EFFECT OF THERMAL AND GEOMETRICAL CONDITIONS ON MOISTURE TRANSPORT THROUGH A POROUS PLATE WITH MICRO PORES

Shixue WANG *, Yoshio UTAKA * & Yutaka TASAKI **
* Division of Systems Research, Faculty of Engineering, Yokohama National University,
** Nissan Research Center, Nissan Motor Co. LTD., Japan
Corresponding author: E-mail: wangs@ynu.ac.jp, Tel & Fax: 81-45-339-3907

Keywords: Heat Transfer, Fuel Cell, Mass Transfer, Moisture Transport, Porous Media

Abstract
Using an experimental apparatus to examine the performance of the heat and mass transfer between constant-temperature water and dry air through a porous plate having extremely small pores, the effects of the thermal conditions in the fluids and the geometric condition of the apparatus on moisture transport were measured. The effects of water temperature, thickness of the porous plate, and channel height of flowing air on moisture transport are noticeable. However, the effect of air temperature in the channel inlet on moisture transport is slight. In addition, in order to evaluate the degree of humidity absorption of air, a parameter called the moisture absorption rate was introduced. It was shown that the moisture absorption rate decreases with increasing air velocity, and varies only slightly for a plate thickness of 1 mm and decreases for a plate thickness of 3.5 mm with increasing water temperature.

1 Introduction
The degree of ion conduction in a fuel cell electrolyte film is determined by the water content of the film; some water content is necessary in order to maintain ionic conduction in the film. Various studies have examined the influence of humidity and the humidification method of air (1-3). In the present study, based on previous studies that examined air dehumidification by a thin porous plate (4,5), we investigate direct recovery and reuse of the moisture from exhaust gas using supply air through a thin porous plate or membrane. In this case, the following phenomena might occur: 1) mass and heat transport and the accompanying phase change inside the porous plate, 2) water evaporation on 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 among these phenomena. Therefore, in order to simplify our research, as a first step, we focus on heat and mass transport characteristics on the supply gas side and inside of 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 sufficient, so that constant-temperature-water can be used rather than the exhaust. Thus, the subject of examination is changed to the heat and mass transport to dry air from 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, gas-liquid two-phase flow, driven by capillary force in porous media and accompanied by evaporation of water, has been experimentally and theoretically investigated, respectively, by Udell (6,7) and Zhao and Liao (8). Wang et al. (9-11) introduced a multiphase mixture model for the heat and mass transport of multiphase and multi-component mixtures, including the phase
change in porous media, based on a separated flow model in which the various phases are regarded as distinct fluids. Various simulations have been performed using this multiphase mixture flow model. For example, Cheng and Wang investigated the infiltration and transport of non-aqueous phase liquids in the unsaturated subsurface, and You and Liu investigated mass transport in the cathode of a PEMFC under isothermal conditions. Using the network method, Prat presented a model by which to investigate drying in porous media under the condition that the media was initially saturated with water. Plourde and Prat 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 proposed in Reference (14).

For these studies, the author has summarized several commonalities. 1) There a lot of theoretical studies and a few experimental studies. 2) The dimensions of the porous media, such as the size and the diameter of the particles that comprise the porous media, used in experimental studies were relatively large. 3) Few studies have examined regarding affecting factors or the mechanism of heat and mass transport in porous media.

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 clarify experimentally both the mechanism of the heat and mass transport in the thin porous plate having very small pores and the influences of various factors. As a first step, the objective of this paper is to evaluate the factors that influence heat and mass transfer from constant-temperature-water to dry air through a porous plate.

In a previous report, the present authors examined the characteristics of heat and mass transport and the variation of moisture transport related to vacuum impregnation, hydrophilic treatment and pore diameter for a porous plate under this process. The effects of vacuum impregnation and pore diameter on the moisture transport were found to depend on the thickness and pore diameter of the porous plate, whereas the hydrophilic treatment had almost no effect on the moisture transport. In the present report, the effects of thermal conditions, such as the temperature of constant-temperature-water and the air temperature in the channel inlet, and of geometric conditions, such as the height of the air channel, on the moisture transport will be examined further.

2 Experimental apparatus and method

Fig. 1(a) shows a schematic diagram of the experimental apparatus, which is composed of a constant-temperature water circulation system and an air flow loop. The constant-temperature water system consists of a circulation water tank, a water transport pump, a water filter, and ion-exchange equipment. Air is pumped to the flow loop and dehumidified by cooling with water at approximately 0°C. The dehumidified air is heated to an established temperature and absorbs the moisture from the constant-temperature water 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 using a flow meter installed after the valve. Thermohygrometers are installed at the entrance and exit of the test device to measure the temperature and humidity of the air. All measurement signals, for example, temperature, humidity, and flow rate, are converted to a digital signal by an A/D converter, and are recorded by a personal computer.

