and 0.04 kg/s. The entire test procedure is as follows. The temperature and humidity of the air are maintained at their preset conditions and air flow is induced into the test section. The refrigerant in a low temperature tank is also cooled down to the test condition. When both the inlet air and the refrigerant reach the state of the preset conditions, the frosting test is conducted for 2 hours by allowing the refrigerant to circulate in the heat exchanger. After the frosting test, air circulation is suspended and heater power is switched on and supplied with a power of 32 W, starting the defrosting test. When the average fin temperature of the heat exchanger reaches 14℃, the defrosting operation is ceased.

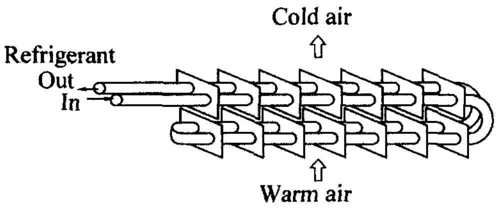

Fig. 2 A schematic of a fin-tube heat exchanger used in this study.

To measure the weight of the draining water during defrosting, absorbent cotton weighed in advance is laid on a drain water tray which is placed on the lower part of the test section. The tray is exchanged at fixed time intervals, and the amount of drained water is calculated by subtracting the weight of the cotton from the total weight. When the fin temperature reaches the test condition, 14℃, the heat supply from the electric heater is suspended. After a certain amount of resting time, the defrosting experiment is ended. Finally, the amount of residual water remaining on the fin and tube surfaces is measured.

Both the melting and defrosting efficiencies are defined to represent the defrosting performance as follows:

$$\eta_m = \frac{m_f L}{q_{heater}\ \tau_m} \tag{1}$$

$$\eta_d = \frac{m_f L}{q_{heater}\ \tau_d} \tag{2}$$

The uncertainties of the measured data in the study were calculated by the root-sum-square method(7) in the credibility range of 95%. The uncertainties of the inlet air absolute humidity, draining rate, and the weight of residual water are 1.94 %, 1.14 % and 1.08 %, respectively.

3. Results and discussion

In this study, the experiments were conducted with the standard frosting conditions to compare the defrosting behaviors and efficiencies of the hydrophilic and hydrophobic heat exchangers with those of the bare exchanger.

3.1 Defrosting behavior at the standard frosting conditions

Defrosting behavior, according to the surface characteristics of a fin-tube heat exchanger, can be examined by the temperature variation of each part of the heat exchanger and its water draining behavior. The defrosting period is divided into the following four periods$^{(6)}$: the melting preparation period(t_p), the frost melting period(t_m), the moisture removal period(t_r) and the rest period(t_{rest}).

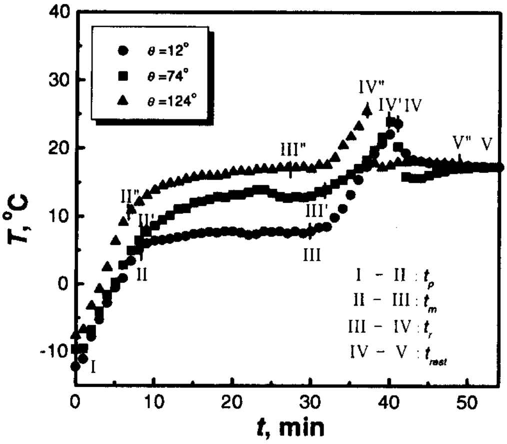

Fig. 3 Variation of heater temperature during defrosting period on the bare, hydrophilic, and hydrophobic fin-tube heat exchangers.

