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FROST FORMATION ON THERMALLY CONDUCTIVE PLASTIC PLAIN PLATE

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ABSTRACT

An experimental study was carried out to investigate the frosting behavior of a thermally conductive plastic (PBT based resin) by comparing it with those of aluminum and plastic test specimens (PTFE based resin) in order to select a new material for heat exchangers. It was found that the frosting behavior on the plastic specimens with 1 mm thickness was similar to those of aluminum but not pure PTFE. The properties of the frost formed on the specimens were affected by both thermal conductivity and surface characteristics of the materials. The results indicate that the heat and mass transfer rates on plastic materials are almost equivalent with those of aluminum.

INTRODUCTION

People's desire for a better environment and more convenient appliances are increasing along with the elevation of the living standard. In order to meet public demand, the HVAC industry has been continuously progressing worldwide, especially in the field of heat exchangers. Extensive researches on the shape and material of heat exchanger have been carried out. The main purpose of the previous researches is to enhance the heat transfer performance by increasing both the heat transfer area and the heat transfer coefficient, while reducing the cost as much as possible. Typical type of the heat exchanger used today is a metallic fin-and-tube type due to the thermal conductivity, productivity, burst pressure, durability, etc.

Studies on the heat exchanger material can be divided into two types. The first type of research focuses on obtaining desired characteristics by surface treatment of the metal heat exchanger [Jhee *et al.*(2002), Östin and Johannesson(1991), O'Neal *et al.*(1997), Tsuda and Iwamoto(1992), Wang and Chang(1998)]. The second type is concerned with the adoption of non-metallic materials such as plastic resins for the purpose of minimizing cost and obtaining special characteristics [Bigg *et al.*(1989), Hetsroni and Mosyak(1994), Jachuck and Ramshaw(1994), Patel and Brission(2000)]. The application of plastics as a material for the heat exchanger is generally known to be effective because plastics have many advantages such as anti-corrosiveness, low material cost, and light weight, compared with traditional metal heat exchangers. On the other hand, plastics have significant drawbacks such as low thermal conductivity and low pressure resistance which have slowed researches on their practical use. In the literature, there are little available on the feasibility of plastic heat exchangers under frosting conditions. However, the problem of low conductivity has been improved by developing what is called a thermally conductive plastic which possesses a thermal conductivity of 10 to 100 times (1~30 W/m℃) larger value than the existing plastics.

Therefore, in the present study, we investigate the feasibility and the frosting behavior characteristics of the plastic to simulate the heat exchanger under frost formation conditions. The frosting characteristics are examined by performing experiments on the surface of thermally conductive plastic specimen based on PBT (polybutylene terephthalate) resin, PTFE (polytetra-fluorethylene) based plastics and aluminum. This study is intended to collect basic data on the usage of the thermally conductive plastic for heat exchangers.

EXPERIMENT

Experimental Apparatus

The experimental set-up 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 air flow, 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 condition of the test section.

The air flow rate at the test section inlet port was controlled by a blower installed in the circulation section, and the uniformity of the flow was ensured by inserting a flow straightener in front of and behind the test section. The test section composed of an acrylic panel of 10 mm in thickness. The height of the air flow duct is 100 mm. By considering the thickness of the typical heat exchanger tube and the permeation characteristics of the refrigerant to the tube, a thickness of 1 mm is chosen for the test specimens. The cross-sectional area is reduced from 100×100 mm^2 at