Fig. 1(b) shows a cross section of the test device. The surface of the porous plate is 100×28 mm. In order to enable observation of the surface state of the porous plate, the top of the test device is made of a transparent material. The channel height of the flowing air can be adjusted by insert a spacer between the frame and the polycarbonate plate. 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-thick 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 on the upper surface of the porous plate were measured using 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 air flow, respectively. Holes in the porous plate for the insertion of the thermocouples were 0.3 mm in diameter and 15 mm in depth. In Fig. 1(b), the ○ and ● symbols represent the thermocouples that measure the temperatures of the air in the channel and on the upper surface of the porous plate, respectively.

In the present study, in order to eliminate the effect of air trapped in the porous plate on the experiment result, the porous plate was treated using a vacuum impregnation method before the experiments. That is, by evacuating air from a closed vessel containing the porous plate in water, any air contained within the porous plate was removed.

In order to evaluate the utilization degree of the moisture absorption capacity of air, the moisture absorption rate \( \eta \), which is given by the ratio of the increase of absolute humidity to the maximum value of moisture absorption of air, as shown in Eq. (1), is introduced:

\[
\eta = \frac{(d_{out} - d_{in})}{(d_w - d_{in})}
\]  

(1)
where \(d_{\text{out}}\) and \(d_{\text{in}}\) are the absolute humidity of air at the exit and entrance, respectively, of the channel in which air is flowing, and the absolute humidity of saturated air at the temperature of the constant-temperature water is denoted by \(d_w\).

### 3 Experimental results and discussion

There are many factors that affect moisture transport from the water to dry air through the porous plate. In a previous report, we discussed the general characteristics of the moisture transport in this process, and examined the effects of air velocity, hydrophilic treatment and pore diameter in the porous plate on moisture transport and the measurement precision. In the present report, based on the results of a previous report, we experimentally examine the effect of the temperature of constant-temperature-water, the temperature of air in the channel inlet, the plate thickness and the height of the channel on the moisture transport. The porosity and heat conductivity of the porous plate used in present study are 30% and 1.7 W/m K, respectively. The experiments were performed under an air velocity of 1.2 to 8.8 m/s. The experimental conditions are shown in detail in Table 1. Except where specifically noted, data was obtained under vacuum impregnation and hydrophilic treatment conditions.

#### 3.1 Effect of thermal conditions

##### 3.1.1 Effect of water temperature

Figs 2(a)-(d) show the variations of mass flux, moisture absorption rate, and temperature and relative humidity in the outlet air with respect to air velocity for different water temperatures. The plate thickness, pore diameter, and height of the channel are 1 mm, 5 \(\mu\)m, and 1 mm, respectively. The mass flux was smaller for lower water temperatures. As shown by the variations in the temperature and relative humidity of the air in the channel exit in Figs 2(c) and (d), when the water temperature is low, the absolute humidity of saturated air at the air temperature in the channel exit as the moisture absorption capacity of air is relative low, because the temperature of air flowing through the channel does not increase easily. In addition, two characteristics were observed in the variation of the moisture absorption rate shown in Fig. 2(b). First, the moisture absorption rate

---

#### Table 1 Specifications of the porous plate and experimental conditions

<table>
<thead>
<tr>
<th>Pore diameter (\mu)m</th>
<th>Plate thickness mm</th>
<th>Channel height mm</th>
<th>Water temperature ºC</th>
<th>Inlet air temperature ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>69</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>69</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>25</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>1</td>
<td>69</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Porosity: 30%, Thermal conductivity of plate: 1.7 W/m K,

Channel height: 1 mm, Air velocity: 1.2-8.8 m/s
EFFECT OF THERMAL AND GEOMETRICAL CONDITIONS ON MOISTURE TRANSPORT THROUGH A POROUS PLATE WITH MICRO PORES

decreased with respect to the increase in air velocity. This is thought to be due to the fact that the rate of increase of the air temperature decreased with the increase in the volume of air flowing through the channel, as mentioned in our previous report (16). Second, the moisture absorption rate was almost constant for different water temperatures. This is thought to indicate that the moisture transport depends only the thermal conditions. That is, for the experimental condition of the present study, the process of moisture transport is controlled by either the thermal resistances formed by the heat conduction inside the porous plate or the convection heat transfer at the plate surface, and is not controlled by the flow resistance caused by the water transport in the porous plate. These findings are supported by the fact that the moisture transport depends only slightly on the pore diameter for the plate thickness of 1 mm, as reported in our previous report (16).

