Characteristic of Frost Formed on Thermally Conductive Plain Plastic Plate

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ABSTRACT: In order to select a new material for a heat exchanger, the frosting behavior of a thermally conductive plastic based on PBT was compared to the frosting behavior of aluminum and three types of plastics based on PTFE. The frosting behavior on the 1 mm thick PBT specimen was similar to that of the aluminum specimen but not that of the pure PTFE specimen. The properties of the frost formed on the specimens were affected by both the thermal conductivity and surface characteristics of the materials. The heat and mass transfer rates of the thermally conductive plastic were almost equivalent to those of the aluminum specimen.

Nomenclature

A : area [m^2]
c_p : specific heat [kJ/kgK]
h_{sv} : heat of sublimation [kJ/kg]
$\dot{m}$: mass flow rate [kg/s]
m_f : frost mass [kg]
$\ddot{m}_f$: frost deposition rate per unit area [kg/m^{2}s]
q : heat transfer rate [W]
q'' : heat flux [W/m^2]
T : temperature [℃]
t : time [min]
w : absolute humidity [kg$_w$/kg$_a$]
x_f : frosting thickness [mm]

Greek symbols

ρ : density [kg/m^3]

Subscripts

a : air-side
in : inlet
out : outlet

1. Introduction

Consumers always require more comfortable environment and more convenient appliances along with the elevation of living standards. In order to meet the requirement, the HVAC industry has been continuously progressing worldwide, especially in the field of heat exchangers. Extensive research related to the shape and material used in heat exchangers has been carried out. One of the main objectives of the previous research has been to enhance the heat transfer performance of heat exchangers by increasing both the heat transfer area and heat transfer coefficient while reducing the overall cost as much as possible. A metallic fin-and-tube heat exchanger is one of the common types used today due to its characteristics such as thermal conductivity, productivity, burst pressure, durability, etc.

Studies on heat exchanger material can be divided into two types. The first type focuses on obtaining the desired characteristics by trea-

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ting the surface of metal heat exchanger.[1-5] The second type involves the adoption of non-metallic materials such as plastic resins to minimize the cost and obtain special characteristics.[6-9] The application of plastics as a material for the heat exchanger is generally known to be effective because plastics are anti-corrosiveness, lightweight, and have a low material cost, compared with traditional metal heat exchangers. On the other hand, plastics have significant drawbacks, such as low thermal conductivities and pressure resistances, which have resulted in few studies on their practical use. As a result, there is little available in the literature on the feasibility of plastic heat exchangers for frosting conditions. However, the problem of low conductivity has been reduced by development of thermally conductive plastic which possesses a thermal conductivity 10 to 100 times (1~30 W/m℃) greater than existing plastics.

In the present study, we investigate the feasibility and frosting behavior characteristics of the plastics for heat exchanger under frost formation conditions. The frosting behavior characteristics of the materials are examined by performing experiments on the surface of thermally conductive plastic based on polybutylene terephthalate (PBT), three types of plastics based on polytetrafluorethylene (PTFE) and aluminum (Al 1050) specimen. This study is intended to collect the basic data required to adopt thermally conductive plastics for heat exchangers.

2. Experiment

2.1 Experimental apparatus

The experimental setup used in this study is shown in Fig. 1. It consists of a test section where the specimen is installed, a wind tunnel to circulate the airflow, a cooling section to maintain the surface temperature of the specimen, and a power supply section to supply electricity to a thermoelectric module. The experimental devices are installed in a climate chamber to control the inlet air conditions of the test section.

The airflow rate at the test section inlet port was controlled by a blower installed in the circulation section, and uniform flow was ensured by inserting a flow straightener both in front of and behind the test section. The test section was composed of 10 mm thick acrylic panel. The height of the airflow duct is 100 mm. After considering the thickness of a typi-