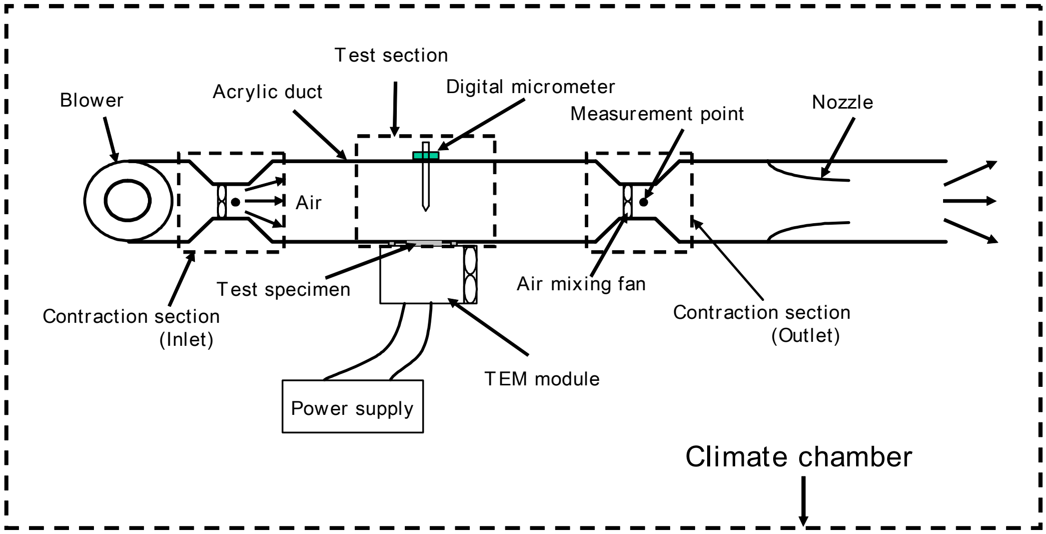

Fig. 1 Experimental apparatus

the test section to 30×30 mm^2 at the contraction section. An air mixing fan was installed at the contraction section in order to measure the inlet and outlet bulk temperatures. The cooling section composed of the thermoelectric module with a power of 150 W and a surface area of 50×50 mm^2, a cooling fan with a diameter of 110 mm and a display panel for indicating both temperatures of the cooling surface and radiating part of the thermoelectric module. The power supply section composed of a DC power supply for the thermoelectric module and its blower.

Test specimens

Five different of specimens are prepared to experimentally investigate the frost formation rate. There are a thermally conductive plastic based on PBT that is strong enough for the heat exchanger, and 3 kinds of plastics based on PTFE(PTFE, PTFE/CG and PTFE/CF/PI). The PTFE specimen is a PTFE used in industrial which is a non-stick, chemical stabile, and resistant plastic. The PTFE/CG specimen is mixed with 25% carbon graphite to enhance the thermal conductivity. The PTFE/CF/PI specimen is a mixture of PTFE with polyimide by 5% and carbon fiber by 10%. The polyimide compound has good thermal and chemical properties, mechanical characteristics which enable the product to maintain its shape, and it has relatively high water adsorption characteristics. The carbon fiber compound has excellent elasticity and strength.

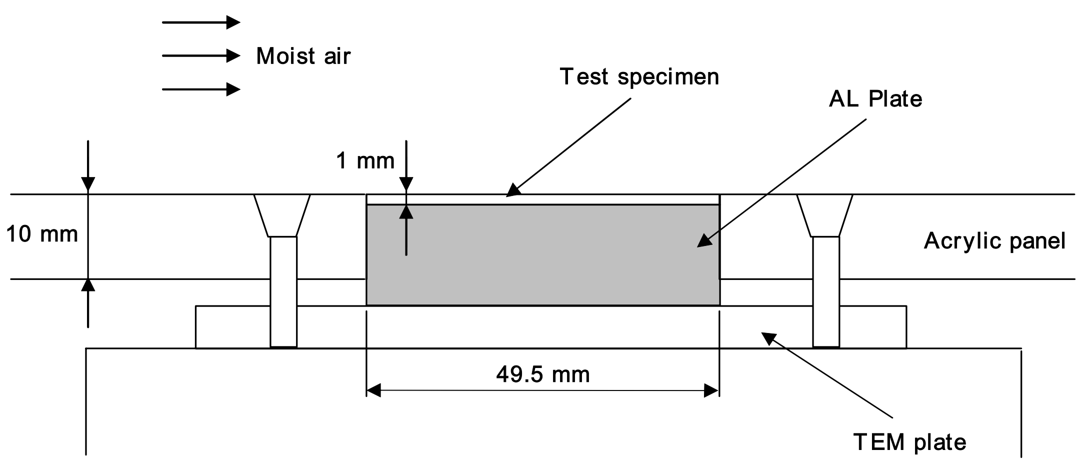

Fig. 2 Schematic diagram of TEM and test plate.

Table 1 Properties of test specimens

	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)	o	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

Fig. 2 shows the schematic diagram of the thermoelectric module (TEM) and the test specimen. Test specimens were attached to the aluminum plate on the TEM. A thermal paste was spread on the upper and bottom sides of the aluminum plate in order to reduce the thermal resistance between the cold thermoelectric module surface and the specimen surface. The specimens have dimensions of 49.5 mm in diameter and 1.0 mm in thickness, and were treated to provide a flat and smooth surface. The properties of each specimen are presented in Table 1. A thermocouple was attached at the center of the thermoelectric module surface to measure and verify the cooling temperature.

Experimental method

A vinyl wrap covered the surface of the test specimen to prevent frosting before the cold surface temperature reached its steady state. Once the measuring system had reached steady-state conditions, the vinyl wrap was removed. Then the experiments were conducted 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 experiments has 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 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℃. The tip of the probe was painted black to easily distinguish it form the frost surface. The measurements were carried out every 15 minutes during the initial one hour and every 30 minutes afterwards.

