Defrosting Behavior of Fin-Tube Heat Exchanger with PTC Heating Sheet

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Key words : PTC(positive temperature coefficient), Defrosting, Water draining rate, Defrosting efficiency

Abstract

In this paper, the defrosting characteristics of a PTC heating sheet is investigated by means of a defrosting heat source for the fin-tube heat exchanger in a refrigerator. The defrosting characteristics of the PTC heating sheet are examined and compared with those of a conventional electric heater experimentally. It is found that the characteristics of the water draining rate with the defrosting time show a smoothly oscillating pattern when the PTC heating sheet is used, and the drained water is completely melted. The defrosting efficiency of the PTC heating sheet is found to be about 75%, which is about 25% higher than that of the electric heater. Also, the reduction of the defrosting time and the increment of the defrosting efficiency may be obtained by improving the arrangement of the heating elements of the heating sheet. It is shown that the defrosting time of the PTC heating sheet increases linearly with the amount of frost, whereas the defrosting efficiency is nearly constant. When applying the PTC heating sheet to the refrigerating system, one should notice the fact that the defrosting performance of the PTC heating sheet may be degraded due to the repetitive operations.

Nomenclature

L : Latent heat of sublimation [J/g]
M_w : Accumulation weight of draining water [g]
m_f : Frost mass [g]
q_{heater} : Power supply for defrosting [Wh]
T : Temperature [℃]
t : Time [minutes]
t_m : Frost melting period [minutes]
t_p : Melting preparation period [minutes]

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t_r : Moisture removal period [minutes]
t_{rest} : Rest period [minutes]
W : Supplying power [W]
$\dot{W}$: Water draining rate [g/s]

Greek symbols

ηd : Defrosting efficiency [%]
τd : Defrosting time [minutes]

1. Introduction

Frost formation can be found in a low temperature heat exchanger such as air to air heat pumps, refrigerators and freezers. This is one of the major problems since it degrades the performance of a heat exchanger. Therefore, in order to maintain the proper performance of the heat exchanger, defrosting should be activated periodically to remove the frost. During the defrosting period, the operation of the heat exchanger needs to be paused and, the heat supplied to the refrigerating system deteriorates system efficiency, reliability and life span. Particularly, in the case of the refrigerator/freezer, the degree of freshness of foods and drinks is highly concerned.

Previous studies to settle these frosting/defrosting related problems can be classified into three categories: 1) The increase of successive operation time of the system by delaying frost accumulation(1-4), 2) The enhancement of defrosting performance by altering defrosting scheme(5-10), and 3) The adaptive demand defrost by optimizing frosting and defrosting operation(11-12). The investigations on the increment of the operation time by delaying the frost formation have been progressed actively, but it has not yet successfully applied to a practical system. Also, the adaptive demand defrost depends on the experimental results as it varies with the heat exchanger and the defrosting heater of the system. Thus, the studies that intend to reduce defrosting time and to increase the defrosting efficiency by enhancing the performance of the defrosting heater have been progressed most actively.

The defrosting methods used in the most low temperature heat exchangers can be classified into two types: 1) refrigerating cycle method(hot gas defrost(7-10), bypass defrost), 2) non-refrigerating cycle method(electric defrost(13), water · brine injection, mechanical removal). Among these, an electric defrost is commonly used. But this method shows a low defrosting efficiency and causes large additive heat loss due to the high temperature of the heater. Recently, it has been suggested that a defrosting method by supplying radiative heat emitted from an infrared lamp to the frost surface by using the fact that the frost layer absorbs infrared energy very well.(5-6) Also, other methods such as defrosting by utilizing the flow layer of infinitesimally small particles and spouting compressed gas have been investigated, but these methods have the problem of large energy consumption and initial cost. In this paper, as a new material for the electric defrost, we introduce a PTC(positive temperature coefficient) heating sheet as a defrosting heat source for an evaporator of a refrigerator. The PTC is a kind of material that exhibits a unique resistance versus temperature characteristic, and then dramatically increases the resistance above a specific temperature called the "Curie" or "Switching" point depending on the impurities(dopants) inserted and the manufacturing process. Thus, the defrosting performance and efficiency of this heater are expected to much higher than the conventional electric heater which consumes electric power constantly until the end of defrosting. However, it has not yet been reported the defrosting behavior and performance of the PTC heating sheet as a defrosting heater for the evaporator of the refrigerator. Hence, it is required to understand the details of characteristics of the PTC for this purpose.