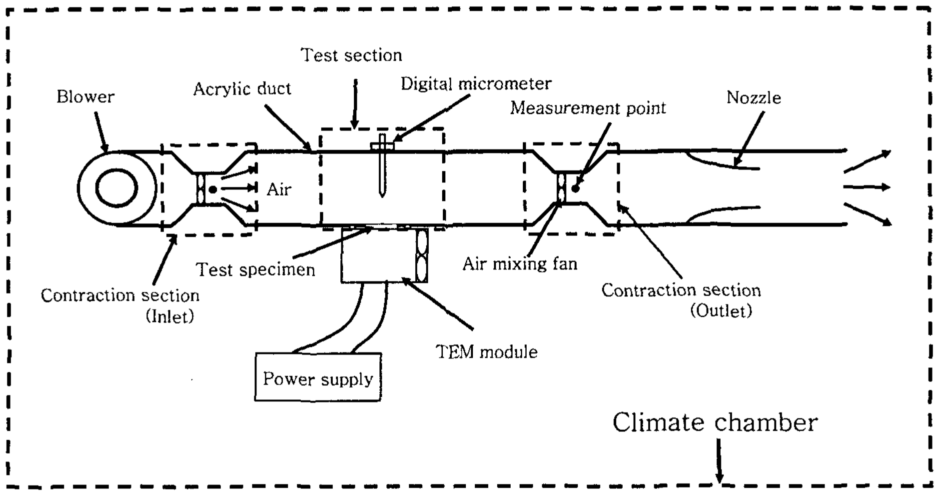

Fig. 1 Experimental apparatus.

cal heat exchanger tube and the permeation characteristics of the refrigerant in the tube, a thickness of 1 mm was chosen for the test specimens. The cross-sectional area was reduced from 100×100 mm^2 at the test section to 30×30 mm^2 at the contraction section. An air mixing fan was installed at the contraction section to measure the inlet and outlet bulk temperatures. The cooling section was composed of a thermoelectric module with power of 150 W and a surface area of 50×50 mm^2, a 110 mm diameter cooling fan and a display panel to indicate the temperatures of both the cooling surface and radiating part of the thermoelectric module. The power supply section was composed of a DC power supply for the thermoelectric module and its blower.

2.2 Test specimens

Five different specimens were prepared to experimentally investigate the frosting behavior. The first was a thermally conductive plastic based on PBT that was strong enough for use as a heat exchanger. There are three types of PTFE: PTFE, PTFE/CG and PTFE/CF/PI. The PTFE specimen consisted of a PTFE used in industrial applications that is a non-stick, chemically stable, and resistant plastic. The PTFE/CG specimen was mixed with 25% carbon graphite to enhance its thermal conductivity. The PTFE/CF/PI specimen was a mixture of PTFE with 5% polyimide and 10% carbon fiber. The polyimide compound had good thermal and chemical properties, as well as mechanical characteristics that enabled the product to maintain its shape. The carbon fiber compound had excellent elasticity and strength. The fifth specimen was made of aluminum.

Figure 2 shows a schematic diagram of the thermoelectric module (TEM) and a test specimen. Test specimens were attached to the aluminum plate on the TEM. A thermal paste was spread on the upper and lower sides of the aluminum plate in order to reduce the thermal resistance between the cold thermoelectric

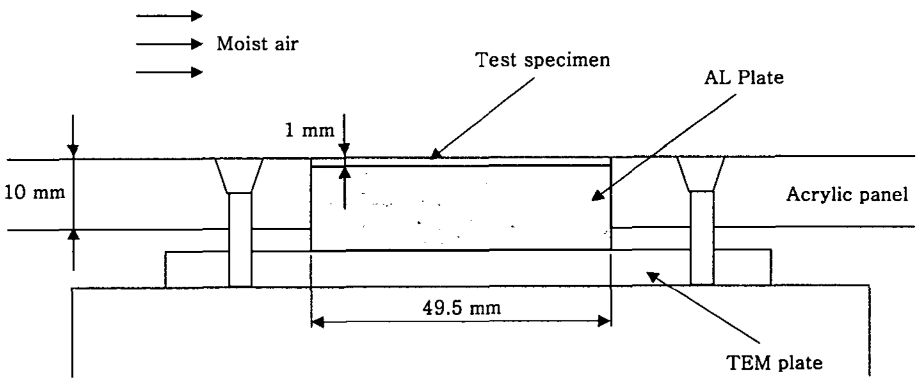

Fig. 2 Schematic diagram of the test specimen.

