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Experimental Studies of Transport Properties of Water Vapor through Membranes

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ABSTRACT

An experimental set-up has been designed and constructed to investigate the water vapor transport properties of membranes. The test section of the experimental set-up consists mainly of an airflow channel, a membrane, and a water tank, which constitute a sandwich structure. An air gap exists between the membrane and the water in the water tank. The air fluid in the channel flows over the membrane and is humidified by the water through the air gap and membrane. The process of moisture transfer from the water to the air stream in the channel is described using a serial resistance model. The channel has a 5×50 mm cross-section and a 800 mm length. Tests were conducted on two membranes including the PES (polyethersulfone) and cellulose membranes. Tests were carried out with fixed air gap thickness of 5 mm for airflow rates from 1 to 5 L/min, yielding Reynolds numbers from 39 to 195. The moisture resistance through membrane was obtained by subtracting the convective moisture resistance in the channel and the moisture resistance caused by the air gap from the total moisture resistance. The experimental results suggest that both membranes have relatively good moisture permeability.

1. INTRODUCTION

Forced ventilation is generally mandatory in large buildings, where a minimum amount of outdoor air is required for occupant health and comfort (ASHRAE, 1993). Although air exchange between the inside and outside is necessary to maintain the indoor air quality, the energy associated with treating the outdoor air can be a significant space-conditioning load. The energy consumption may be reduced by recovering energy from the exhaust air to treat the supply air. To recover both the sensible heat and moisture from the exhaust air, an air-to-air heat exchanger with a vapor-permeable membrane core can be used. Since the performance of such an exchanger is largely determined by the moisture permeability of the membrane, studies on the transport properties of moisture through membranes are of practical importance.

Our literature survey reveals some publications on the water vapor permeations of various membranes. Aranda et al. (1995) studied the water transport properties of composite membranes consisting of a sulfonated-polystyrene film supported on a microporous-alumina support membrane. They used a mathematical approach developed by Reineke et al. (1989) to investigate the effect of the water vapor pressure on the water diffusivity. Liu et al. (2001) investigated the water vapor permeation through a silicone rubber-PSF (polysulfone) composite membrane and analyzed the resistance of this asymmetric composite membrane to the permeation of water vapor on the basis of a serial resistance model. Gugliuzza and Drioli (2003) investigated the water vapor transport of a modified poly (amide-12-b-ethyleneoxide) and reported that the water vapor permeability was influenced by the hydrophilicity of the membrane. Zhang (2006a, 2006b) recently performed a series of studies on the water vapor permeations of hydrophilic polymer membranes, he used a standard field and laboratory emission cell as the test chamber to investigate the water vapor permeability coefficients of the membranes.

In this research, the transport properties of moisture through the PES and cellulose membranes were studied experimentally. The moisture diffusivities in the membranes were estimated based on the experimental data.

2. EXPERIMENTAL

2.1 Membrane samples

Tested were two membranes including the PES (polyethersulfone) and cellulose membranes, whose micro-structures are illustrated in Fig. 1. The average pore sizes of the PES and cellulose membranes are $0.45\mu m$ and $0.2\mu m$, respectively, while the thicknesses are 0.0988mm and 0.1192mm, respectively. The sorption curves of these two membranes are presented in Fig. 2.