Thus, in this paper, a common evaporator, which can be found in most refrigerator, is modified for the experiments. The PTC heating sheet and the conventional electric heater are installed on the fin-tube heat exchanger under the same frosting conditions, respectively. The defrosting time and efficiency, total supplying power, and temperature variation inside the test section and heat exchanger during the defrosting are examined in order to evaluate the defrosting performance.

2. Experiment

2.1 Experimental apparatus

As shown in Fig. 1, the experimental setup is constructed as a closed circuit system with a wind tunnel that is composed of test, circulation, cooling, heat supply sections and climate chamber. Each section of the setup is designed to control individually.(13)

Figure 2 shows the fin-tube exchanger and the defrosting heater. There are two columns and eight rows of tubes in the heat exchanger, and the length of the tube is 400 mm without the curved section. The pin pitches of each row of the heat exchanger are arranged as 20, 10, 10, 7, 7, 5, 5, 5 mm from the bottom row, respectively. Figure 2 (a) shows a heat exchanger with a conventional electric heater that is attached to the fins staggered between the tubes and consumes 167 W at 220 V of input.

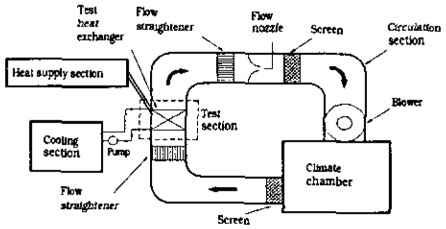
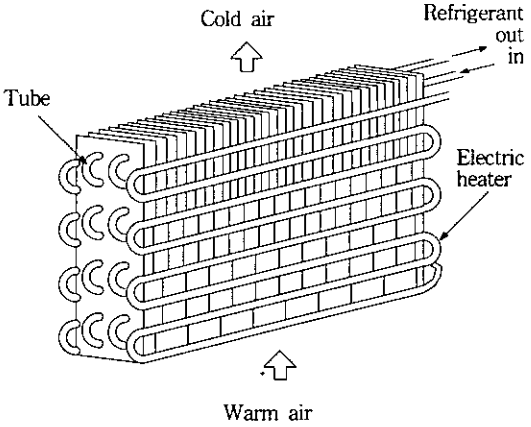


Fig. 1 Schematic diagram of experimental apparatus.

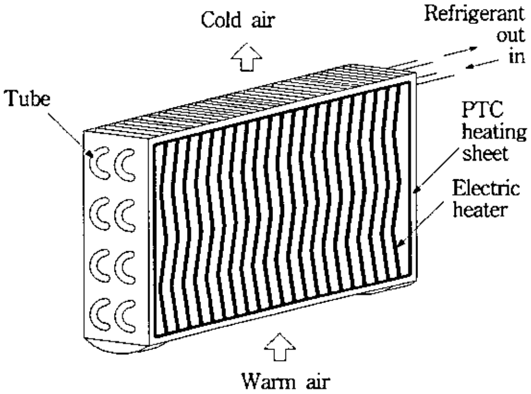
Figure 2 (b) shows a heat exchanger with the PTC heating sheet attached on the front and rear surface of the heat exchanger. The heating elements of the PTC sheet placed vertically with the heat exchanger tube are 1cm wide. The PTC material used for the heating sheet has 60℃ of Curie temperature and 317 Ω of resistance at room temperature. In order to measure the temperature of the fin, tube and heater in the heat exchanger during the defrosting period, type-T thermocouples(φ0.1 mm) are placed onto those located at the center of the upper, middle, and lower sections of the heat exchanger.