Figure 3 shows the variation of the heater temperature during the defrosting on the bare, hydrophilic, and hydrophobic fin-tube heat exchangers under the standard frosting conditions. It is common to examine defrosting behavior with the temperature variations of the fin, tube, air, and heater. However, only the heater temperature has been shown in this study because temperature variations of the other parts are very similar to each other. Until the defrosting ending time, τ_d, the heater temperature is lower in the hydrophilic heat exchanger and higher in the hydrophobic one than that in the bare one. This is particularly evident during the frost melting period when the average heater temperature of the hydrophilic and hydrophobic heat exchangers is 4.8 ℃ lower and 2.4 ℃ higher than that of the bare one. The reason why the hydrophilic heat exchanger shows a lower heater temperature is due to the fact that it deposits a frost with high density at the beginning of frosting, as reported in a previous study$^{(8)}$, and the heat generated by the heater can easily be transferred to the frost layer. The heat transferred to the frost layer leads the frost to the pure melting water, which is drained from the heat exchanger. In the case of the hydrophobic heat exchanger, the melted water permeates into the frost at the beginning of defrosting and then the frost is separated from the surface by the hydrophobic characteristic. Therefore, only some patches of frost are attached to the surface before it is detached completely from the surface. Namely, the hydrophobic heat exchanger has a small contact area between the fin and frost. This causes the heat exchanger to transfer less heat and also to record a higher temperature than the bare one.

The draining rates of melted water with time in the bare, hydrophilic, and hydrophobic heat exchangers are shown in Fig. 4. In the bare one, it begins draining at $t = 23.5$ min after the heat is supplied. The mass of draining wa-

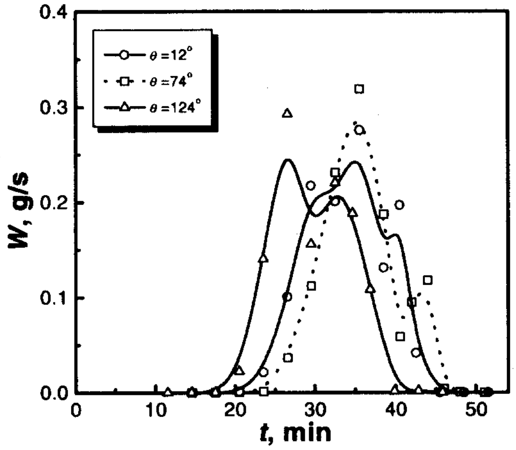

Fig. 4 Draining rate of melted water with time on the bare, hydrophilic, and hydrophobic heat exchangers.

ter increases to the maximum point when $t = 35$ min and then decreases rapidly. When $t = 40.7$ min, the fin temperature increases to 14℃ and the power supply to the heater is cut off. The defrosting is completed after another peak in the draining rate. However, in the hydrophilic one, draining begins at $t = 20$ min, which is 3.5 min faster than the bare one. It reaches the maximum draining rate when $t = 35$ min and defrosting is completed at $t = 41$ min. In the hydrophobic one, draining commences 6.5 min earlier than the bare one. The maximum rate of draining occurs at $t = 25$ min and defrosting is completed when $t = 36.5$ min. The total amount of drained water of each heat exchanger increases with the draining of melted water, but only traces of the melted water drains after τ_d. The bare heat exchanger has a relatively greater draining weight after τ_d compared to other heat exchangers.

The respective heat exchangers have the following characteristics in the draining behavior of melted water. As described before, the bare one has two peaks of the draining. This is explained by the frost melting mechanism. The melted water permeates into the frost layer by the capillarity, and then the unmelted frost is detached from the heat exchanger with pure melted water by gravity. The hydrophilic heat exchanger has the maximum point of draining of melted water but does not have the clear peaks relative to the bare one. Its draining rate is dispersed evenly throughout the frost melting period. This is attributed to the fact that the hydrophilic heat exchanger drains more pure melted water than the bare one because of the dense frost and its surface characteristics. The hydrophobic heat exchanger shows an evenly dispersed draining rate similar to the hydrophilic one. Because the frost containing melted water is easily detached from the surface because the contact area between the frost and the heat exchanger becomes smaller by the hydrophobic surface characteristic. These findings are in very good agreement with the results of Saito et al.(4) in that the adhesion force to the surface of wet snow decreases, corresponding with the increment of the contact angle in a hydrophobic surface.