Table 1 Test specimen properties

	Unit	Al.	PBT	PTFE		
				PTFE	PTFE/CG*	PTFE/CF† /PI§
Specific gravity		1.69	1.69	2.168	2.08	2.07
Contact angle (static)	°	72	82	95	96	97
Thermal conductivity	W/m℃	220	1.5	0.24	0.72	0.47

* : 25% carbon graphite, † : 10% carbon fiber, § : 5% polyimide

module surface and the specimen surface. The specimens were 49.5 mm in diameter and 1.0 mm in thickness, and were treated to provide a smooth flat surface. The properties of each specimen are presented in Table 1. A thermocouple was attached to the center of the thermoelectric module surface to measure the cooling temperature.

2.3 Experimental method

The surface of the test specimens was covered with a vinyl wrap to prevent frosting before the cold surface temperature reached its steady state value. Once the measuring system had reached steady-state conditions, the vinyl wrap was removed. The experiments were run for 180 minutes. The experimental conditions are shown in Table 2.

Frost thickness was measured by inserting a depth micrometer through a hole drilled into the upper plane of the test section. The micrometer used in this experiment had an accuracy of 0.001 mm. The base of the micrometer was mounted flush with the upper plane of the duct, and the micrometer acrylic probe was advanced downward until it contacted the frost surface. In order to prevent the melting of the frost surface by the acrylic probe, the probe was contained in a refrigeration system maintained at −18℃ during testing. The tip of the probe was painted black to easily distinguish it from the frost surface. The measurements were carried out every 15 minutes during the first hour of the experiment and every 30 minutes afterwards.

The weight of the frost formed on the specimen surface was measured using an electronic chemical balance with an accuracy of 0.0001 g. The average density of the frost was calculated by combined the measured frost thickness and its weight as follows:

$$\rho_f = \frac{m_f}{Ax_f} \tag{1}$$

The heat transfer rate through the test specimen was calculated from

$$q = \dot{m}_a c_{p,a}(T_{a,in} - T_{a,out}) + \dot{m}_a h_{sv}(w_{a,in} - w_{a,out}) \tag{2}$$

where the air flow rate, the air-side temperature and the absolute humidity at the inlet and outlet were obtained from the experiments. The frosting rate was calibrated by comparing the calculated value obtained by the humidity sensor installed at the duct inlet and outlet with the measured mass every 30 minutes.

The airflow rate was controlled by adjusting the rpm of the blower equipped with an inverter in the circulation section and calculated from the pressure difference through the flow nozzle. The inlet and outlet air temperatures and humidities were measured using type T thermocouples and humidity sensors at the contraction section where the air mixing fan was installed to uniform the airflow temperature and humidity. Two-by-two thermocouple arrays were installed at the measuring points to accurately measure the temperatures. All the data were recorded every 10 seconds by a data logging system and a PC. In order to enhance the reliability of the results, five sets of experiments were conducted for each specimen. These data were averaged to obtain the final result.

The uncertainties in this study were calculated by means of the uncertainty analysis method proposed by Kline and McClintock.[10] The uncertainties were 5.66% for the frost thickness, 7.55% for the frost density and 2.77 % for the heat transfer rate.

Table 2 Experimental conditions

Experimental condition	Value
Air velocity	1.3 m/s
Air temperature	10℃
Air humidity	0.006628 kg_w/kg_a
Cooling temperature (TEM)	−28℃

3. Results and discussion

In this study, the frosting behavior characteristics of thermally conductive plastic were investigated through a series of experiments on specimens of thermally conductive plastic based on PBT, three types of plastics based on PTFE, and aluminum.

3.1 Frost growth behavior

Figure 3 shows the temporal growth of the frost thickness for each specimen. The frosting behaviors of the test specimens were similar except for the pure PTFE. The similarity in frosting behavior was due to the thickness of the test specimens (1.0 mm) which made no difference in the thermal conductivity effects. Among the specimens, the PBT recorded a surface temperature almost the same as that of aluminum. Between these two specimens, the frost growth on the PBT, which had a relatively large contact angle, was faster than that on the aluminum surface. On the other hand, the two composite materials of PTFE (PTFE/CG and PTFE/CF/PI), which had almost the same contact angles and surface temperatures, had similar frost growth behaviors. For the pure PTFE specimen, which had the lowest thermal conductivity among the test specimens, the frost layer grew slowly due to the relatively high temperature of the test surface. To verify the above results, the initial surface temperatures of each specimen were recorded by attaching a thermocouple at their centers. The temperatures are given in Table 3.

