International Journal of Heat and Mass Transfer 52 (2009) 4386–4389

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

An experimental study on moisture transport through a porous plate with micro pores

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ARTICLE INFO

Article history:
Received 27 October 2008
Received in revised form 19 March 2009
Accepted 23 March 2009
Available online 8 May 2009

Keywords:
Fuel cell
Humidity transport
Mass transfer
Porous media

ABSTRACT

An experiment was carried out to examine heat and mass transfer between constant-temperature water and dry air through a porous plate having extremely small pores. The effects of the thermal conductivity in the porous plate on moisture transport were investigated. The controlling factor for moisture transport was found to be the thermal resistance inside the porous plate having a low-thermal-conductivity and the heat transfer at the surface of the porous plate having a high-thermal-conductivity.

1. Introduction

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 and White [1] and Yoshikawa et al. [2], respectively.

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 [3], 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 [4,5] and Zhao and Liao [6]. Wang et al. [7–9] 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 and Wang [10], and the mass transport in the cathode of a PEMFC under isothermal conditions was investigated by You and Liu [11].

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.

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doi:10.1016/j.ijheatmasstransfer.2009.03.037

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 previously investigated moisture transport through a porous plate having a thermal conductivity of 1.7 W/(mK) to dry air from constant-temperature water [12,13]. We found that moisture transport depends on heat and mass transfer at the surface of the plate and the heat and mass transport inside the plate. The basic characteristics of heat and mass transport on this process and the effect of various factors, such as the pore diameter, the thickness of the porous plate, the temperature of the constant-temperature water, the air temperature of the channel inlet and the channel height, etc., on the moisture transport were examined. It was found that the variation of the moisture transport with the air volumetric flow increased as the channel height was varied from 1.5 mm to 1.0 mm, but did not change for the channel heights between 1.0 mm and 0.5 mm. As mentioned above, for the process of moisture transport from constant-temperature water to dry air through a porous plate, the effect of thermal conductivity of the plate on moisture transport was remarkable. For example, for the conditions shown in Fig. 1, the temperature difference between the constant-temperature water and the dry air was approximately 22 K, but the temperature difference between the upper and lower sides of the porous plate was approximately 10 K, which is very large relative to the total temperature difference of 22 K. The present report extends the work done in the previous investigations by examining the effect of thermal conductivity of the porous plate on moisture transport.

2. Experimental apparatus

Fig. 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. 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. 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. Further details of the experimental apparatus and procedures may be obtained from the earlier paper by authors [12].

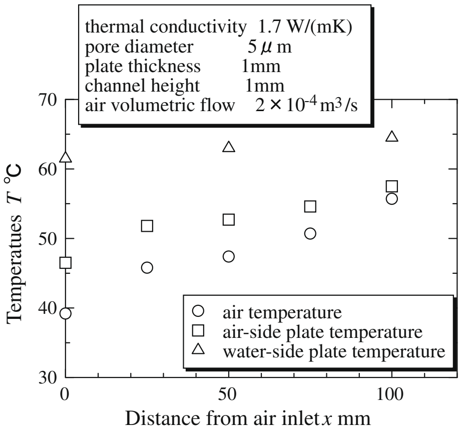

Fig. 1. Distributions of temperature in an air channel and a porous plate with flow direction.

3. Experimental results and discussion

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). The condition of detail is shown Table 1.

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.

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

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

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

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.

Fig. 3 shows the variations in mass flux and relative humidity of the outlet air with respect to the air volumetric flow for porous plates having different thermal conductivities with channel height of 1 mm. For the case of plate thickness of 2 mm, 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 in the outlet air is less remarkable than the saturation state. 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

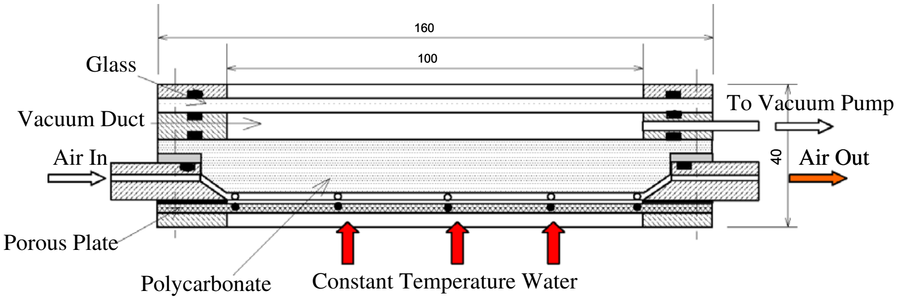

Fig. 2. Schematic diagram of the test section.

