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Moisture Transport Through a Porous Plate with Micro Pores

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1. Introduction

Considering the variety of environment problems, including global warming, that call for a reduction in emission gases, increasing the fuel efficiency and reducing exhaust gases from automobiles has become an important issue for the automobile industry. Compared to traditional automobiles, fuel cell vehicles have many advantages, including high efficiency, low emissions, and diversification of fuel supply. Therefore, fuel cell vehicles are expected to become a viable means of transportation in the 21st century. Consequently, extensive research is being conducted to develop fuel cell vehicles that use polymer electrolyte membrane fuel cells as a power source.

Fuel cell systems for vehicles are composed primarily of a fuel and air supply unit, a humidifier, a cooling device, and the polymer electrolyte membrane fuel cell (PEMFC). Since the degree of ion conduction in an electrolyte film in the fuel cell is determined by the water content of the film, some water content is necessary in order to maintain ion conduction in the film. Generally, the film is humidified through gas diffusion layer (GDL) using high humidity work gases. The research on the humidifying methods and the influence of the humidity of work gases on the performance of fuel cells have been reported by Nguyen & White (1993) and Yoshikawa et al. (2000), respectively. Buchi & Scherer (2001) investigated the effects of the water content and the membrane thickness on the resistance of Nafion membranes in PEMFC.

From the point of view of saving space, it is desirable to recover and reuse the humidity in the exhaust gas using the supply air. In the present study, a method involving a thin porous plate for air dehumidification(Asaeda et al., 1984, 1986),in which direct recovery of the moisture of the exhaust gas to the supply air through a thin porous plate or membrane, is considered. In this case, the following phenomena may occur: 1) mass and heat transport and an accompanying phase change inside the porous plate, 2) water evaporation from the surface of the porous plate and moisture diffusion around the surface of the plate on the supply air side, and 3) condensation of moisture on the porous plate surface on the exhaust gas side. Analysis is difficult because of the complex interaction between these phenomena. Therefore, in order to simplify our investigation, as a first step, we focus on the heat and mass transport characteristics on the supply gas side and inside the porous plate. In order to fix the heat and mass transfer characteristics of the exhaust side, we assume that the moisture supply capacity of the exhaust side is sufficiently high so that constant-temperature water can be used rather than the exhaust gas. Thus, the subject of the examination becomes the heat and mass transport between dry air and constant-temperature water through a porous plate.

A number of studies have examined the heat and mass transport accompanied by a phase change in porous media. For example, the gas-liquid two-phase flow, driven by capillary force in the porous media and accompanied by the evaporation of water has been experimentally and theoretically investigated by Udell (1983, 1985) and Zhao & Liao (2000). The sizes of the porous media used in these studies were ϕ54×254 mm and 40×99×29 mm, respectively. In addition, the diameter of the particles that composed the porous media were 0.1 ~ 0.8 mm and 1.09 mm, respectively, and the corresponding pore diameters were 0.05 ~0.3 mm and 0.46 mm, respectively. Wang et al. (1993a, 1993b, 1996) introduced a multiphase mixture model for the heat and mass transport of multiphase and multi-component mixtures, including the phase change in the porous media, based on a separated flow model in which various phases are regarded as distinct fluids. Simulations were performed employing this multiphase mixture flow model. The infiltration and transport of non-aqueous phase liquids in the unsaturated subsurface were investigated by Cheng & Wang (1996), and the mass transport in the cathode of a PEMFC under isothermal conditions was investigated by You & Liu (2002). Vafai & Whitaker (1986) applied a volume averaging technology to analyze the accumulation and migration of moisture in an insulation material, and, based on a previous study (Vafai & Whitaker, 1986), Vafai & Tien (1989) reduced the number of assumptions and simulated the same problem. Using the network method, Prat (1993) presented a model to investigate drying in porous media under the condition whereby the media was initially saturated with water. Plourde & Prat (2003) studied the influence of a surface tension gradient induced by thermal gradients on the phase distribution within a capillary porous media by developing the model described in Reference (Prat, 1993). Furthermore, Usami et al. (2000, 2001) conducted a quantitative evaluation of the controlling factors, both experimentally and via numerical analysis, for the heat and mass transport in the reforming catalyst bed of a steam reforming fuel cell using methane.

In summarizing the above studies, we observed the following. 1) Several theoretical studies have been performed. 2) The dimensions of the porous media used as an experimental object in previous studies (e.g., the size of the porous media and the diameter of the particles that comprise the porous media) were relatively large. 3) Few studies have examined the influencing factors or mechanism of heat and mass transport in porous media. Therefore, it is difficult to apply the results of the above-mentioned studies in the present study. In particular, research regarding the moisture transport through porous media plate depends of the heat and mass transport inside the porous media and the conditions of heat and mass transfer on the surface of the porous media plate are not reported.

In order to clarify the characteristics of moisture recovery from the exhaust gas of fuel cell vehicles with a porous plate, it is necessary to determine experimentally both the mechanism of heat and mass transport in a thin porous plate having very small pores and the influence of various factors on heat and mass transport in this process. As a first step towards this goal, we evaluate the factors that influence heat and mass transfer from constant-temperature water to dry air through a porous plate. The present authors have investigated moisture transport through a porous plate having a thermal conductivity of 1.7W/(mK) to dry air from constant-temperature water (Wang et al., 2005, 2006). And the present authors have also investigated the effect of thermal conductivity of the porous plate on the moisture transport (Wang et al., 2009). Here,we will summarize the work done in these previous investigations.

2. Experimental apparatus and method

Figure 1 shows a schematic diagram of the experimental apparatus, which is composed of a constant-temperature water circulation system and an airflow loop. The constant-temperature water system consists of a circulation water tank, a water transport pump, a water filter, and ion-exchange equipment. The water used in the experiment is generally maintained in a pure state, using both a water filter that removes particles larger than 0.1 μm and the ion-exchange equipment. Air is pumped to the flow loop and is dehumidified by cooling with water at approximately 0°C. The dehumidified air is heated to an established temperature and absorbs moisture from the constant-temperature water that is in contact with the bottom of the porous plate when supplied to the test device. High-humidity air is discharged to the atmosphere from the test device. The flow rate of air is adjusted by a valve installed at the exit of the air pump and is measured by a flow meter installed after the valve. Thermo-hygrometers are installed at the entrance and exit of the test device to measure the temperature and humidity of the air. In order to prevent the formation of dew at the thermo-hygrometer, a heater was installed around the duct, including the thermo-hygrometer. The heater was also used to control the air temperature in the duct and to maintain the temperature to be consistent with the air temperature in the channel outlet. The temperature of the water was measured by a thermocouple installed on the undersurface of the porous plate in contact with the constant-temperature water. All measurement signals, for example, temperature, humidity, and flow rate, were converted to digital signals by an A/D converter and were recorded by a personal computer.