In Fig. 5, the effect of the contact angle on the melting efficiency and the draining water ratio during the rest period is presented. The melting efficiencies of the hydrophilic and hydrophobic heat exchangers are about 15% greater than that of the bare one. This is due to the fact that the draining distribution of melted water of those heat exchangers is relatively even during defrosting as shown in the draining behavior of melted water in Fig. 4. The draining water ratio during the rest period is relatively lowered by 38.8% and 43.3% in the hydrophilic and hydrophobic heat exchangers, respectively. Therefore, it is possible to decrease the duration of the rest period of these exchangers com-

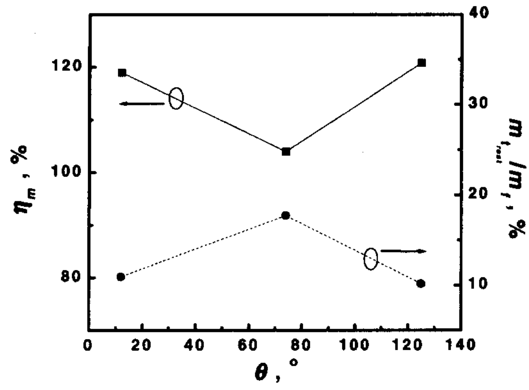

Fig. 5 Effect of contact angle on melting efficiency and water draining ratio during the rest period.

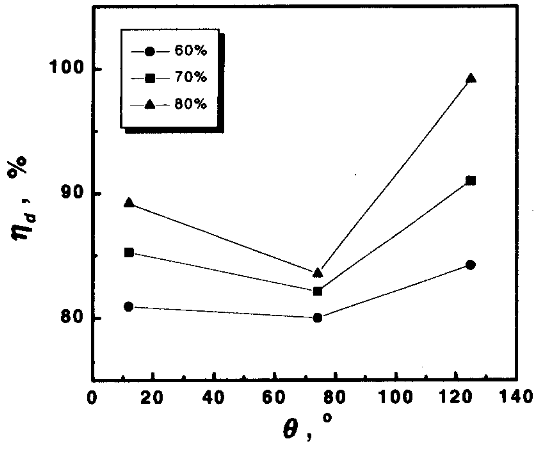

Fig. 6 Effect of contact angle on the defrosting efficiency for the various values of relative humidity.

pared to the bare one. The efficiency of the refrigerant and the cooling system can also be improved by the reduction of the defrosting time if this behavior is applied to the system.

3.2 The influence of inlet air humidity

To examine the effects of the air humidity on the defrosting behavior according to the surface characteristics of the heat exchangers, only the relative humidity of the inlet air was altered.

Figure 6 represents the effect of a contact angle on the defrosting efficiency for the relative humidity on the bare, hydrophilic, and hydrophobic heat exchangers. As shown in the figure, the defrosting efficiencies of all three heat exchangers increase as the relative humidity increases. This is due to the fact that high relative humidity leads to frost with larger mass and lower density. Therefore, it is very easy for melting water to permeate into the frost layer, and it accelerates the melting process. Particularly, as the frost mass increases, the defrosting efficiency of the hydrophobic heat exchanger becomes higher than that of the hydrophilic one. This results from the fact that the frost with a higher density requires a longer melting time in the hydrophilic surface, but the inherent characteristic of the hydrophobic surface helps the detachment of frost by gravity as the frosting mass increases.

Figure 7 shows the weight of residual water with the contact angle in the heat exchangers. The residual water on the surface of a heat exchanger after defrosting has a great effect on the subsequent frosting because frosting and defrosting are performed periodically in the system. The weight of the residual water in the hydrophilic and hydrophobic heat exchangers are 23.9% and 19.4% less than that of the bare one. The decrement of residual water has a great effect on the reduction of flow resistance and the frosting mass in the subsequent operation. Moreover, if the super-hydrophobic surface heat exchanger having a contact angle of over 150° is developed in the future, its residual water weight will be even smaller than that in the heat exchangers considered in the present work.