In addition, Figs 2(c) and (d) show that the relative humidity of air in the channel exit depends only on the air velocity and not on the water temperature, although the air temperature in the channel exit varies with the water temperature. The reason is same as the moisture absorption rate doesn’t depending the water temperature pointed above. For air velocities less than 4 m/s, since the relative humidity of the air in the channel exit is greater than 90% and the air temperature in the channel exit approaches the water temperature very closely, the effect on moisture transport is not so large, to increase the length of the porous plate more than 100 mm, as is the case in the present experiment.

Based on our previous report (16), the moisture transport is controlled by the heat resistance when the thickness of the porous plate is 1 mm. Therefore, in the present study, measurement was performed using a porous plate, of 2 µm in pore diameter and 3.5 mm in thickness, which the effect of flow resistance in the porous plate appear easily. Figs 3(a)-(d) show the variations of mass flux, moisture absorption rate, and temperature and relative humidity in outlet air with respect to air velocity for different water temperatures in this condition. Compared to the results shown in Fig. 2, the variation in the mass flux obtained under this condition showed same tendency and
relative low values. However, the tendency of the moisture absorption rate changed. That is, the moisture absorption rate decreased with respect to the increase in water temperature. This is thought to be due to the fact that the heat transported to the surface of the porous plate increase with increasing water temperature, so increasing the air temperature and the water evaporation at the plate surface, but toward this, water flow to the plate surface through the very small pores in the porous plate is not enough due to the relative thick plate. This is also supported by the variation in the air relative humidity of the channel exit shown in the Fig. 3(d). That is, the air relative humidity of the channel outlet shown in Fig. 2 (d) does not depend on the water temperature and varies in the range of 70% ~ 100%. Comparatively, for the experimental conditions of Fig. 3, the relative humidity decreased to 56% ~ 78% for a water temperature of 25°C and to 38% ~ 60% for water temperatures of 50°C and 69°C. This is thought to be due to the flow resistance in the plate.

3.1.2 Effect of inlet air temperature

Fig. 4 shows the variation of the mass flux under different air temperatures in the channel inlet. This graph shows that the mass flux is somewhat large when the air temperature in the channel inlet is high (equal to the water temperature), but the difference is less than 10% at most. This is thought to be due to the fact that the effect of air temperature in the channel inlet on the average temperature of air flowing in the channel is relatively weak because the air thermal capacity is relatively small.
3.2 Effect of geometric conditions

For the moisture transport through a porous plate, the properties of the porous media, such as the pore diameter and porosity, and the geometric conditions, such as the plate thickness and channel height, are thought to cause the variation of the mass flux. In our previous report (16) the effect of the porous plate properties on moisture transport was examined. In the present study, we will examine the characteristics of the variation of moisture transport due to changes in the plate thickness and channel height.

3.2.1 Effect of plate thickness

Figs 5(a), (b), and (c) show the variation of the mass flux with respect to the air velocity for plates of three plate thicknesses having pore diameters of 2 µm, 5 µm, and 14 µm, respectively. The graph shows that the mass flux decreases with increasing plate thickness for any pore diameter. This is because both the flow resistance and the thermal resistance of moisture transport in the plate increase with increasing plate thickness. In addition, the variation of the mass flux due to an increase in the air velocity increased initially and later became nearly constant. This figure also reveals two characteristics of the variation of the mass flux.