2.2 Experimental method

In order to reveal the defrosting behavior and to compare the defrosting performance of a PTC heating sheet with an electric heater, both frosting and defrosting experiments are conducted successively. As the conditions of a standard frosting test, the temperature, the relative humidity and the velocity of inlet air are 8℃, 70% RH and 2 m/s, respectively. After 3 hours of frosting experiment, defrosting is carried out immediately. 220V of power is supplied to the heater during the defrosting. When the tube surface temperature of the upper section of the heat exchanger reaches 13℃, the defrosting experiment is suspended. Moreover, the effect of the frosting mass is investigated to observe the defrosting characteristics of the PTC heating sheet by controlling the inlet air humidity.



(a) Electric heater



(b) PTC heating sheets

Fig. 2 Fin-tube heat exchanger with heater.

For the experiments, the inlet air is induced into the test section at a fixed velocity under the desired experimental conditions, and the circulating air temperature and humidity are also controlled. At the same time, the refrigerant in the brine tank is cooled down to a pre-determined temperature. After the inlet air temperature and the refrigerant temperature are reached to their preset values, the frosting experiment is started by circulating the refrigerant through the heat exchanger and proceeds for three hours. When the frosting experiment is done, the defrosting experiment is started by stopping the air flow into the circulation section and turning on the power with the defrosting heater adhered to the heat exchanger. In order to measure the amount of draining water during the defrosting, some sheets of tissue, which are weighed in advance, are laid on the drain water tray placed on the lower part of the test section.(13) The tray is exchanged at fixed time intervals and the amount of the drained water is calculated by subtracting the weight of the tissues from the total weight. And tissues, which are measured by digital chemical balance, are replaced at every exchange. In the case of the PTC sheet, the power consumption of the heating sheet is recorded with the amount of draining water because the input power of the heater is changed with the increment of temperature and resistance. When the tube surface temperature of the central location of the upper section of the heat exchanger is reached to 13℃ the power supply from the electric heater is suspended. And after certain intervals of resting(layoff) period similar to a domestic refrigerator, the defrosting experiment is completed.

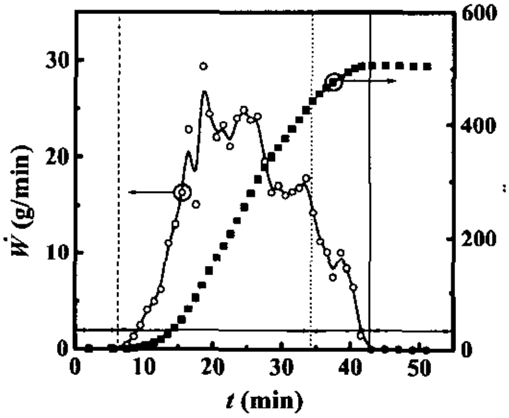
The uncertainties of the data on the inlet air temperature and relative humidity are 2.48 %, 3.46 %, and the water draining rate during defrosting is 3.46 %.

3. Experimental results and discussions

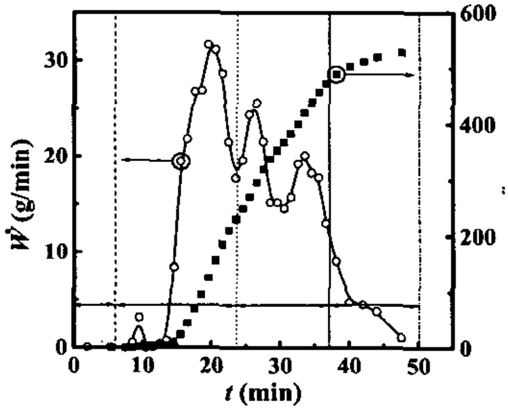
In this study, the experiments are conducted at the standard frosting conditions to compare the defrosting behaviors and performances of the fin-tube heat exchanger with PTC heating sheet installed with those of the conventional electric heater. The effect of the operating parameter(inlet humidity) is also analyzed to investigate the defrosting characteristics of the PTC heating sheet