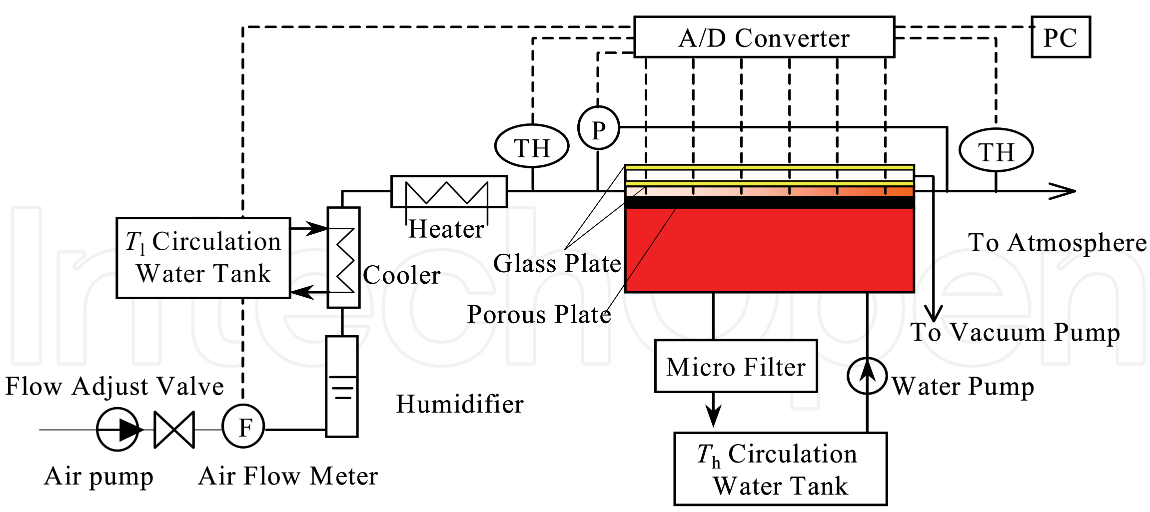

Fig. 1. Experimental system

Figure 2 shows a cross-section of the test device. The surface of the porous plate is 100×28 mm. To observe the surface state of the porous plate, the top of the test device is constructed of a transparent material. A space for vacuum thermal insulation exists at the top of the test device, and insulation is accomplished by the drawing of a vacuum pump. In addition, 1-mm Teflon sheets were installed as insulating material on two sides of the channel in order to prevent heat loss from the sides of the metal frame. The air temperature in the channel above the porous plate and the temperature in the upper surface of the porous plate were measured by ten K-type thermocouples (±0.1°C) of 0.25 mm in diameter that were installed in the channel and the plate along the path of the airflow, respectively. Holes in the porous plate for the insertion of the thermocouples were 0.3 mm in diameter and 15 mm in depth. In Figure 2, the symbols ○ and ● represent the thermocouples, which measure the temperatures of the air in the channel and the upper surface of porous plate, respectively. The temperature of the porous media plate measured here is used as the air-side plate temperature. In addition, the temperature of the plate measured by the thermocouples attached to the bottom of the plate contacting the liquid is used as the liquid-side plate temperature. In the present study, since the temperature of the constant-temperature-water is adjusted to have a small range, the experiments were carried out under an approximately constant liquid-side plate temperature.

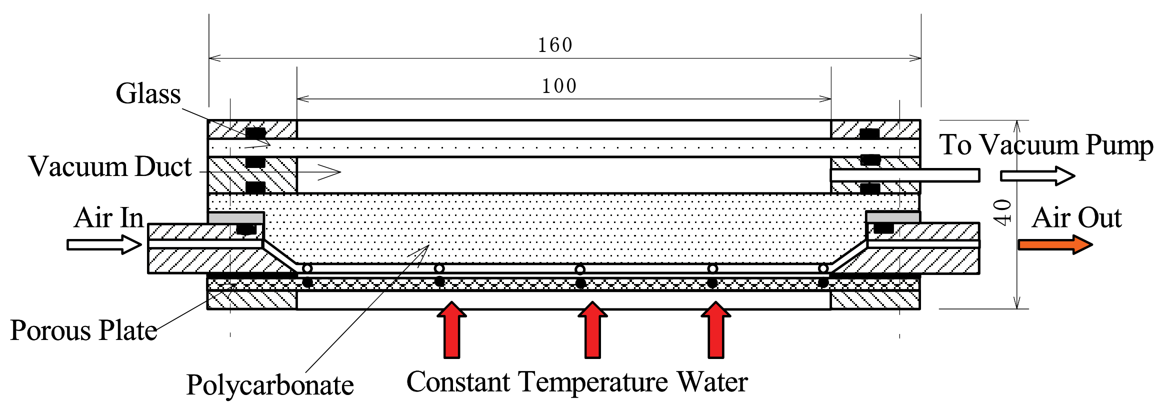

Fig. 2. Schematic diagram of the test section

Alternatively, in present study, in order to remove the effect of the air that is trapped in the porous plate on the experiment result, the porous plate, as a specimen, was impregnated by a vacuum impregnation method before beginning the experiments. In other words, air was evacuated from a closed vessel containing the porous plate in water in order to remove the air contained within the porous plate. Figures 3(a) ~ 3(c) show the variation in the mass flux of the moisture transport through the porous media plate with respect to the air volumetric flow under the conditions of both vacuum impregnation and non-vacuum impregnation. This graph indicates that the variation of the mass flux caused by the vacuum impregnation depends on the thickness and the pore diameter of the porous plate. In other words, the effect of vacuum impregnation appears to be more remarkable for porous plates having smaller pore diameter and greater thickness. The reason for this is thought to be that almost all of the air inside the pores of the porous plate was removed by the impregnation, so that the water transposition in the porous plate driven by capillary forces becomes easier. Therefore, the vacuum impregnation was carried out for the porous plate used in the present study before the experiments.

3. Experimental results and discussion

Since there are many factors that affect moisture transport from the constant-temperature water to the dry air through the porous plate, in the present study, we first examine the

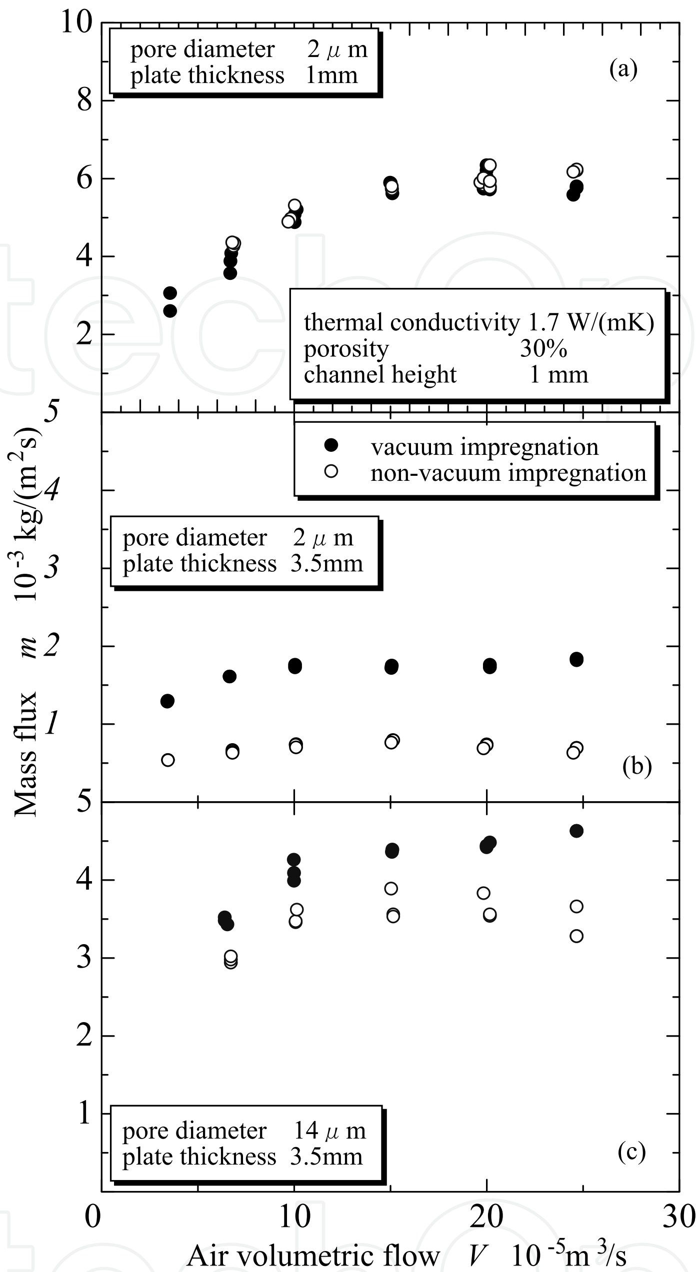

Fig. 3. Effect of impregnation on mass flux

effects of the flow condition of air, the physical properties of the porous plate, and the geometrical size of the channel on the moisture transport. Considering the conditions of practical use, experiments were performed under an air volumetric flow of 3.3 ~ 24.7×10^{-5} m^3/s. To examine the effect of the heat conductivity of the porous plate on the moisture transport, in present study, we used porous media having heat conductivities of 1.7 W/(mK) and 20.2 W/(mK). For reasons related to material manufacture, the experiment to investigate the effect of pore diameter was performed using the porous media with low heat conductivity (1.7 W/(mK))and three average pore diameters D of 2, 5, and 14 μm, and the experiment regarding the effect of porosity was performed mainly using the porous media with high heat conductivity (20.2 W/(mK))and average porosities of 12%, 20%, and 30%. The condition of detail is shown Table 1.