Figure 4 represents the temporal variations of the frost density of each specimen. Generally, frost becomes denser at higher surface temperature. The frost density of the pure PTFE was the highest among the specimens because of its high surface temperature (Table 3). Even

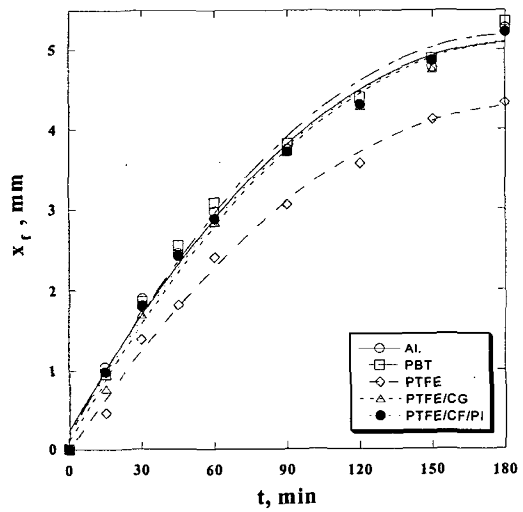

Fig. 3 Temporal variations of the frost thickness for different test specimens.

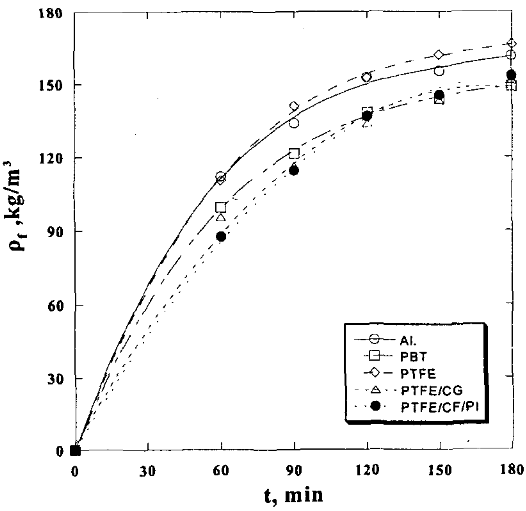

Fig. 4 Temporal variations of the frost density for different test specimens.

Table 3 Initial frosting surface temperature of the test specimens

Item	Unit	Al.	PBT	PTFE		
				PTFE	PTFE/CG	PTFE/CF/PI
Surface temp	℃	−26.6	−26.5	−24.5	−25.9	−25.9

though the aluminum specimen had the lowest surface temperature, it had a greater frost density than the PBT and the PTFE composite plastics. The contact angle of the aluminum specimen was 72° and that of both the PTFE composites was about 96°, as shown in Table 1. This difference induced the frost density variation.[1] The frost density of PBT was less than that of the aluminum because of the larger contact angle. On the other hand, the frost density of the PBT was similar to that of the PTFE composites because the effects of the lower surface temperature and smaller contact angle of the PBT cancelled each other out.

3.2 Heat and mass transfer

Figure 5 depicts the variation of the heat flux with time for each specimen. In the early stages of frost formation, the aluminum and PBT specimens, which had low initial surface temperatures, had larger heat fluxes than the other specimens. The pure PTFE had the smallest heat flux among all the specimens. As the frost grew with time, the decrease in the amount of heat transfer of the pure PTFE was relatively small because of the slow growth of the frost layer. On the other hand, the rapid growth of frost on the other specimens caused the surface temperature to increase. As a result, the heat flux of the PTFE was greater than that of the other materials after 120 minutes of running time, but the differences did not exceed 3%.

Figure 6 shows the variation of the mass flux with time for each specimen. In the early stages of frost formation, the PTFE specimens with the highest initial surface temperature had the smallest mass flux, whereas both the PBT and aluminum specimens, which had the lowest initial temperature, had the largest mass fluxes. The mass flux of the PBT was similar to that of the aluminum specimen during the early stages of frost formation, but because of the relatively low density of the formed frost, the mass flux changed to values that were similar to the other PTFE composites as time increased. The rate of mass flux decrease for the pure PTFE specimen was less than that of the other specimens because growth of frost density on the PTFE surface exceeded the increase in frost thickness.