3.1 The defrosting performance and characteristics of the PTC heating sheet

Figure 3 shows the temporal variation of the water draining rate($\dot{W}$) and the total weight of draining water(m_w) of the conventional electric heater(615g of frosting mass) and the PTC heating sheet(639g of frosting mass) in the standard frosting condition. The electric heater drains melted water continuously after about time t=7 minutes after supplying power. On the other hand the PTC heating sheet first discharges the frost formed on the heating sheet by about t=9 minutes, but it drains melted water actively after t=14 minutes. A noticeable characteristic of the behavior of the water draining rate during defrosting is that the PTC heating sheet shows a smoothly oscillating pattern with local maxima at t=20, 26, 33 min, whereas the electric heater exhibits a rather irregular pattern because the large amounts of frost drops before melting. The reason why the curve of the water draining rate shows an oscillating pattern is that the melting velocities in the heat exchanger are different with each row. When the frost formed on the upper section of the heat exchanger is melted to drain, it does not discharge directly to the drain water tray but the melted water with a relatively high temperature flows over the heat exchanger. Thus, the melted water imposes additional heat to the frost attached on the lower section of the heat exchanger and the melting velocity of the lower section becomes faster. The water draining rate of the PTC heating sheet shows a smoothly curved shape because it almost drains melted water by heating the surface of the heat exchanger evenly as it is a surface-type heater. But in the case of the electric heater, which is the line-type heater, it heats partly and thus drains unmelted frost occasionally. Another characteristic of the water draining behavior of the PTC heating sheet is that a large



(a) Electric heater

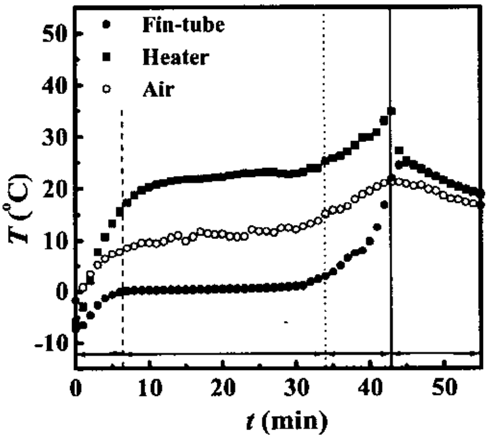


(b) PTC heating sheet

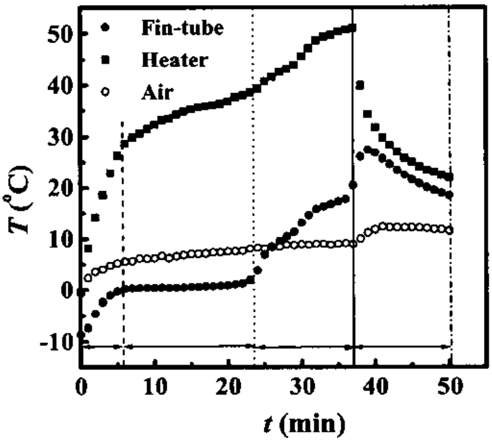
Fig. 3 Water draining rate and total amount weight of draining water with defrosting time.

portion of draining water(reaching up to about 11% of the total amount of the draining water) is flown out during the rest period after the cease of power supply to the heater, whereas the electric heater scarcely drains. The reason is that the time gap between the last maxima of the water draining rate and the completion of melting is relatively short and it takes time to drain out the pure melting water without the unmelted frost.

The defrosting characteristics of a heater can be deduced from the temperature variation of air and each component of the heat exchanger and the corresponding behavior of the draining water. The defrosting process can be divided into four periods according to the characteristics of the temperature of the heat exchanger: the melting preparation period(t_p), the frost melting period(t_m), the moisture removal period(t_r), and the rest period(t_{rest}).(13) Figure 4 shows the variation of temperature of the heater, fin-tube of the heat exchanger and air in the test section with defrosting time. The heater temperature represents the average temperature of the upper and middle section of the heater, and the fin-tube temperature of the heat exchanger means the average temperature of fin and tube of the upper and middle sections which show similar values. As the air flow is stagnant during the defrosting, the air temperature in the test section is obtained by averaging the inlet and outlet air temperature. From Fig. 4 the characteristics of the temperature variation of the PTC heating sheet can be investigated by the defrosting periods. During the melting preparation period, the increment of temperature in the heating element is larger than the conventional electric heater. The temperature of the heating element of the PTC sheet shows 10℃ higher than the conventional electric heater at the starting of the frost melting period. During the frost melting period the temperature of the PTC heating sheet increases continuously, whereas that of the electric heater remains constant. And the time interval of the heating sheet is relatively short. During the moisture removal period, the air temperature increases slowly compared with the rapid increment of the case of the electric heater. But