<table>
<tr><th>Heat conductivity
λ_p W/(mK)</th><th>Porosityε</th><th>Pore diameter
D μm</th><th>Plate thickness
Δx mm</th><th>Channel height
h mm</th></tr>
<tr><td rowspan="13">1.7</td><td rowspan="2">20%</td><td rowspan="5">2.0</td><td>1.0</td><td rowspan="5">1.0</td></tr>
<tr><td>2.0</td></tr>
<tr><td rowspan="11">30%</td><td>1.0</td></tr>
<tr><td>2.0</td></tr>
<tr><td>3.5</td></tr>
<tr><td rowspan="5">5.0</td><td rowspan="3">1.0</td><td>0.5</td></tr>
<tr><td>1.0</td></tr>
<tr><td>1.5</td></tr>
<tr><td>2.0</td><td rowspan="7">1.0</td></tr>
<tr><td>3.5</td></tr>
<tr><td rowspan="3">14.0</td><td>1.0</td></tr>
<tr><td>2.0</td></tr>
<tr><td>3.5</td></tr>
<tr><td rowspan="8">20.2</td><td>12%</td><td rowspan="8">2.0</td><td>0.5</td></tr>
<tr><td rowspan="5">20%</td><td>0.5</td></tr>
<tr><td rowspan="3">1.0</td><td>0.5</td></tr>
<tr><td>1.0</td></tr>
<tr><td>1.5</td></tr>
<tr><td>2.0</td><td rowspan="3">1.0</td></tr>
<tr><td rowspan="2">30%</td><td>0.5</td></tr>
<tr><td>2.0</td></tr>
</table>

Air volumetric flow: 3.3-24.7×10^{-5} m^3/s, temperature of air at the inlet: 32ºC, relative humidity of air at the inlet: 15%, temperature of constant-temperature water: 69ºC.

Table 1. Specifications of the porous plate and experimental conditions

3.1 Basic characteristics of moisture transport through the porous plate

Figures 4(a) ~ 4(d) show the variations of parameters that represent the basic characteristics of the moisture transport from water to air flowing the channel through theporous plate, such as the mass flux, the heat flux, the temperature, and the relative humidity of the outlet air, with respect to the air volumetric flow. The experimental conditions are a plate thickness of 1 mm, a channel height of 1 mm, a heat conductivity in the plate of 1.7 W/(mK), a pore diameter of 5 μm, and a plate porosity of 30%. From this graph, it is first understood that the mass flux increases with respect to the increase in the air volumetric flow and varies little when the air volumetric flow exceeds approximately 10×10^{-5} m^3/s. This is thought to be because, even though the moisture absorption ability of the air increases with respect to the increase in the amount of air flowing through the channel, when the air volumetric flow exceeds approximately 10×10^{-5} m^3/s, the moisture transport through the porous plate or the heat transport required by the water vaporization were limited by the properties of the porous plate, e.g., the permeability of liquid or the thermal conductivity. In addition, the heat flux was determined from the heat transfer quantity in the heat and mass transport

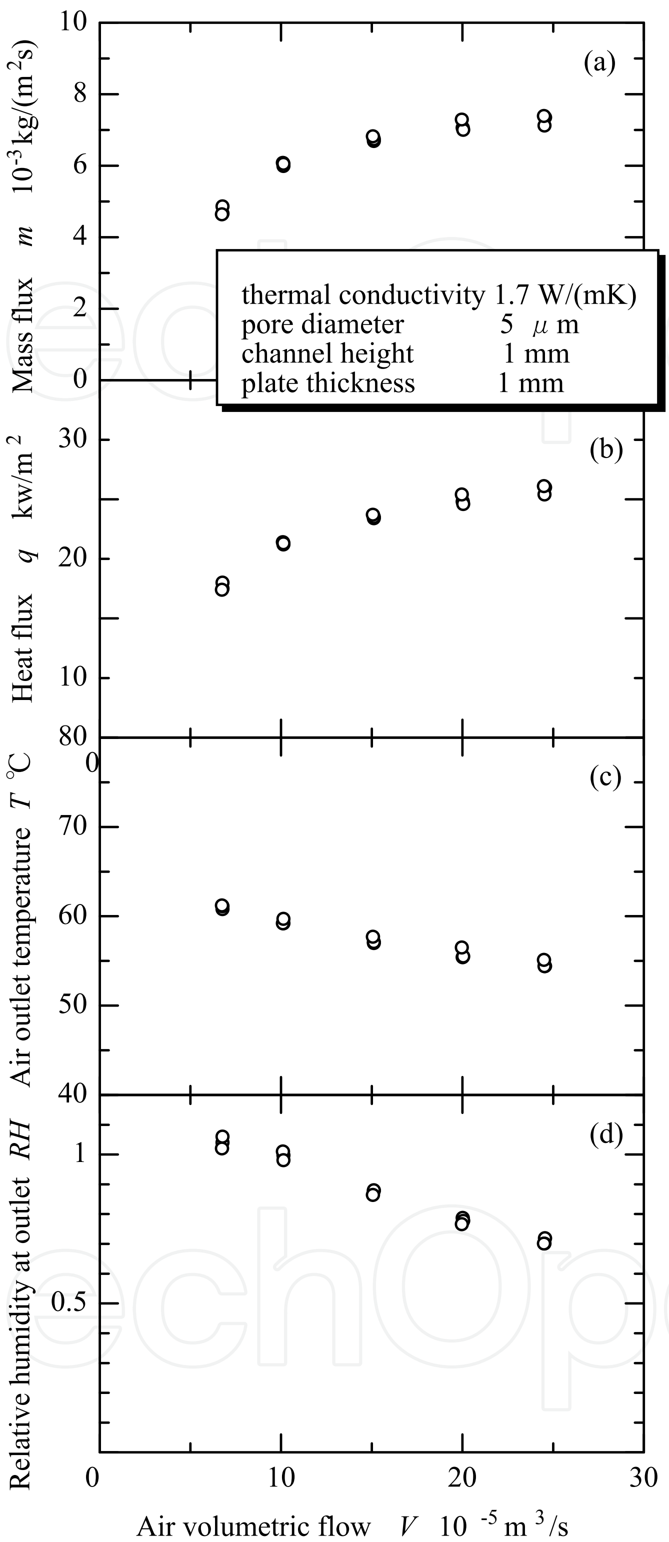

Fig. 4. Basic characteristics of moisture transport from water to air through a porous plate

process calculated from the airflow and the change in enthalpy of the air between the entrance and exit of the channel. The variation in the heat flux showed the same tendency as that for the above mass flux, because the heat flux is primarily caused by the transport of latent heat accompanying the mass transport in this process.

Furthermore, Fig. 4(d) shows that for the case in which the air volumetric flow is less than approximately 10×10^{-5} m^3/s, the relative humidity of the air in the channel exit is approximately 100%. This also explains the tendency of the mass flux variation shown in Fig. 4(a).That is, for the case of the small air volumetric flow, since the moisture absorption capacity of the air is comparatively small, the heat and moisture applied to the air through the porous plate is sufficient.

Figure 5 shows the distribution of temperature in the air flowing through the channel and porous plate. This graph indicates that the temperature of the air and the porous plate increase as the exit of the channel is approached. In the case of a water temperature of 69°C, in the flow direction, the liquid-side porous plate temperature changed from 62°C to 64.4°C due to the water evaporation to the air side. Since the temperature difference between the liquid side and air side of the porous plate decreases in the direction of the air flow, the heat flux, and the moisture transport accompanying it become small as the channel exit is approached. In addition, the temperature difference is found to be greater than that between the air and the porous plate. In particular, this tendency is clearly observed in the vicinity of the channel inlet. Compared to the thickness of 1 mm and thermal conductivity of approximately 1.7 W/(mK) for the porous plate, the heat transfer coefficient of the single-phase air flow in the channel is only a few tens of $W/(m^2K)$. This means that the heat transport by the heat conduction passing through the porous plate is far greater than that by the heat transfer of sensible heat on the porous plate surface. This can explain why the heat transport is approximately equal to the latent heat transport accompanying the moisture transport in this moisture transport process, as mentioned above, and indicates that the heat flux and mass flux are bigger in the vicinity of the channel inlet.