The first is the tendency for the transition position to the region in which the mass flux increases only slightly with air velocity shift to the direction of lower air velocity with increasing plate thickness. This tendency is especially clear for the case of the pore diameter of 2 µm. The second is a change in the transition position shift to the direction of high air velocity with the increase of the pore diameter. This was especially evident for the case of the 3.5-mm-thick plate. As mentioned in our previous report (10) for the process of moisture transport through a porous plate, the controlling factors are the mass flow resistance and the thermal transport resistance inside the porous plate and the mass transfer resistance and the heat transfer resistance at the surface of porous plate. When the air velocity is relatively low, as the capacity of the air to absorb moisture is small, the moisture transport is thought to be controlled by the heat and mass transfer at the plate surface. However, with the increase in the air velocity, the capacity of the air to absorb moisture should...
increase, so the influences of the mass flow resistance and the thermal transport resistance inside the porous plate gradually become stronger, and become important when a certain velocity is exceeded. Simultaneously, the effect of air velocity on the variation of mass flux almost disappears. Consequently, the commencement position of the approximately zero-grade region of the change in mass flux with respect to air velocity shifts toward the direction of lower air velocity with increasing plate thickness. The smaller the pore diameter, the lower the air velocity of the commencement position. Fig. 5 indicates that the variation of the mass flux with air velocity is almost constant for different pore diameters for the plate thickness of 1 mm and decreases with decreasing pore diameter for the plate thickness of 3.5 mm. As mentioned in Section 3.1.1, this indicates that the resistance of the moisture transport inside the porous plate is the thermal resistance for the plate thickness of 1 mm and is the flow resistance for the plate thickness of 3.5 mm.

3.2.2 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, 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 of the air flow channel are projected. However, the variation of the mass flux cannot be easily predicted.

Fig. 6 shows the variations of the mass flux with respect to the air velocity for the channel heights of 0.5, 1.0 and 1.5 mm. The mass flux increased when the channel height varied from 1.5 mm to 1.0 mm. However, the mass flux not only no increase and conversely showed a low value in the low air velocity region when the channel height varied from 1.0 mm to 0.5 mm. The moisture transport is thought to be promoted by the improvement of the heat and mass transfer at the plate surface for channel heights ranging from 1.5 mm to 1.0 mm. However, for channel height varies from 1.0 mm to 0.5 mm, because the effect of the
improvement of the heat and mass transfer at the plate surface is limited by the rapid decrease in the moisture absorption ability of the flowing air. In particular, the moisture absorption ability is the main controlling factor in the region of low air velocity having a high moisture absorption rate.

Fig. 7 shows the variation of the mass flux with respect to the air volumetric flow, representing the air moisture absorption ability for the three channel heights, when only the channel height is varied. This figure shows that the mass flux increased when the channel height varied from 1.5 mm to 1.0 mm and varied only slightly when the channel height varied from 1.0 mm to 0.5 mm. In addition, based on these results, the same mass flux can likely be obtained using a smaller apparatus.

Fig. 8 shows the variation of pressure drop in air against the air volumetric flow for three channel heights. The solid line represents the air pressure drop in the tube for a laminar flow obtained using the Hagen-Poiseuille equation as follows:

\[
\Delta P = \frac{32}{Re} \cdot \frac{L}{D} \rho \left( \frac{v^2}{\rho} \right) \tag{2}
\]

where \(L\) is the channel length, \(D\) is the equivalent diameter of the channel, \(v\) is the air velocity, and \(\rho\) is the density of the air. The pressure drop increases rapidly when the channel height decrease, and the experimental results are comparatively higher that 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 fact that the existence of the air volumetric flow that the mass flux varies only slightly with the air flow, as shown in Fig. 7, and that the increase in the pressure drop with respect to the increasing air flow and decreasing channel height, as shown in Fig. 8, indicate that a device having a small channel and a proper velocity, for example, approximately 4 m/s or 10 m/s, for channel heights of 1 mm and 0.5 mm, respectively, is favorable for moisture recovery.

4. Conclusions

The present study was an attempt to clarify the characteristics of the heat and moisture transports 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 effects of the temperature of the constant-temperature water, air temperature in the channel inlet, plate thickness and the height of the channel of flowing air on the performance of moisture transport were experimentally examined. 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 respect to the temperature of the constant-temperature water, and the moisture absorption rate depends only slightly on water temperature for the case of a 1-mm-thick plate and decreases with respect to the water temperature for a 3.5-mm-thick plate.

(2) The variation of moisture transport caused by the air temperature in the channel inlet is relatively small, less than 10% at most.

(3) The effect of plate thickness on the variation of moisture transport depends on the pore diameter. For increasing plate thickness and decreasing pore diameter, the commencement position of the approximately zero-grade region of the change in mass flux with respect to air velocity shifts toward the direction of lower air velocity.

(4) The moisture transport increases for channel height varying from 1.5 mm to 1.0 mm, and the moisture transport varies little with the air volumetric flow for channel heights varying from 1.0 mm to 0.5 mm. For the moisture recovery device, an optimum size exists that provides high efficiency and compact size for a certain use condition.
Acknowledgements

We would like to thank Yoshihiro Takahashi and Akinori Sakurai at the Graduate School of Yokohama National University for their cooperation in this study.

References