Figure 1: SEM photos of the PES (left) and cellulose (right) membranes



Figure 2: Sorption curves of the PES and cellulose membranes

2.2 Experimental set-up

Fig. 3 is a schematic diagram of the experimental set-up. Air fluid driven by a compressor flows in a pipeline and then in a channel in which water vapor transports from the water in the water tank embedded in the channel to the air stream across the membrane whose water vapor permeation is to be investigated. When the air flows in the pipeline, it is split into two streams, one of them is humidified through a flask of distilled water and then re-mixed with the other air stream. Since the humidity of the humidified air stream can reach nearly 100%, the desired humidity of the mixed air stream can be obtained by adjusting the ratios of the two air streams. The airflow rate is controlled by valves and measured using an airflow meter (Alicat Scientific, Inc., Model: 5LPM) whose precise is 2.5%. Before the air enters the upstream chamber that acts to stabilize the air flow, it exchanges heat with room air through an air-to-air heat exchanger to ensure that the air stream has the same temperature with the environment. The channel has a trapezoid-shaped entrance that can reduce the entrance length of the flow and a baffle-type exit whose role is to uniform the moisture in the air stream. The channel has a cross-section of 5×50 mm and a length of 800 mm. The distance from the channel inlet to the water tank is 400 mm and that from the water tank to the channel outlet is 250 mm, while the sizes of the upstream and downstream chambers are both $200 \times 200 \times 300$ mm, with the 300 mm dimension in the airflow direction. The channel, chambers and water tank are all made of plexiglas. The air humidity and temperature at the channel inlet and outlet are measured using humidity/temperature

sensors (ROTRONIC AG Company, Model: Hygrolog NT-3) that are installed in the chambers. The measuring accuracy is 1.5% for relative humidity and 0.3° C for temperate.



2.3 Test section

Fig. 4 shows the test section that consists mainly of an airflow channel, a membrane, and a water tank, which is equipped with a heater. The channel, membrane and water tank form a sandwich structure. The channel has a height of 5 mm and a width of 50 mm, while the water tank has a length of 150 mm and a width of 50 mm. An air gap exists between the membrane and the water in the water tank to avoid any possible wetting of the membrane by the water. When air with a relatively low humidity passes over the membrane in the channel, water vapor transports from the water surface to the air stream through the air gap and membrane. The water tank has a L-shape water

pouring pipe on its side wall. During test, water can be easily added to the water tank to ensure a constant air gap thickness. The water tank is equipped with a heater that is used to compensate the heat of vaporization of water. A thermocouple is placed under the water surface to monitor the water temperature. The power of the heater is automatically controlled to ensure that the water surface has the same temperature as the air stream in the channel.



2.4 Experiments

To be able to extract the membrane resistance from the total moisture resistance, three kinds of tests were performed. The first test was to obtain the convective mass transfer coefficient over the membrane in the channel. In this test, no membrane is used, the water tank is maintained full of water with the water surface exposed directly to the air stream in the channel. To investigate the variation of the mass transfer coefficient along the airflow direction, plastic plates with different lengths are prepared. In each test, a plate is used to cover a portion of the water surface. Special care is given to ensure that the water surface is on the same horizon as the plate upper surface and at the same time the water does not wet the plate upper surface. The area of the water surface in contact with the air stream can be altered by using different plates. When the air flows through the test section, it gains moisture from the water and is humidified. The average convective mass transfer coefficients can be calculated from the moisture gain of the air stream and the humidity difference between the air stream and the water surface. Through the tests with different plates, the variation of the convective mass transfer coefficient along the airflow direction can be investigated.

The second test was to obtain the mass transfer resistance caused by the air gap between the membrane and the water in the water tank. To ensure the membrane not to be wetted by the water, an air gap between the membrane and water is required. So, the effect of the air gap on the total moisture resistance should be investigated. Unlike the test on the convective mass transfer coefficient, membrane is used in this test. To make the membrane adaptable to the experimental circumstance, test is run at least 12 hours after the membrane setting and water addition. Tests were conducted for different air gap thicknesses from 5 to 15 mm. The moisture resistance caused by the air gap can be determined based on the experimental data.

(1)

The third test was to investigate the water vapor permeation of different membranes. This is the main test, the above two tests serve for it. Test is run in a way similar to that of the air gap resistance test. The difference is that, the membrane permeation tests were carried out for different membranes with fixed air gap thickness, while the air gap resistance tests were done for different air gap thicknesses with identical membrane.