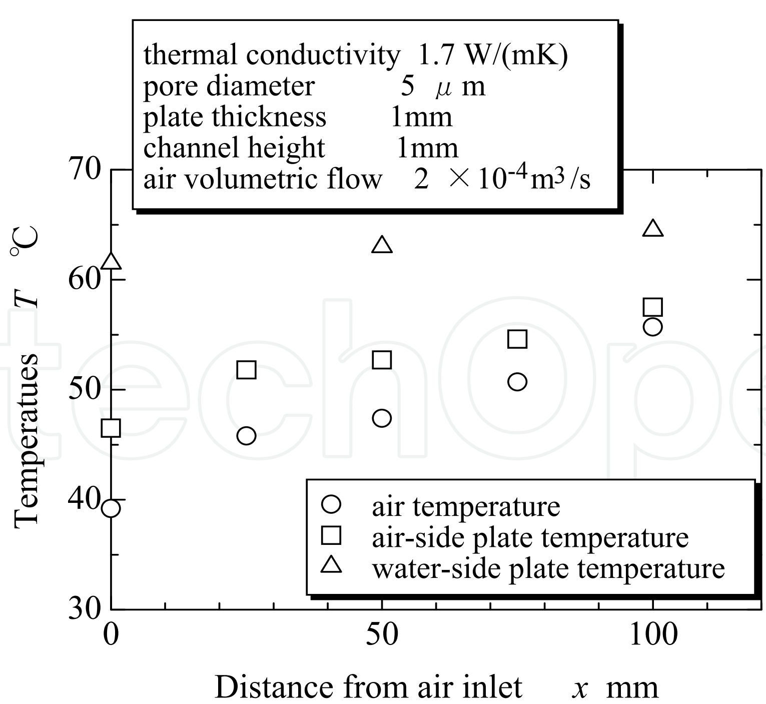

Fig. 5. Distributions of temperature in an air channel and a porous plate with flow direction

Figure 6 shows the distribution of the heat flux to the air from the constant-temperature water for the experimental conditions shown in Figure 5. This graph shows that, in the heat transport to the air from the constant-temperature water through the porous plate, 77% of the heat transport is by the heat conduction in the porous plate, 15% is by the heat conduction in the water including in the porous plate, and 8% is by the transport of the sensible heat accompanying the water transportation through the porous plate. Thus, 85% of the heat transport is used for the evaporation of the water to the air and 7% of the heat transport is used for the temperature increase of the air. That is, the heat transfer between the porous plate and the air is mainly the transport of the latent heat accompanying the water transportation.

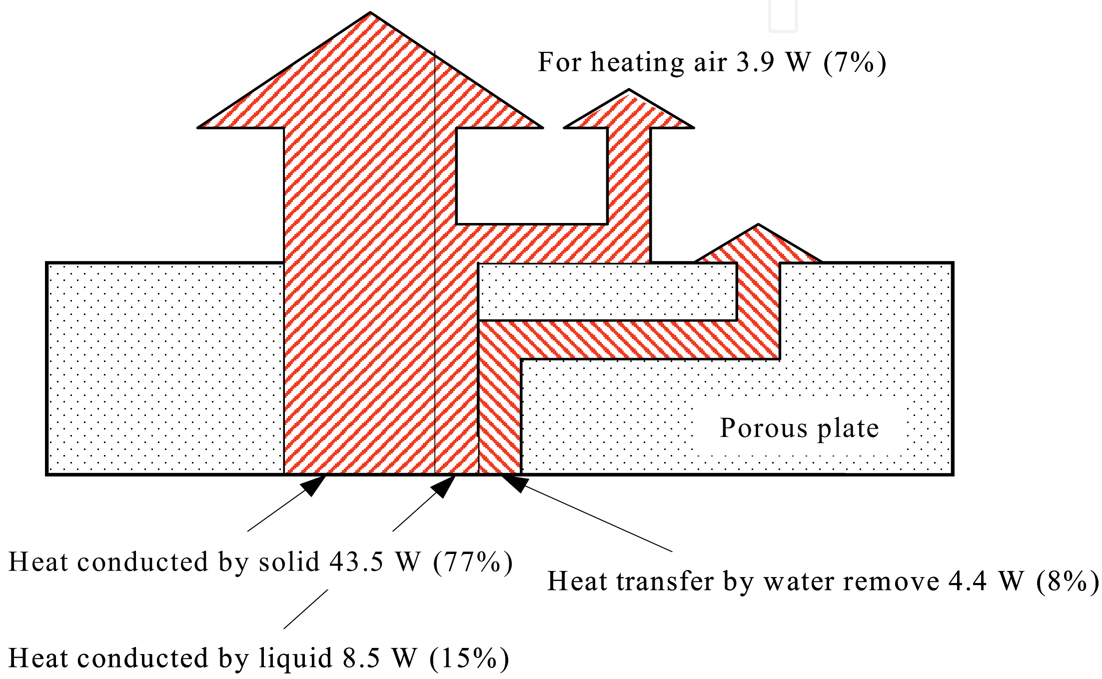

Fig. 6. Distribution of heat flux in the process of moisture transport through a porous plate

As described above, in the process of moisture transport through the porous plate, there are several factors controlling the phenomenon, e.g., the water flow resistance R_{fp} and heat transfer resistance R_{tp} inside the plate, and the mass transfer resistance R_{ms} and heat transfer resistance R_{ts} on the surface of the porous plate. Considering the influence of each factor involved and based on the one-dimensional system, the resistances of the mass transfer and heat transfer in the porous plate are defined and their influence on the performance of the moisture transport is discussed. Here, R_{fp} depends on the material structure, such as the size and distribution of the pore, and the surface properties of the plate, such as the wettability. Thus, based on the Darcy law, the maximum flux of the liquid water through the porous plate, in which the surface tension, as the driving force, can be determined as follows:

$$m^{f}_{\max} = \frac{4\sigma\cos\theta}{D} \cdot \frac{1}{\mu R_{fp}} \tag{1}$$

$$R_{fp} = \Delta x / K(\varepsilon, D) \tag{2}$$

$$K(\varepsilon, D) = C(\varepsilon)D^2 \tag{3}$$

where σ is the surface tension of the water, D is the characteristic pore diameter of the porous plate, $K(\varepsilon,D)$ is the permeability of the plate, Δx is the thickness of the plate, and $C(\varepsilon)$ is a coefficient depending on the porosity of the plate. In addition, as mentioned above, most of the heat from the constant-temperature water to the air through the porous plate is used for the water evaporation at the air-side of the plate. Therefore, the maximum evaporation of the liquid water at the air side can be determined by the heat transfer resistance of the porous plate:

$$m^t{}_{\max} = \frac{1}{R_{tp}} \cdot \frac{t_c - t_s}{h_{gl}} \tag{4}$$

$$R_{tp} = \Delta x / \lambda_p \tag{5}$$

where t_c is the temperature of the plate surface at the constant-temperature water side, t_s is the temperature of the plate surface at the air-side, h_{gl} is the latent heat of the vaporization of the water and λ_p is the thermal conductivity of the plate.

3.2 Effect of thermal conductivity

Figure 7 shows the variations in mass flux, temperature and relative humidity of the outlet air with respect to the air volumetric flow for porous plates having different thermal conductivities. The plate thickness and the height of the channel are 2 mm and 1 mm, respectively. In either high or low thermal conductivities of the porous plate, the mass flux first increases with the increase of the air volumetric flow, and then changes slightly when the air volumetric flow exceeds a threshold. This indicates that, as mentioned above, for the range in the low air volumetric flow, the factors controlling the moisture transport process are the moisture absorption capacity of the air and the resistances of the heat and mass transfer between the porous plate surface and the air, and those for the range in the high air volumetric flow are the thermal resistance and mass transport resistance inside the plate. In particular, in the range of the high air volumetric flow, the relative humidity and temperature in the outlet air are less remarkable than the saturation state or the temperature of the constant-temperature water, respectively. Therefore, for this range, it is remarkable that the moisture transport is controlled by the resistance of the heat and mass transfer inside the porous plate. Moreover, (1) the increase of the mass flux caused by the increase of the thermal conductivity of the porous plate is remarkable, and (2) although the thermal conductivity in the high-thermal-conductivity plate is approximately 11 times that in the low-thermal-conductivity plate, the mass flux in the former case less than twice that in the latter case. Therefore, it is thought that, the moisture transport is controlled by the mass transfer resistance inside the plate in the former case and by the thermal resistance inside the plate in the latter case. That is, for the former case, the maximum mass flux is limited to the maximum flux $m^f{}_{\max}$ of the liquid water through the porous plate determined by the mass transfer resistance inside the porous plate defined by equation (1), and, for the latter case, the maximum mass flux is limited to the maximum flux $m^t{}_{\max}$ of the water vaporization at the plate surface determined by the thermal resistance inside the porous plate defined by equation (4).