(a) Electric heater

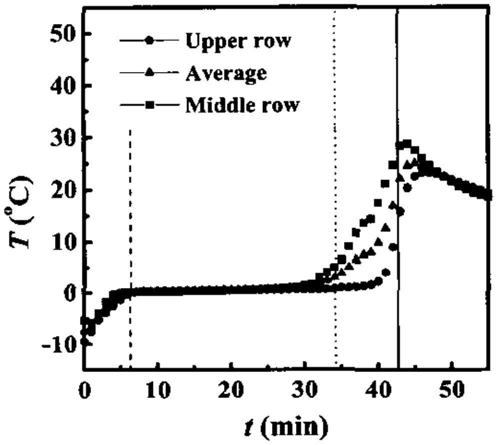


(b) PTC heating sheet

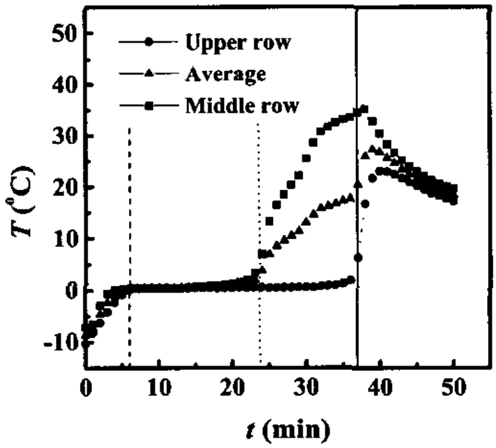
Fig. 4 The variation of temperature in test section with defrosting time.

the temperature of the heating element of the PTC sheet shows about 15℃ higher than the electric heater, and the average fin-tube of the heat exchanger shows a much higher value of 24℃ than the defrost ending temperature of 13℃. When the defrosting is completed after the rest period, the fin-tube temperatures of the heat exchanger using the PTC heating sheet and the electric heater are almost similar. But the air temperature using the PTC heating sheet records about 6℃ lower value of 10℃ than the electric heater, and the defrosting time is shortened by about 5 min.

The characteristics of the temperature variation of the PTC heating sheet during the defrosting are as follows. Firstly, the temperature of the heating element is considerably high. Secondly, the increment of air temperature is small. Finally, the temperature variation of the fin-tube of the heat exchanger is faster. It is considered that the higher temperature of the heating element is caused rather by the arrangement of the sheet than the property of the PTC itself. As shown in fig. 2, the sheet is adhered to the heat exchanger vertically and a relatively small amount of frost is formed on it. Thus, the surface is rarely wetted with the melted water. However, it is always wetted with the melted water on the electric heater drained from the heat exchanger, and the water absorbs relatively large portions of the heat supplied by the heater. When using a PTC heating sheet, the increments of the air temperature are small because the sheet constructed as a surface heater heats a larger area than the electric heater. Thus the heat loss to the surrounding air becomes small. The fact that the variation of the fin-tube temperature of the heat exchanger is rapid and the difference is high acts as a disadvantage in view of efficiency. It is however considered that this phenomenon is not owing to the characteristics of the PTC itself, but to the arrangement of the heating elements on the PTC heating sheet. As discussed in the water draining rate, the frost melting velocity of the upper part of the heat exchanger is relatively slow which means that the temperature of this part is lower than that of the lower part. As



(a) Electric heater



(b) PTC heating sheet

Fig. 5 The spatial variation of fin-tube temperature.

can be seen in Fig. 2(b), heating elements of the PTC sheet used in this paper is located about 2cm inside from the edge of the heat exchanger connected to the input terminal. This structure makes the upper part with lower melting velocity to further slow down, on the other hand, it causes no problem at the lower part with relatively faster melting velocity. Thus, in the middle and lower parts of the heat exchanger that are already melted completely, the temperature rises continuously to an exceedingly higher temperature of 24℃ than the defrost ending temperature.