We note that all tests were run at a constant temperature of 23° C and with a constant entering air humidity of 15%. The purpose for using a relatively dry air stream was to get a more remarkable humidity increase when the air passes over the membrane in the channel. Further, tests were run for airflow rates from 1 to 5 L/min, yielding Reynolds numbers from 39 to 195. In each test, data are recorded only when the experimental system becomes stable.

3. DATA REDUCTION

According to the solution-diffusion model (Wijmans and Baker, 1995), the moisture transport process involved in the present research can be considered to include five (5) steps:

- 1) The moisture from the water transfers through the air gap to the membrane
- 2) The moisture dissolves in the membrane material
- 3) The moisture diffuses through the membrane
- 4) The moisture desorbs from the membrane
- 5) The moisture humidifies the air stream by convection

The moisture flux from the membrane upper surface to the air stream in the channel can be represented by

$$J = k(w_{ma} - w_a)$$

 w_a is the average humidity ratio of the entering and leaving air, given by

$$w_a = (w_{in} + w_{out})/2$$
 (2)

Because of the large dimensional differences in membrane geometry, moisture diffusion in membrane can be treated as a one-dimensional mass transfer process in the membrane thickness direction. This yields the following equation for the moisture flux through the membrane

$$J = \frac{D_{wm}}{\delta} (\theta_{mw} - \theta_{ma}) = \frac{D_{wm}}{\delta} \frac{\theta_{mw} - \theta_{ma}}{w_{mw} - w_{ma}} (w_{mw} - w_{ma})$$
(3)

The moisture flux through the air gap between the membrane and water can also be treated as a one-dimensional mass transfer process but with an equivalent diffusivity of water vapor in the air gap, the moisture flux can thus be written as

$$J = \frac{D_{va}}{L} (w_s - w_{mw}) \tag{4}$$

 D_{va} expresses the equivalent diffusivity, which is determined through the air gap resistance test introduced in Section 2.4.

The moisture flux in the whole mass transfer process can, therefore, be represented by

$$J = k(w_{ma} - w_a) = \frac{D_{wm}}{\delta} \frac{\theta_{mw} - \theta_{ma}}{w_{mw} - w_{ma}} (w_{mw} - w_{ma}) = \frac{D_{va}}{L} (w_s - w_{mw})$$
(5)

To get a better understanding of the moisture transport mechanism through a membrane, it is rational to summarize the moisture resistance in a form similar to that of the thermal resistance. From Equations (1) to (5), we get

$$J = \frac{W_s - W_a}{\frac{1}{k} + \frac{\delta}{D_{wm}} \frac{(W_{mw} - W_{ma})}{(\theta_{mw} - \theta_{ma})} + \frac{L}{D_{va}}}$$
(6)

So the total moisture resistance can be represented by

$$R_{tot} = \frac{1}{k} + \frac{\delta}{D_{wm}} \frac{(w_{mw} - w_{ma})}{(\theta_{mw} - \theta_{ma})} + \frac{L}{D_{va}} = R_c + R_m + R_g$$
(7)

As shown by the equation, the total moisture resistance is comprised of three components: the convective moisture resistance in the channel, the moisture resistance through the membrane and the moisture resistance caused by the air gap between the membrane and water.

The relationship between the moisture uptake into the membrane and the relative humidity of the air stream on each side of the membrane can be expressed as follows (Simonson and Besant, 1999)

$$\theta = \frac{\omega_{\text{max}}}{1 - C + C / \phi} \tag{8}$$

where ω_{max} denotes the maximum moisture content of the membrane material and *C* is a constant that determines the shape of the curve and type of sorption. From the data shown in Fig. 2, it is obtained that the ω_{max} is 0.0583 kg/kg for the PES and 0.2995 kg/kg for the cellulose membrane, while the *C* is 2.49 for the PES and 8.11 for the cellulose membrane.