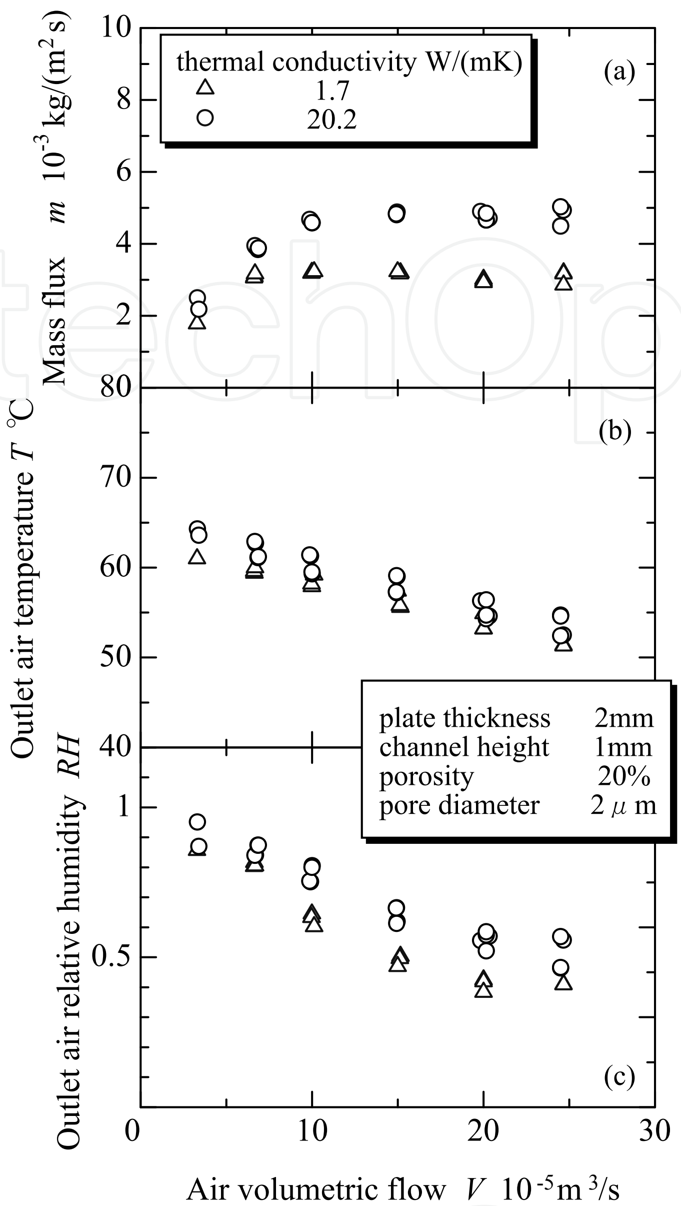

Fig. 7. Effect of thermal conductivity of a porous plate on moisture transport (plate thickness: 2 mm)

Figure 8 shows the variations in mass flux, temperature and relative humidity of the outlet air with respect to the air volumetric flow for porous plates having different thermal conductivities and thickness of 1 mm. In the case of the low-thermal-conductivity plate, the mass flux increases with respect to the increase of the air volumetric flow when the air volumetric flow is less than $1.0\times10^{-4}m^3/s$, and the relative humidity in the outlet air is approximately 100%. However, the mass flux changes slightly when the air volumetric flow exceeds $1.0\times10^{-4}m^3/s$. The reason is as mentioned above. Moreover, as shown in Figure 8(a), for the case of the high-thermal-conductivity porous plate with a thickness of 1 mm, there is no range in which the mass flux changes slightly with the air volumetric flow. Furthermore, the temperature in the outlet air is less than the temperature of the constant-temperature water, and the difference exceeds 7 K. At the same time, the relative humidity in the outlet air is approximately 100% with the air volumetric flow. Therefore, it is thought that, in this case, the factor controlling the moisture transport is the heat transfer at the plate surface. That is, in the case in which the thin porous plate having a high thermal conductivity is used, it is best to promote the moisture transport that enhances the heat transfer at the plate surface facing the channel side.

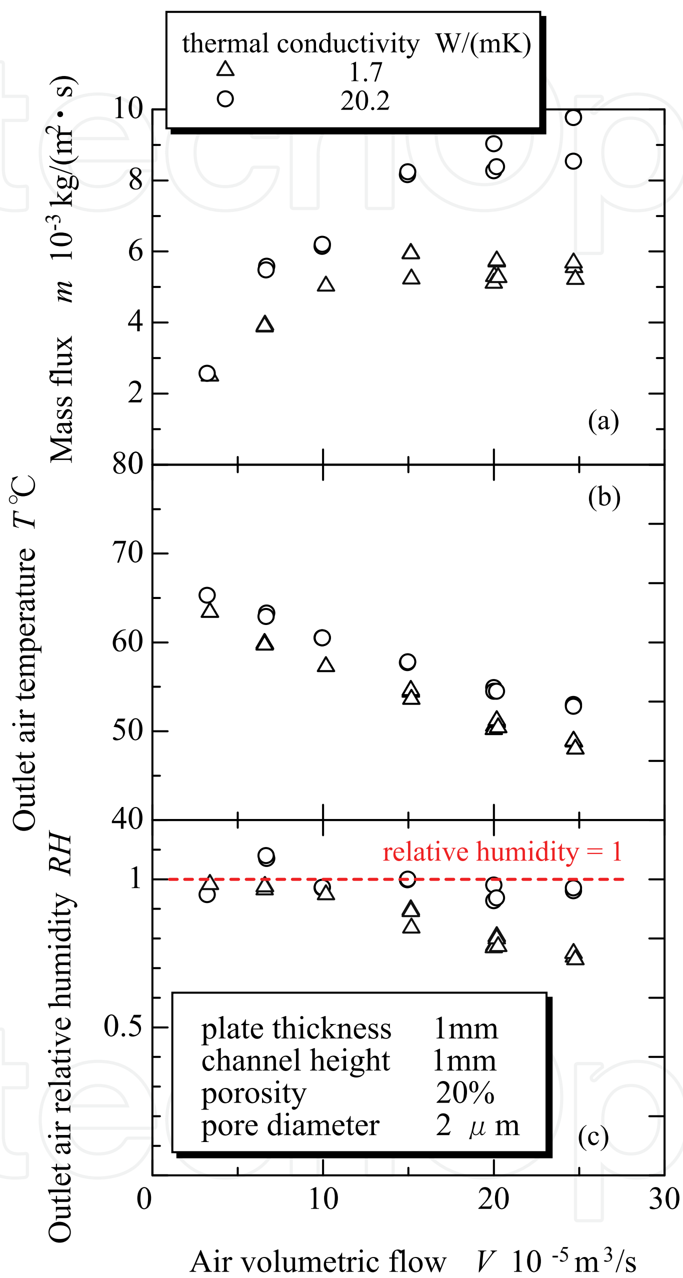

Fig. 8. Effect of thermal conductivity of a porous plate on moisture transport (plate thickness: 1 mm)

Moreover, comparing the results shown in Figures 7 and 8, in the range of the large air volumetric flow in which the moisture absorption capacity is sufficient, the mass flux, which is almost constant at approximately 3×10^{-5} kg/(m^{2}s) for the case of the low-thermal-conductivity porous plate with a thickness of 2mm, and is approximately 5×10^{-5} kg/(m^{2}s) for the case of the high-thermal-conductivity porous plate with a thickness of 2mm. In contrast, the value is approximately 6×10^{-5} kg/(m²s) for the case of the low-thermal-conductivity porous plate with a thickness of 1mm. That is, when the thermal resistance and the mass transfer resistance inside the plate are the controlling factors, the mass flux doubled by halving the plate thickness. Furthermore, comparing the experimental results for the high-thermal-conductivity plate with a thickness of 2mm and the low-thermal-conductivity plate with a thickness of 1 mm reveals that although the mass transfer resistance inside the plate for the latter is half that for the former, the mass flux in the latter is only 1.2 times the mass flux in the former. Therefore, as in the case for a low-thermal-conductivity plate with a thickness of 2mm, for the case of the low-thermal-conductivity porous plate with a thickness of 1 mm, the mass flux is also controlled by the thermal resistance inside the plate, and the maximum mass flux is limited to m^t_{max}, as defined in Equation (5). This is also understood by that fact that the relative humidity in the outlet air is approximately 100% for the case of the high-thermal-conductivity porous plate with a thickness of 1 mm.

3.3 Effect of porosity

Figures 9 and 10 show the effect of the porosity in the porous plate on the mass flux for plate thicknesses of 0.5mm and 2mm, respectively. The thermal conductivity of the plate is 20.2W/(mK). For the plate thickness of 0.5mm, under the condition of the present study, although the porosity varied from 12% to 30% and the variation range is more than one time, no difference was observed to be caused by the porosity. As mentioned above, since, in this case, the mass transport is controlled by the heat transfer between air and the plate surface, it is ineffective to the moisture transport by changing the mass transport resistance inside the plate. However, for the plate thickness of 2mm, since the mass transport is controlled by the mass transport resistance inside the plate, the mass flux increases with the increase of the porosity. The increase is remarkable in the range of the large air volumetric flow.