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℃

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

$$\rho_f = \frac{m_f}{A x_f} \tag{1}$$

The heat transfer rate through the test specimen can be calculated as follows:

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

where the air flow rate, the air-side temperature and the absolute humidity at the inlet and outlet are obtained from 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 air flow rate was controlled by adjusting the rpm of the blower equipped with an inverter in the circulation section and measured by means of pressure difference through the flow nozzle. The inlet and outlet air temperatures and humidities were measured by using type T thermocouples and humidity sensors at the contraction section where an air mixing fan was installed to uniform the air flow temperature and humidity. Two by two thermocouple arrays were installed at measuring points to accurately measure the temperature. All the data were recorded by a data logging system and a PC every ten seconds. In order to enhance the reliability of the results, 5 sets of experiments were conducted for each specimen and 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(1953). The uncertainties were 5.66% for the frost thickness, 7.55% for the frost density and 2.77% for the heat transfer rate.

RESULTS AND DISCUSSION

In this study, the feasibility and the frosting behavior characteristics of thermally conductive plastic were investigated by performing experiments on specimens of thermally conductive plastic based on PBT resin, 3 kinds of PTFE based plastics, and aluminum.

Table 3 Initial frosting surface temperature of 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

The Frost Growth Behavior

The Fig. 3 shows the temporal growth of the frost thickness for each specimen. The frosting behaviors of the test specimens were similar except the pure PTFE. The similarity in frosting behavior is due to the thickness of test specimens (1.0 mm) which caused variations in the surface temperature to be small. Among the specimens, the PBT recorded a surface temperature almost the same as that of aluminum. Between the two specimens, the frost growth on the PBT surface that has a relatively larger contact angle was faster than that of the aluminum surface. On the other hand, the two composite materials of PTFE (PTFE/CG and PTFE/CF/PI) that had almost the same contact angle and surface temperature had similar frost growth behavior with each other. But in the case of the pure PTFE specimen that 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 the center of the test specimen. The temperatures are given in Table 3.

Fig. 4 represents the temporal variations of the frost density of each specimen. Generally, frost becomes denser at higher surface temperature. The frost density of PTFE was the highest among the specimens because of its high surface temperature (Table 3). Though the surface temperature of the aluminum specimen had the lowest value,

test specimens.

it had a higher density than that of the PBT and the composites of PTFE. The contact angle of the aluminum specimen is 72° and those of the PTFE composites are about 95°, as shown in Table 1. This difference is considered to induce the variation of the frost density [Jhee *et al.*(2002)]. The frost density of PBT was smaller than that of aluminum because of a larger contact angle. On the other hand, the PBT density was similar to that of the PTFE composites because effects of the lower surface temperature and smaller contact angle of PBT were cancelled out.

Heat and Mass Transfer

Fig. 5 depicts the variation of heat flux with time for each specimen. In the early stage of frost formation, aluminum and PBT specimens that had low initial surface temperature had larger heat flux than the other specimens and the pure PTFE had the smallest value among all specimens. As the frost grows with time, the amount of heat transfer decrease of pure PTFE is relatively small because of slow growth of the frost layer whereas rapid growth of frost on the other specimens causes to ascend the surface temperature. As a result, the heat flux of PTFE showed a larger value than those of the other materials after 120 minutes of running time, but the differences did not exceed 3%.