The humidity ratio and relative humidity are related by

$$w = 0.622 \frac{\phi p_s}{p_0 - \phi p_s} \tag{9}$$

where

$$\ln p_s = C_1 / T + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 \ln T$$
(10)

 p_s is the saturation vapor pressure and C_1 =-5800, C_2 =1.3915, C_3 =-0.0486, C_4 =0.4176×10⁻⁴, C_5 =-0.1445×10⁻⁷, and C_6 =6.5460.

On the other hand, the moisture flow rate across the membrane can be obtained from the following equation

$$AJ = \frac{A\Delta w}{R_{iot}} = (w_{out} - w_{in})m_a \tag{11}$$

A is the mass transfer surface area, m_a is the airflow rate, and Δw is the logarithmic humidity ratio difference between the water surface and the air stream, given by

$$\Delta w = \frac{\left(w_s - w_{in}\right) - \left(w_s - w_{out}\right)}{\ln \frac{w_s - w_{in}}{w_s - w_{out}}}$$
(12)

So the total moisture resistance can be calculated from

$$R_{tot} = \frac{A\Delta w}{\left(w_{out} - w_{in}\right)m_a} \tag{13}$$

From Equation (7), we have

$$R_m = R_{tot} - R_c - R_g \tag{14}$$

Therefore, the moisture diffusivity in membrane can be computed from

$$D_{wm} = \frac{\delta}{R_m} \frac{(w_{mw} - w_{ma})}{(\theta_{mw} - \theta_{ma})}$$
(15)

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Convective mass transfer coefficient

The tests to obtain the convective mass transfer coefficient were conducted with the water surface exposed directly to the air stream in the channel. The test results are presented in term of Sh vs. x^* in Fig. 5, in which Sh is the Sherwood number, defined by

$$Sh = kd_e/D_{va} \tag{16}$$

and x* is the dimensionless axial distance, defined by

$$x^* = x/(d_e \cdot \operatorname{Re} \cdot Sc) \tag{17}$$

According to Shah and London (1978), for the convective heat transfer in parallel plates within the thermal entrance region, the local Nusselt number, Nu, can be expressed as a function of dimensionless axial distance, x^* , in a form of $Nu=a(x^*)^b$, where x^* is defined by $x^*=x/(d_e \cdot Re \cdot Pr)$. We referred to the form of this function and utilized the heat and mass transfer analogy principle when we summarized the test data. In Equation (17), Re is the Reynolds number, given by

$$Re = ud_{a}/v \tag{18}$$

Sc is the Schmidt number, defined by

$$Sc = v/D_{va} \tag{19}$$

Similar to the convective heat transfer case, the Sh is correlated with the x^* in the form of exponential function based on the experimental data, and the resulting regression correlation is as follows

$$Sh = 3.92 \times (x^*)^{-0.365} \tag{20}$$

Fig. 6 shows the variation of the convective moisture transfer coefficient, k, with the axial distance, x. The figure shows that the k decreases with x, but the decreasing rate becomes smaller for greater x. This result is reasonable.



Figure 5: Variation of *Sh* with x^*

4.2 Moisture resistance caused by air gap

The tests to determine the moisture resistance caused by the air gap were conducted for different air gap thicknesses and the test data are plotted in Fig. 7. The figure shows that the total moisture resistance increases almost linearly with the air gap thickness, L. According to Equation (7), the total moisture resistance can be represented by

$$R_{tot} = R_c + R_m + R_g = R_c + R_m + \frac{L}{D_{va}},$$

The linear variation of R_{tot} with L supports that the equivalent diffusivity of water vapor in the air gap, D_{va} ', can be obtained by calculating the slop of the regression line shown in Fig. 7. The calculated value of D_{va} ' is 5.37×10^{-5} m²/s, as compared to 2.55×10^{-5} m²/s of the D_{va} given by ASHRAE (2001), the former is about two times





of the latter. A possible explanation is that the vapor transfer in the air gap may not be an ideal one-dimensional diffusion from the water surface to the membrane, multi-dimensional diffusion even convective transfer may exist

and contribute to the vapor transfer in the air gap. With the calculated D_{va} , the moisture resistance caused by the air gap, R_{g} , can be obtained for any air gap thickness.