Figure 5 shows the middle row, upper row and average temperatures of the heat exchanger during the defrosting to investigate the spatial variation of the fin-tube temperature. The temperature difference between the upper and middle row is not considerable in the case of the electric heater, but in the case of the PTC heating sheet the difference is prominent as the temperature of the middle row increases quickly. The middle and lower rows, where the melting of frost is already complete, act as increasing the temperature of the air and heat exchanger when the frost on the upper row melts. Thus it increases the additive heat to remove after the defrosting. Therefore, the improvement of the arrangement of the heating elements on the PTC heating sheet can achieve the reduction of the defrosting time and the increase of the defrosting efficiency.

Figure 6 presents the variation of the power supply with the defrosting time. The electric heater consumes a constant power of 167 W at input of 220 V, but the PTC heating sheet spends a gradually decreasing power as the resistance varies with the temperature. This has the advantage of the defrosting efficiency because of the reduction of the total consumption of electric power.

The defrosting efficiency can be defined as a function of the frosting mass, power supply and defrosting time;

$$\eta_d = \frac{m_f L}{\int_0^{\tau_d} q_{heater}\, dt} \tag{1}$$

The reduction of the defrosting time and a lower consumption of electric power of the

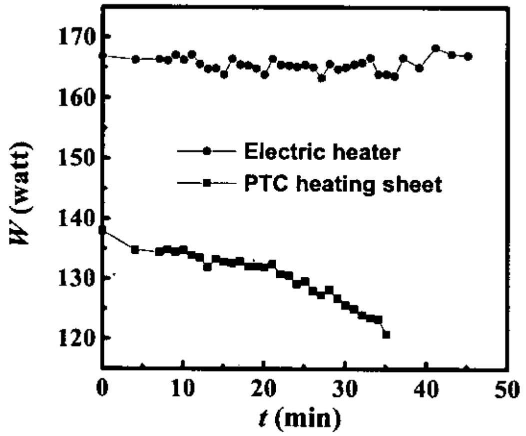


Fig. 6 The variation of power supply with defrosting time.

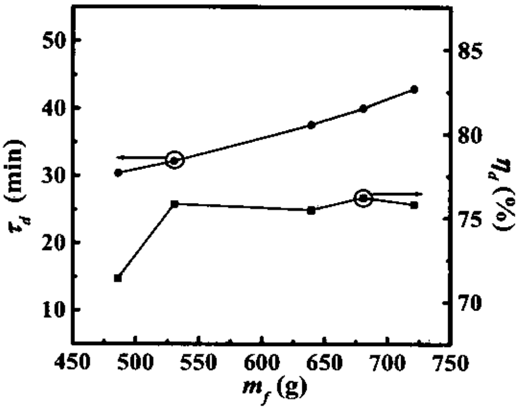


Fig. 7 Defrosting times and efficiencies with the weight of frost for relative humidity.

PTC heating sheet are shown in Fig. 6. From this, the PTC sheet has a higher value of defrosting efficiency than that of the electric heater. Also, under the standard frosting condition, a PTC heating sheet shows a higher efficiency of 75.5% compared with the 50.5% of the electric heater.

3.2 The effect of operating parameters

Figure 7 shows the defrosting times(τ_d) and efficiencies(η_d) of the PTC heating sheet with the weight of frost by controlling the inlet air humidity. The defrosting time increases linearly with the weight of frost, but the defrosting efficiency remains constant at about 75 % more than 530 g of the frosting mass. In the case of 486 g of frosting mass, the efficiency shows a lower value of 71%. Therefore, it is believed that if the heat transfer performance and defrosting time are decided, the optimum frosting mass can then be selected by considering these parameters.