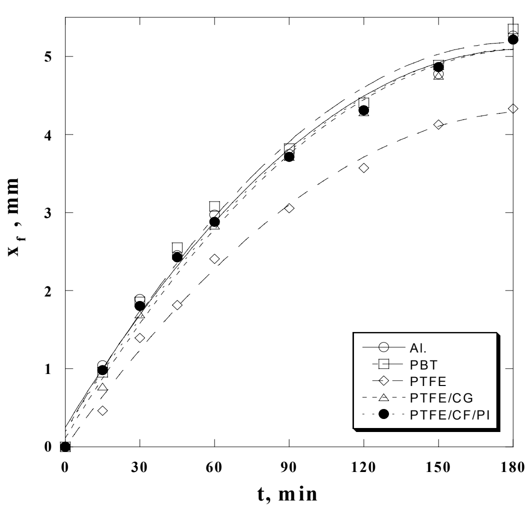

Fig. 3 Temporal variations of frost thickness for different

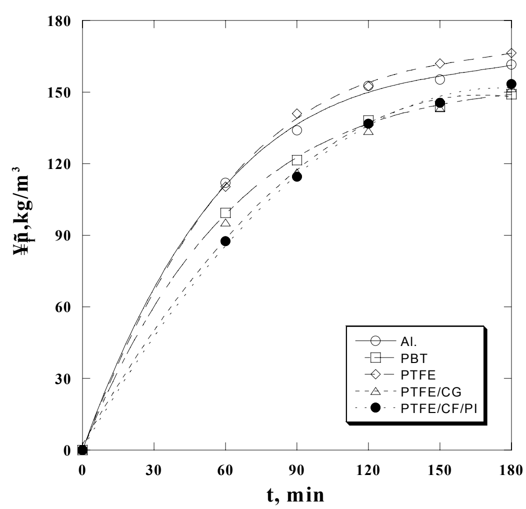

Fig. 4 Temporal variations of frost density for different test specimens

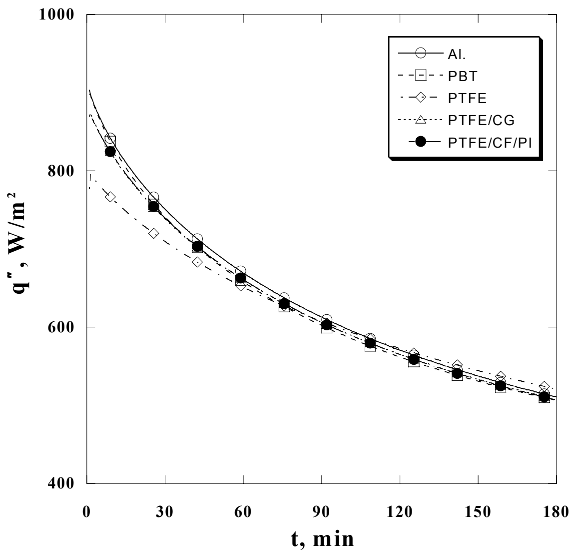

Fig. 5 Temporal variations of heat transfer for different test specimens**.**

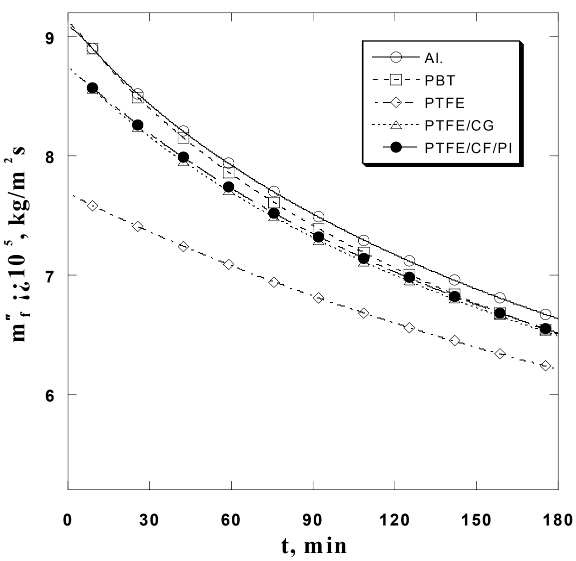

Fig. 6 Temporal variations of mass transfer for different test specimens.

Fig. 6 shows the variation of mass flux with time for each specimen. In the early stage of frost formation, the PTFE specimen with the highest initial surface temperature showed the smallest mass flux, whereas both PBT and aluminum specimens that had the lowest initial temperature had the largest value. The mass flux of PBT is similar to that of aluminum during the early stages of frost formation, but because of the relatively low density of frost formed it is changed to similar values to the other PTFE based plastic specimens with elapsing time. The decrease rate of pure PTFE mass flux is smaller than the others because growth of frost density on the PTFE surface surpasses that of the thickness.

CONCLUSIONS

An experimental investigation was carried out to characterize the frosting behavior of thermally conductive plastic (PBT based resin) by comparing with those of aluminum and other plastics (PTFE based resin). The conclusions are as follows:

1. The frosting behavior on the thin plastic surface is qualitatively similar to that of aluminum.

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

3. The heat and mass transfer rate of the thermally conductive plastic are equivalent with those of aluminum.

ACKNOWLEDGMENTS

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NOMENCLATURE

A area, m^2
C_p specific heat, kJ/kgK
h_{sv} heat of sublimation, kJ/kg
k thermal conductivity, W/mK
m_f frosting mass, kg
m mass transfer rate, kg/s
Q heat transfer rate, W
T temperature, °C
t time, min
u velocity, m/s
w absolute humidity, kg$_w$/kg$_a$
x_f frosting thickness, mm
ρ density, kg/m^3

Subscripts

a air-side
in inlet
out outlet

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