4.3 Moisture permeation through membrane

The tests to investigate the moisture permeations of the PES and cellulose membranes were conducted with fixed air gap thickness (5 mm) for different airflow rates, and the results are presented in Fig. 8. The figure shows that the two membranes yield comparable total moisture resistances. As the airflow rate increases, the total moisture resistances tend to decrease.



Figure 8: R_{tot} for the PES and cellulose membranes

Figure 9: Various resistances for the PES membrane

Fig. 9 shows the total moisture resistance, along with the three component resistances including the convective moisture resistance in the channel, the moisture resistance through membrane, and the moisture resistance caused by the air gap, for the PES membrane. It is seen that all resistances almost stabilize for the airflow rates from 2 to 5 L/min. For 5 L/min airflow rate, the convective moisture resistance accounts for 26.9% of the total moisture resistance through membrane for 26.6%, and the moisture resistance caused by the air gap for 46.5%. The results for the cellulose membrane are similar to those for the PES membrane. For 5 L/min airflow rate, the percentages of these three component resistances are 28.9%, 21.4% and 49.8%, respectively.

From Equation (15), the moisture diffusivity in membrane can be calculated. For 5 L/min airflow rate, the calculated moisture diffusivity in the PES membrane is 8.64×10^{-7} kg/ms, while that for the cellulose membrane is 5.41×10^{-7} kg/ms, the former is significantly greater than the latter. However, as compared to the membranes treated by the other investigators [e.g., Cha et al. (1996) and Niu and Zhang (2001)], we should say that both membranes have relatively good vapor permeability.

5. CONCLUSIONS

An experimental approach for evaluating the moisture diffusivity in membrane has been developed in this research. The moisture diffusivities in two membranes including the PES and cellulose membranes were estimated through this approach and the results show that both membranes have relatively good moisture permeability.

NOMENCLATURE

A	mass transfer surface area	(m^2)	Subscripts	
С	constant in sorption		а	air, or airside
d_e	equivalent diameter	(m)	in	air entering
D_{va}	vapor diffusivity in air	(m^2/s)	m	membrane, membrane surface,
D_{va} '	equivalent vapor diffusivity in air gap	(m^2/s)		or membrane side
D_{wm}	moisture diffusivity in membrane	(kg/ms)	out	air leaving
J	moisture flux across membrane	(kg/ms)	S	saturation
k	convective mass transfer coefficient	(m/s)	v	vapor

L	air gap thickness	(m)	W	water, water vapor, or waterside
m_a	airflow rate	(kg/s)		
p_0	atomospheric pressure	(Pa)		
p_s	saturation vapor pressure	(Pa)		
R_c	convection resistance	(m ² s/kg)		
R_g	air gap resistance	(m^2s/kg)		
R_m	membrane resistance	(m ² s/kg)		
R_{tot}	total moisture resistance	(m ² s/kg)		
Re	Reynolds number			
Sc	Schmidt number			
Sh	Sherwood number			
V_a	volumetric airflow rate	(m^{3}/s)		
и	air velocity	(m/s)		
w	humidity ratio	(kg/kg)		
Δw	logarithmic humidity ratio difference	(kg/kg)		
x	axial distance	(m)		
<i>x</i> *	dimensionless axial distance			
Greek l	etters			
δ	membrane thickness	(m)		
θ	moisture content in membrane	(kg/kg)		
v	kinematic viscosity of air	(m^2/s)		
ϕ	relative humidity			
ω_{max}	maximum moisture content of membrane	(kg/kg)		

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ACKNOWLEDGEMENT

This research is funded by National Natural Science Foundation of China (50576040).