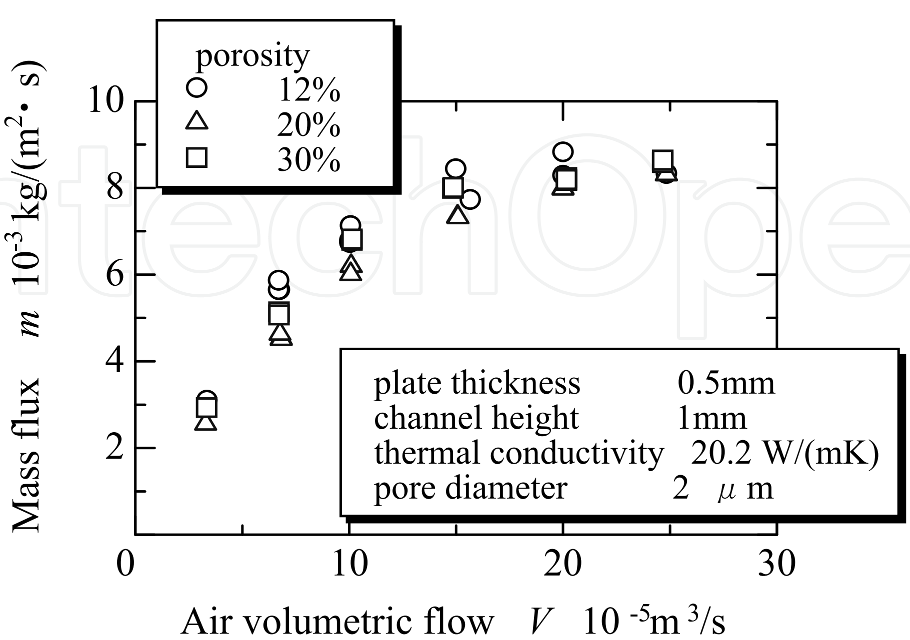

Fig. 9. Effect of porosity on mass flux (plate thickness: 0.5 mm)

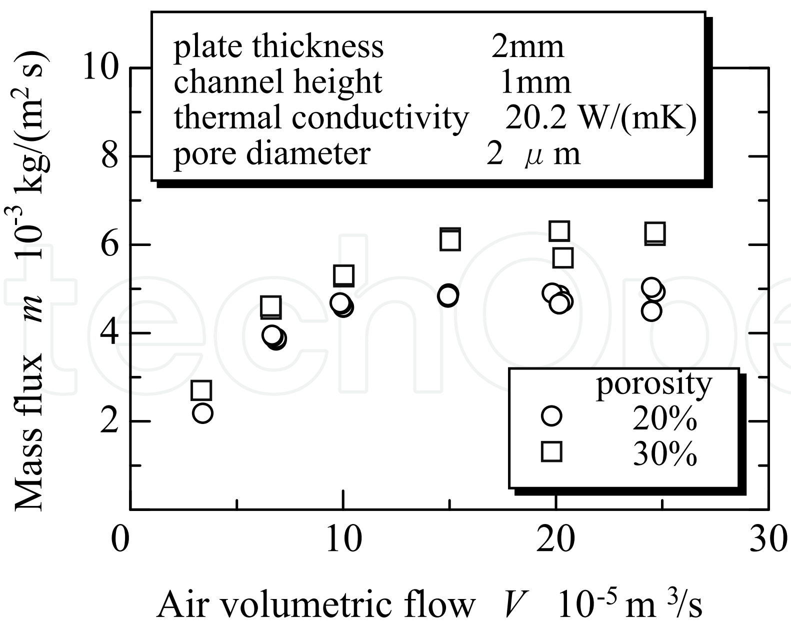

Fig. 10. Effect of porosity on mass flux (plate thickness: 2 mm)

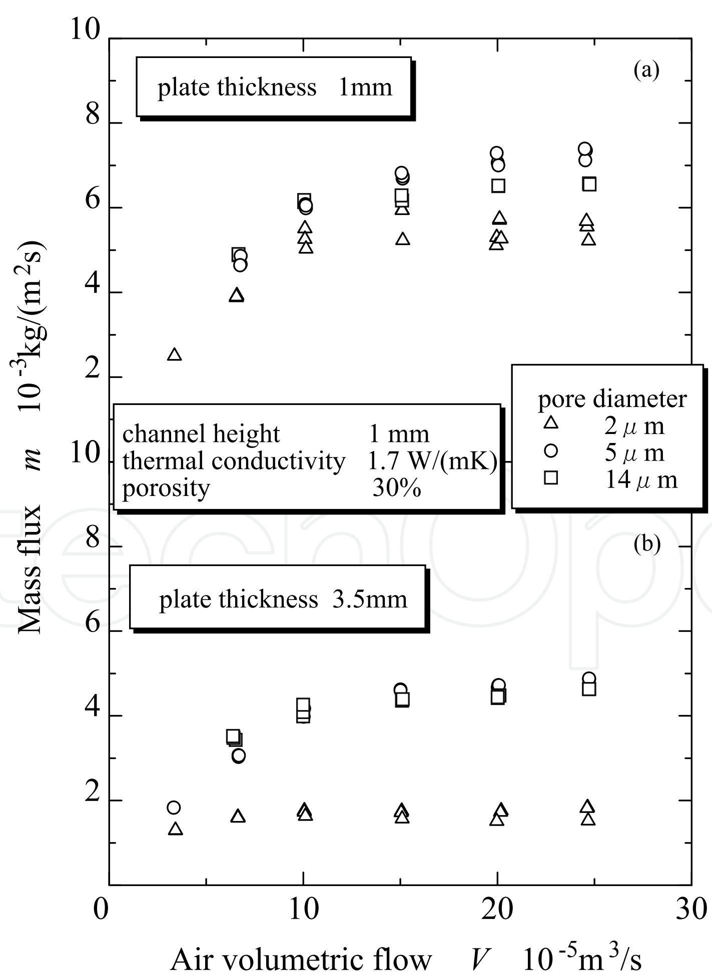

Fig. 11. Effect of pore diameter on mass flux for porous plates of different thickness

3.4 Effect of pore diameter

Figure 11 presents the variation of the mass flux for different pore diameters in plates having thicknesses of 1 mm and 3.5 mm. The thermal conductivity of the plate is 1.7 W/(mK). Similar values were observed for pore diameters of 5 μm and 14 μm. However, a comparatively low value was observed for a pore diameter of 2 μm. The difference increases with the increase in air volumetric flow, and the largest differences are approximately 25% and 60% for the plate thicknesses of 1 mm and 3.5 mm, respectively. This is thought to be caused by the remarkable resistance to the flow within the porous media for small pore diameters or thick plates. That is, in this moisture transport process, we suppose that the mass transfer resistance at the surface of a porous plate became small and the influence of flowing resistance inside the plate became strong.

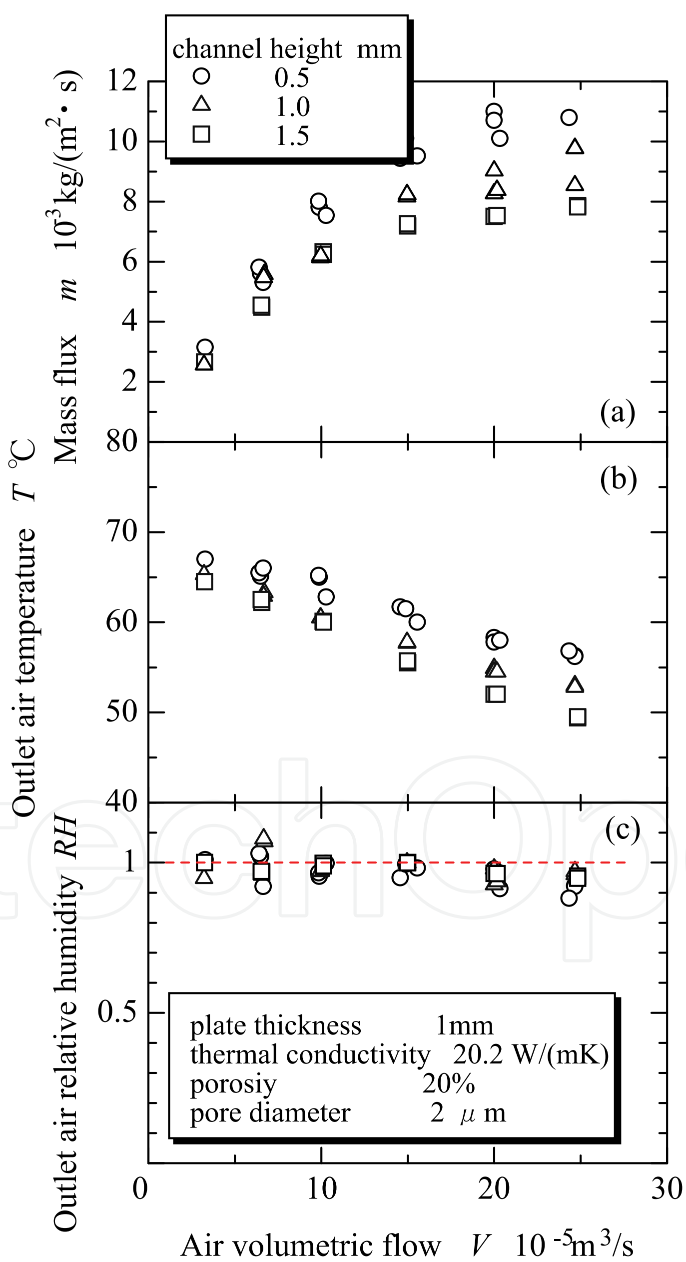

Fig. 12. Effect of channel height on moisture transport for a plate of high thermal conductivity

3.5 Effect of channel height

As mentioned above, the heat transfer and the mass transfer at the plate surface strongly affect the moisture transport through the porous plate. Consequently, the variations of the heat and mass transfer at the plate surface and the moisture absorption capacity of air caused by the variation in the quantity or the velocity of the airflow channel are projected. However, the variation of the mass flux cannot be easily predicted.