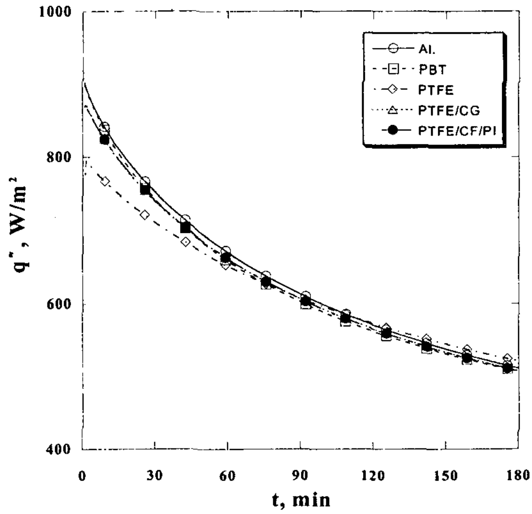

Fig. 5 Temporal variations of the heat transfer for different test specimens.

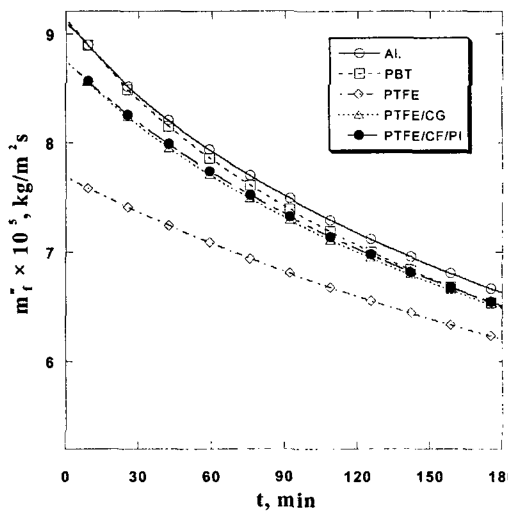

Fig. 6 Temporal variations of the mass transfer for different test specimens.

4. Conclusions

An experimental investigation was carried out to characterize the frosting behavior of thermally conductive plastic based on PBT by comparing it with that of aluminum and three types of plastics based on PTFE. The conclusions are as follows.

(1) The frosting behavior on the thin PBT surface was qualitatively similar to that of aluminum but not that of the pure PTFE.

(2) The frosting behavior on the surface was affected by both the thermal conductivity and surface characteristics of the material.

(3) The heat and mass transfer rates of the thermally conductive plastic were equivalent to those of aluminum.

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References

1. Jhee, S., Lee, K. S. and Kim, W. S., 2002, Effect of surface treatments on the frosting/defrosting behavior of a fin-tube heat exchanger, Int. J. Refrigeration, Vol. 25, No. 8, pp. 1047-1053.
2. Tsuda, Y. and Iwamoto, A., 1992, Anti-frosting heat exchanger, National Technical Report, Vol. 38, No. 1, pp. 108-113.
3. Wang, C. C. and Chang, C. T., 1998, Heat and mass transfer for plate fin-and-tube heat exchangers with and without hydrophilic coating, Int. J. Heat Mass Transfer, Vol. 41, No. 20, pp. 3109-3120.
4. Östin, R. and Johannesson, G., 1991, A polymetric approach to counteract frosting in air-to-air heat exchanger, Heat Recovery Systems & CHP, Vol. 11, No. 5, pp. 15-421.
5. O'Neal, D. L., Bryant, J. A. and Parker, B., 1997, Impact of hydrophobic coating on the frost buildup and defrost performance of a heat pump evaporator, 45th Oji International Seminar, pp. 181-187.
6. Hetsroni, G. and Mosyak, A., 1994, Heat transfer and pressure drop in a plastic heat exchanger with triangular channels, Chemical Engineering and Processing, Vol. 33, pp. 91-100.
7. Bigg, D. M., Stickford, G. H. and Talbert, S. C., 1989, Applications of polymeric materials for condensing heat exchangers, Polymer Engineering and Science, Vol. 29, No. 16, pp. 1111-1116.
8. Jachuck, R. and Ramshaw, C., 1994, Process intensification: Polymer film compact heat exchanger (PFCHE), Trans. IChemE, Vol. 72, No. 2, pp. 255-262.
9. Patel, A. B. and Brisson, J. G., 2000, Design, construction, and performance of plastic heat exchanger for sub-Kelvin use, Cryogenics, Vol. 40, pp. 91-98.
10. Kline, S. J. and McClintock, F. A., 1953, Describing uncertainties in single-sample experiments, Mechanical Engineering, Vol. 75, pp. 3-8.