Table 1
Specifications of the porous plate and experimental conditions.

Heat conductivity λ_p (W/(mK))	Plate thickness Δx (mm)	Channel height h (mm)
1.7	1.0	1.0
	2.0	
20.2	1.0	0.5
		1.0
		1.5
	2.0	1.0

Air volumetric flow: 3.3–24.7 × 10^{-5} m^3/s, temperature of air at the inlet: 32 °C, relative humidity of air at the inlet: 15%, temperature of constant-temperature water: 69 °C, porosity: 20%, pore diameter: 2 μm.

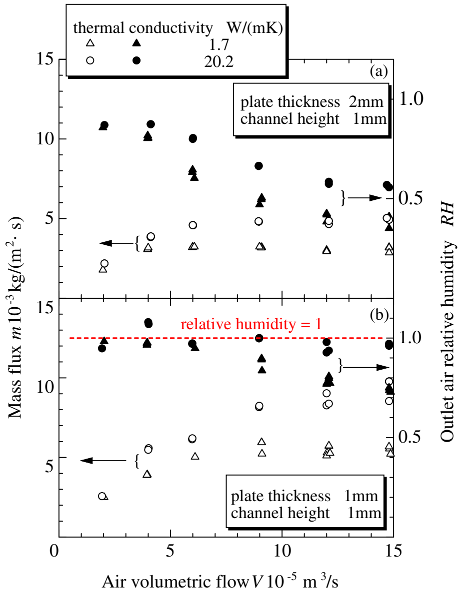

Fig. 3. Effect of thermal conductivity of a porous plate on moisture transport.

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 Eq. (1), and, for the latter case, the maximum mass flux is limited to the maximum flux $m^f_{\max}$ of the water vaporization at the plate surface determined by the thermal resistance inside the porous plate defined by Eq. (4).

But, as shown in Fig. 3(b), 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. And, 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.

Moreover, comparing the results shown in Figs. 3(a) and (b), 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 2 mm, and is approximately 5 × 10^{-5} kg/(m^2 s) for the case of the high-thermal-conductivity porous plate with a thickness of 2 mm. In contrast, the value is approximately 6 × 10^{-5} kg/(m^2 s) for the case of the low-thermal-conductivity porous plate with a thickness of 1 mm. 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 2 mm 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 2 mm, 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 $m^f_{\max}$, as defined in Eq. (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.

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.

Fig. 4 shows the variation in mass flux 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, and 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

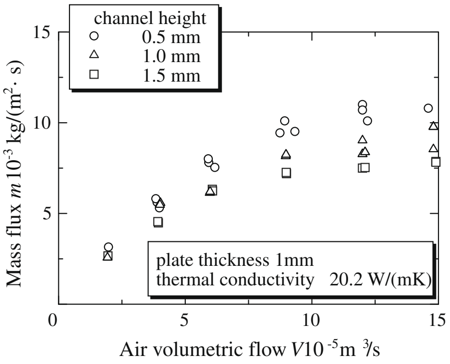

Fig. 4. Effect of channel height on moisture transport for a plate of high-thermal-conductivity.

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 Fig. 4 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 about the result shown in Fig. 3 above. But it was different the result for low-thermal-conductivity plate presented by reference [13] that the variation of the moisture transport with the air volumetric flow did not change for the channel heights between 1.0 mm and 0.5 mm. The reason is thought to be that for the low-thermal-conductivity plate the controlling factor is the thermal resistance inside the plate.

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.

4. Conclusion

For the process of moisture transport from constant-temperature water to dry air through a porous media plate, 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. Moreover, the effect of the channel height on the moisture transport depends on the thermal conductivity of the porous plate.

Acknowledgements

The authors thank Yoshihiro Takahashi and Akinori Sakurai of the Graduate School of Yokohama National University for their cooperation in this study. In addition, this study was carried out under cooperation between Yokohama National University and Nissan Motor Company.

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