Figure 12 shows the variation in mass flux, temperature, and relative humidity in the outlet air with respect to the air volumetric flow using the high-thermal-conductivity plate for channel heights of 0.5, 1.0, and 1.5 mm. The mass flux increased when the channel height was varied from 1.5 mm to 1.0 mm and from 1.0 mm to 0.5 mm. As shown in Figure 12(b), over the entire range of the air volumetric flow, when the channel height was reduced, the heat transfer at the porous plate surface was promoted, resulting in an increase in the air temperature in the outlet air. This means that the moisture absorption capacity of air increased when the channel height was reduced. In addition, from Figure 12(c), the relative humidity of the air in the outlet air was approximately 100%, irrespective of the channel height and the air volumetric flow. This result has two implications. One is that there was sufficient water supplied from the constant-temperature water to the plate surface next to the air. The other implication is that mass transfer due to gas convection or diffusion at the plate surface has not hampered moisture transport under the experimental conditions. In other words, the results shown in Figure 12 confirmed that the controlling factor for the moisture transport through the porous plate under the experimental conditions is the heat transfer at the plate surface near the air channel and is not the thermal resistance or the mass transport resistance inside the plate. This result agrees with the discussion in Section 3.2. that is, in the case of the thin porous plate with high thermal conductivity, the factor controlling the moisture transport is the heat transfer resistance at the plate surface next to the channel.

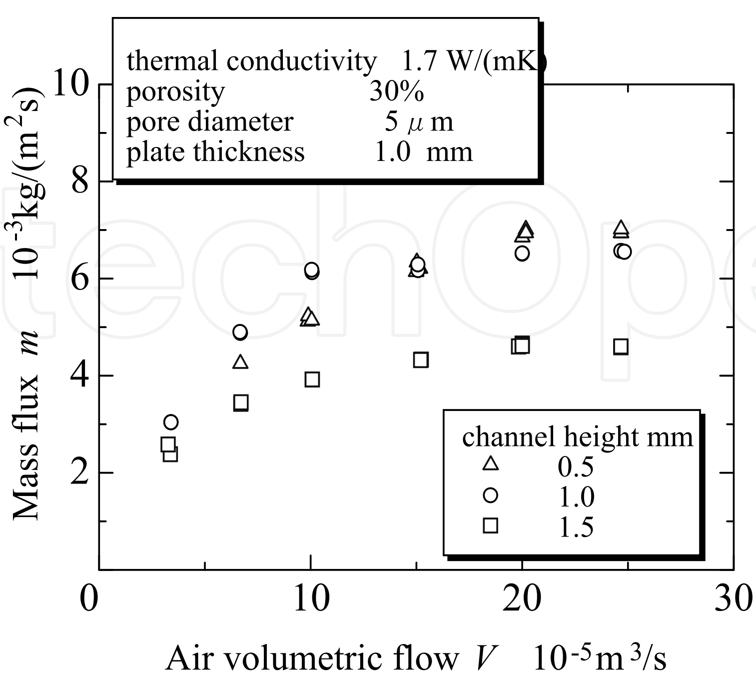

Fig. 13. Effect of channel height on moisture transport for a plate of low thermal conductivity

Figure 13 shows the variation in the mass flux with respect to the air volumetric flow using the low-thermal-conductivity plate for channel heights of 0.5, 1.0, and 1.5 mm. In contrast to the case for the high-thermal-conductivity plate, the mass flux increased when the channel height was varied from 1.5 mm to 1.0 mm, but it did not change much with air volumetric flow for channel heights between 1.0 mm and 0.5 mm. This is thought to be caused by that the main factors controlling the moisture transport are the thermal resistance inside the plate and the resistances of the heat and mass transfer at the plate surface next to the channel for a channel height of 1.5mm, and, the controlling factor just is the thermal resistance inside the plate for the channel height of less than 1mm.
Based on these results, to increase the moisture transport, a smaller apparatus would be used under the condition in which the pressure drop is less than a limited range.
Figure 14 shows the variation of pressure drop in air with respect to the air volumetric flow for the experimental conditions shown in Figure 13. The solid line represents the air pressure drop in the tube for a laminar flow obtained using the Hagen-Poiseuille equation (Welty et al., 1976), as follows:

$$\Delta P = \frac{32}{\mathrm{Re}} \cdot \frac{L}{D_e} v^2 \rho \tag{6}$$

where L is the channel length, D_e is the equivalent diameter of the channel, v is the air velocity, and ρ is the density of the air. The pressure drop increases rapidly when the channel height decreases, and the experimental results are higher than the calculation results for any channel height. This is thought to be due to the effect of the roughness of the porous plate surface and the water vaporization at the plate surface. In addition, the existence of the air volumetric flow that the mass flux varies only slightly with the air flow, as shown in Figure 13, indicates that a proper air volumetric flow (when the air volumetric flow exceeds the value the mass flux increases only slightly but the pressure drop increases. For example, approximately $10{\times}10^{-5}$ m^3/s for channel heights of 1 mm) is favorable to

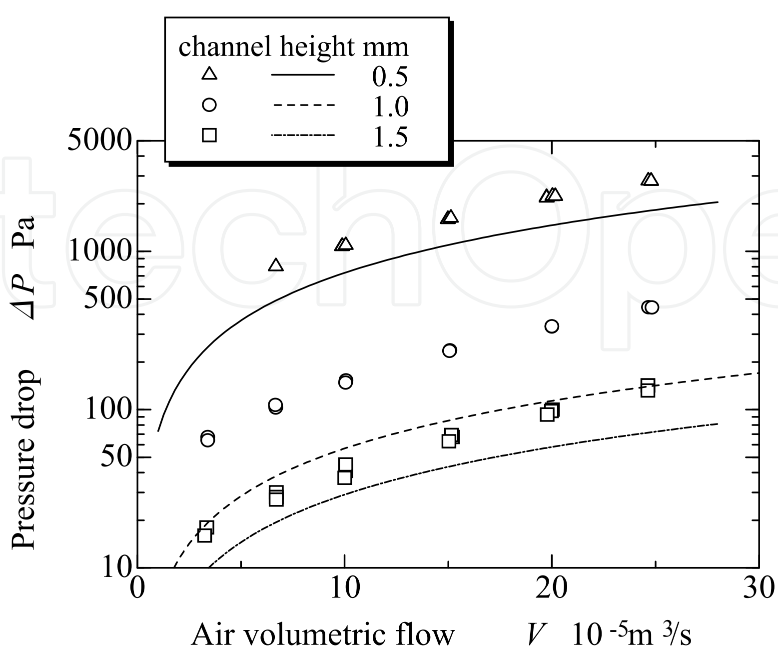

Fig. 14. Variation of pressure decrease with air volumetric flow for different channel heights

moisture recovery for the channel height is fixed. As same, the fact that the increase in the pressure drop with respect to the increasing air flow and decreasing channel height, as shown in Figure 14, shows that a proper channel height (the mass flux increase hardly if even the channel height is decreased further. For example, approximately 1.0 mm for the conditions of the channel length 100 mm and the pressure drop 200 Pa) is favorable to moisture recovery for the pressure drop is limited.