Figure 8 gives the draining water ratio for the defrosting period according to the weight of the frost. At the condition of 639g of frosting mass(RH 70%) the draining water ratio during the frost melting period and the moisture removal period have similar values of about 45%, but for the other conditions, the moisture removal period has a higher value. Also compared with the case of 639g of frost, the draining water ratio during the frost melting period decreases with the change of the weight of frost, whereas it increases during the moisture removal period and the rest period.

3.3 The repetitive performance of the PTC heating sheet

In order to maintain proper system performance, it is required to preserve not only the heat transfer performance of the heat exchanger during frosting but also the defrosting performance of the defrosting heater. The repetitive defrosting performance of a heater can be ascertained by comparing the power supply during the defrosting, defrosting time and efficiency. Figure 9 compares the power

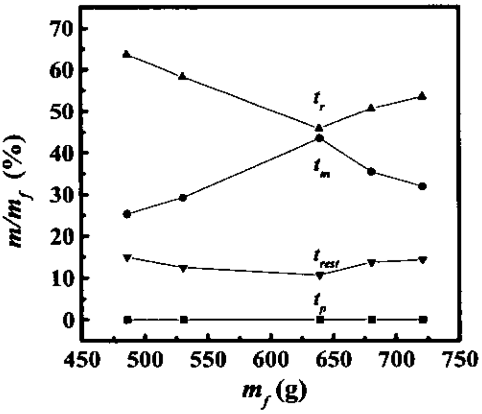


Fig. 8 Draining water ratio for defrosting period with the weight of frost for relative humidity.

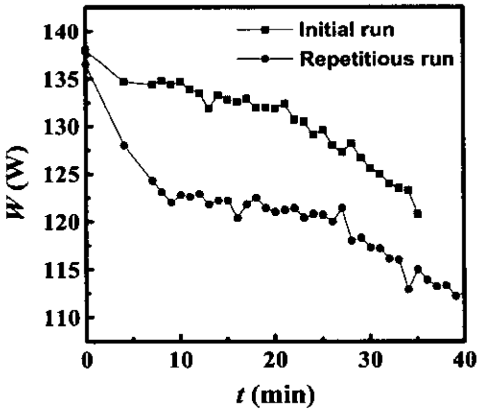


Fig. 9 The comparison of power supply between initial run and repetitive run during defrosting.

supplying between the initial run and the repetitive run during the defrosting under the standard frosting condition. The starting power of the repetitive run(639g of frosting mass) is almost the same with that of the initial run (636g of frosting mass), but it decreases rapidly to 9W of difference after finishing the defrosting process. As a result, the defrosting time requires 42 minutes which takes longer by 5 minutes than that of the initial run(37 minutes). Moreover, the air temperature of the test section after defrosting increases by 1.5 ℃, and the defrosting efficiency shows 70% that is decreased by 5%, compared with an initial run. Therefore, the application of the PTC heating sheet to practical system needs further research on the material to maintain the defrosting performance, and also needs to take into consideration the performance degradation by repetitive usage.

4. Conclusions

In this paper, defrosting experiments are conducted with fin-tube heat exchangers installed with an electric heater and a PTC heating sheet, respectively. From the experiments, the following conclusions are obtained through the investigation of the temperature variation in the test section and the draining behavior of melted water.

(1) The water draining rate of the PTC heating sheet shows an oscillating pattern because the melting velocities of a heat exchanger are different with each row.

(2) The PTC heating sheet drains out fully melted water because it heats uniformly as a surface heater, and a larger portion of draining water is discharged during the rest period compared with the conventional electric heater.

(3) For the PTC heating sheet, the increments of the air temperature are very small whereas the increments in the heating element are high. Therefore it records a 25% higher value of defrosting efficiency than that of the electric heater.

(4) The defrosting efficiency remains constant over 530g of frosting mass. Thus, if the heat transfer performance and defrosting time are decided, the optimum frosting mass can be selected.

(5) The defrosting performance of the PTC heating sheet degrades with repetitive usage and this should be considered in practical applications.