3.6 Moisture absorption rate

In order to evaluate the utilization degree of the moisture absorption capacity of the air, the moisture absorption rate η, which is the ratio of the increase in the absolute humidity to the maximum moisture absorption of the air, is introduced and is given by

$$\eta = (d_{out} - d_{in}) / (d_w - d_{in}) \tag{7}$$

where d_{out} and d_{in} are the absolute humidities of the air at the exit and entrance, respectively, of the channel in which the air is flowing, and d_w is the absolute humidity of saturated air at the temperature of the constant-temperature water.

Figure 15 shows the variations in moisture absorption rate with respect to the air volumetric flow for porous plates having different thermal conductivities. This figure shows that the moisture absorption rate decreases as the air volumetric flow increases, and the values for both the high- and low-thermal-conductivity plates were approximately the same and exceeded 80% at an air volumetric flow of 3.3×10^{-5} m^3/s. However, as the air volumetric flow increases, the moisture absorption rates of the high- and low-thermal-conductivity plates gradually diverge, and at a volumetric flow rate of 24.7×10^{-5} m^3/s, the moisture absorption rate for the low-thermal-conductivity plate is 26%, while that for the high-thermal-conductivity plate is 40%, approximately 1.5 times that for the low-thermal-conductivity plate. That is, from the standpoint of the moisture recovery, it is effective to use the high-thermal-conductivity plate for the case of the large air volumetric flow.

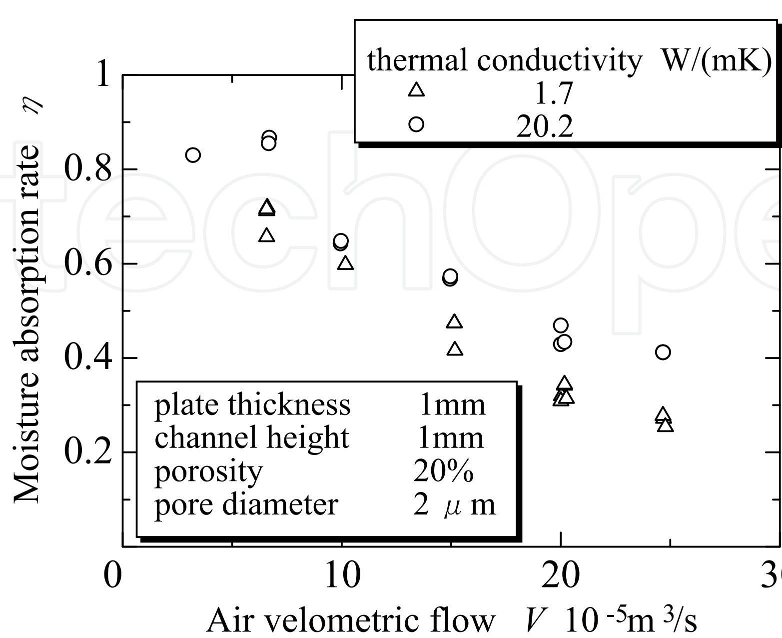

Fig. 15. Effect of thermal conductivity of the porous plate on moisture absorption rate

Figure 16 shows the variations in the moisture absorption rate with respect to the air volumetric flow using the high-thermal-conductivity plate for channel heights of 0.5, 1.0, and 1.5 mm. As mentioned in Section 3.5, the moisture transport increased with decreasing channel height because the heat transfer at the plate surface next the channel is promoted, so that the moisture absorption rate increased with the decrease of the channel height. In particular, the moisture absorption rate shows a high value that exceeds 90% for the case of an air volumetric flow of less than 6.7×10^{-5} m^3/sand a channel height of 0.5mm. That is, a high moisture recovery rate can be expected for a suitable working condition for the device design.

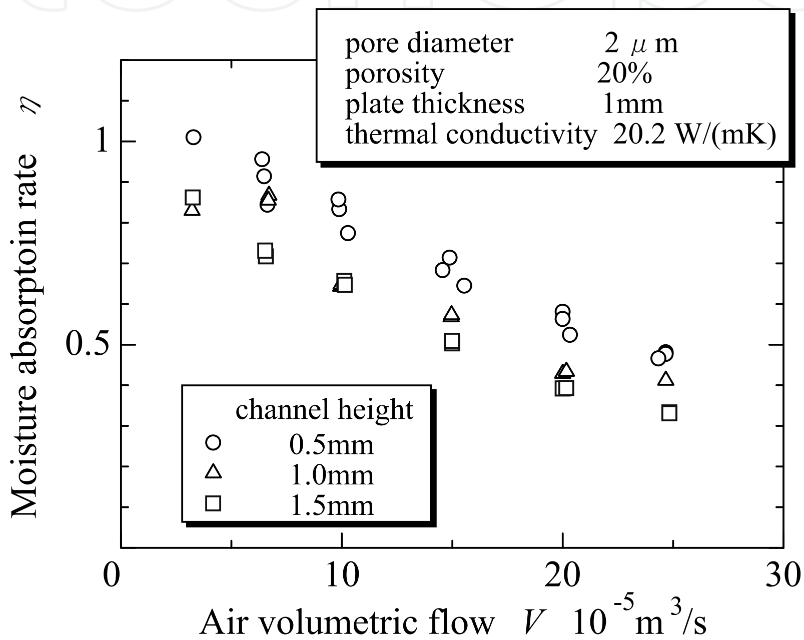

Fig. 16. Effect of channel height on moisture absorption rate

4. Conclusion

The present study attempted to clarify the characteristics of the heat and moisture transport in the process of moisture recovery from the exhaust gas of fuel cell vehicles using a porous plate having extremely small pores. As a first step, the moisture transport from constant-temperature water to dry air through the porous plate was measured. The general characteristics of moisture and the effects of the thermal conductivity, porosity and pore diameter in the porous plate, and the height of the channel of flowing air on the performance of moisture transport were examined experimentally. The results are summarized as follows:

1. For the process of moisture transport from constant-temperature water to dry air through a porous media plate, the mass flux increases with the increase of air volumetric flow, and the heat transport in this process is caused primarily by the transport of latent heat accompanying the mass transport.
2. The thermal conductivity of the porous plate is a very important factor and the controlling factor for moisture transport is different for the high- and low-thermal-conductivity plates. That is, for a plate thickness of 1 mm, the controlling factor is the

thermal resistance inside the porous plate for the low-thermal-conductivity plate; whereas, for the high-thermal-conductivity plate the controlling factor is the heat transfer at the surface of porous plate.

3. Under the experimental conditions of the present study, the effect of the porosity of the porous plate on the performance of moisture transport was not significant.
4. The effect of pore diameter on the moisture transport depends on the pore diameter and the plate thickness. That is, the smaller the pore diameter and the thicker the plate, the greater the effect.
5. The effect of the channel height on the moisture transport depends on the thermal conductivity of the porous plate. For the low-thermal-conductivity plate, the moisture transport increased when channel height varied from 1.5 mm to 1.0 mm, and the moisture transport varied little when the channel height varied from 1.0 mm to 0.5 mm. However, for the high-thermal-conductivity plate, the moisture transport increased when the channel height varied from 1.5 mm to 1.0 mm and from 1.0 mm to 0.5 mm. Thus, for highly efficient moisture recovery, a compact device is preferable, provided that the pressure drop ends in a limited range.

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6. Nomenclature

d	absolute humidity (g/kg′)
D	pore diameter (μm)
D_e	equivalent diameter (m)
h_{gl}	latent heat (kJ/kg)
$K(\varepsilon,D)$	permeability (m^2)
L	channel length (m)
M	mass flux (kg/(m^2s))
ΔP	pressure drop (Pa)
q	heat flux (W/m^2)
R_{fp}	moisture transport resistance (1/m)
R_{tp}	thermal resistance (m^2K/W)
RH	relative humidity
v	air velocity (m/s)
V	air volumetric flow (m^3/s)
Δx	thickness of porous plate (m)

Greek symbols

ε	porosity
η	moisture absorption rate
λ_p	thermal conductivity (W/(mK))
μ	viscosity (Pa.s)
θ	contact angle

ρ air density (kg/m^3)
σ surface tension of water (N/m)

Subscripts

c plate surface, water side
in inlet of the channel
out outlet of the channel
s plate surface, air side
w constant-temperature water

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Our knowledge of mass transfer processes has been extended and applied to various fields of science and engineering including industrial and manufacturing processes in recent years. Since mass transfer is a primordial phenomenon, it plays a key role in the scientific researches and fields of mechanical, energy, environmental, materials, bio, and chemical engineering. In this book, energetic authors provide present advances in scientific findings and technologies, and develop new theoretical models concerning mass transfer. This book brings valuable references for researchers and engineers working in the variety of mass transfer sciences and related fields. Since the constitutive topics cover the advances in broad research areas, the topics will be mutually stimulus and informative to the researchers and engineers in different areas.