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Abstract: Humidification and dehumidification are common processes in air conditioning industry. In this study, a new technique-the hydrophobic membrane based air humidification and dehumidification are investigated. The effects of membrane characteristics on moisture exchange effectiveness of the system are studied. A two-dimensional transient model which takes into account the combined mechanisms of Knudsen flow and ordinary diffusion in membrane pores is proposed and validated. Four membranes, 2 hydrophobic treated Nylon and 2 PVDF, are used in the test to validate the model. Then the effects of variations of membrane properties on the system performance and membrane to total resistance ratio, are evaluated. A dimensionless Number of Transfer Units (NTU) can be summarized to govern the moisture exchange performance. Following, a correlation has been obtained to reflect the relations between the moisture exchange effectiveness and the Number of Transfer Units.

Keywords: Air dehumidification/humidification, hydrophobic membranes, mass transfer

INTRODUCTION

Today, a large variety of membranes are used in numerous processes devoted to molecular-scale separation in liquids or gases. The most classic operations

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are ultrafiltration, electro-dialysis, pervaporation, distillation, and gas separation. In the past few years, new techniques that can be summarized under the name "membrane contactors" have been proposed (1, 2). In these processes the membrane, which is generally macro and micro porous, acts as a barrier, preventing downstream and upstream phase mixing and allowing the transfer of some fluid components through the membrane porosity. In contrast to the phenomena through occurring in classic membrane processes, there is no selectivity due to the material itself, and diffusion mechanisms generally prevail.

Among the various applications of hydrophobic macro and microporous membranes, air dehumidification and humidification is one that attracts increasing interest in HVAC (Heating, Ventilating, and Air Conditioning) industry. Achieving suitable environmental conditions in both living and working spaces often requires control of the relative humidity of air, its range of variation or its maximum or minimum values, and civil and industrial air conditioning is expected to grow significantly worldwide. This is particularly important in certain residential or industrial environments, where air humidity control is related to improved human well-being and health, the reduction of static electricity, lower rates of chemical or biochemical reactions in storage, attenuation of shrinkage or expansion of artifacts, etc. (3).

The mostly widely used method of air humidification is ultrasonic vaporization of liquid water in a room. Though simple, carry-over of liquid water droplets to indoor air is often prohibited. Compared to air humidification, air dehumidification is a non-spontaneous behavior and is difficult and complicated to accomplish. The most widely practiced method of air dehumidification from a built environment involves condensing the water vapor by cooling the atmosphere below the dew point. The process and the subsequent re-heating process are energy intensive. The place that accumulates liquid water droplets has hygienic problems. Mildew may grow below wet cooling coils.

The absorption of water vapor by means of liquid desiccant may offer advantages in comparison with air cooling dehumidification. The use of these absorption systems can prevent frost forming on the coils when air chilling to subfreezing dew-point is required, and improve the quality of indoor air by the coabsorption of many volatile organic compounds into the solution (4). Indeed, an LiCl solution shows a marked bacteriostatic activity, thus ensuring a better biological quality of handled air.

However, whether air humidification or dehumidification, direct contact systems show some disadvantages, since liquids are often sprayed into the air stream or wetted onto contact surfaces to absorb water vapor from the supply air or to humidify the air. The serious consequences include fouling of the various orifices, tubes, seals, and channels.

To overcome these problems, some new systems named membrane-based air humidification/dehumidification in which a membrane permeable to the vapor phase, but not to the liquid one, is used, have been proposed (4–6).

In such systems, the hydrophobic membrane acts as a barrier between the air stream and the salt solution, preventing the carryover of liquid droplet into air stream. This separation of air and water droplet is extremely important for spacecraft life support systems (7).

The concepts of membrane-based humidification/dehumidification have been validated by many investigators (4–7) by experimental work and field tests, however, regretfully, detailed studies of moisture transfer mechanisms in the systems are quite limited. The effects of membrane characteristics and operating conditions on system performance, in terms of moisture diffusion through membranes, need to be evaluated imperatively. This will be the focus of this study. As a first step, a detailed two-dimensional, transient mathematical model governing the moisture transport in the cell and in the membrane itself, is built up. A test is then done to verify the model, followed by parametric studies.

EXPERIMENTAL WORK

Membrane Materials

Four commercial hydrophobic membranes, two hydrophobic treated Nylon and two PVDF, manufactured by a local supplier are tested. Table 1 lists the characteristics of membranes tested. The mean pore diameters of the materials are measured by an Automatic Surface Area and Pore Size Analyzer, which works on the theory of liquid nitrogen adsorption. The tortuosity values are empirical values provided by the material supplier, which are related to manufacturing processes. Table 1 also gives an estimation of the effective moisture diffusivity in membranes under current conditions.

Test Rig

The experimental device used in this study is designed at a laboratory scale and it simulates an air humidification/dehumidification set-up. It allows controlling relative humidity within a range of $\pm 1\%$ and air flow rates with a

Table 1. Membrane characteristics tested

Symbol	Material	d_p (μm)	δ (μm)	ε	τ	Estimated D_{eff} (m^2/s)
M1	Nylon	0.16	99.5	0.65	1.8	2.78×10^{-6}
M2	Nylon	0.43	147.5	0.30	2.4	8.0×10^{-7}
M3	PVDF	1.2	120.5	0.21	2.7	7.2×10^{-7}
M4	PVDF	0.1	101.0	0.59	2.0	1.7×10^{-6}

range of $\pm 10\,\text{ml/min}$. The membrane module is a circular cell having an exchange area of $176.7\,\text{cm}^2$. It is composed of two parts: the lower chamber and the cap, as shown in Fig. 1. When testing, the flat sheet membrane is placed on the lower chamber inside which saturated salt solution is contained. The cap is then covered on the membrane surface and forms a sandwiched structure. The membrane and the inner surface of the cap form a cone-shaped cavity. The air is supplied through the air slits in the cap. It is introduced through two diametrically positioned inlets (symmetrically placed) into a circular-shaped channel at the perimeter, from where the air is distributed over the membrane surface through the circular air slit. The air flows inward radially, until it exits the cap outlet in the center. The cap is designed in a manner that a constant axial air velocity is realized. When flowing across the membrane, the air stream exchanges moisture with the salt solution through membrane pores, and is dehumidified or humidified, depending on the type of salt solution contained. For example, air is dehumidified when LiCl solution is employed, while it is humidified when NaCl solution or pure water is used. The difference between dehumidification and humidification is that the direction of moisture diffusion is opposite for the two cases. In this study, only air humidification with NaCl solution is tested. The equilibrium RH of saturated NaCl solution at room temperature is around 75%, therefore for the sake of protecting RH sensors (capacity type), the maximum outlet RH is 75% during the test. In the test, the vapor emission rate is relatively low, and the cell is well conductive, therefore it is considered isothermal.

The whole experimental set-up is shown in Fig. 2. The cell is supplied with clean and humidified air from an air supply unit. The supply air flows from a compressed air bottle and is divided into two streams. One of them is humidified through a bubbler immersed in a bottle of distilled water, and then re-mixed with the other dry air stream. The humidity of the mixed air stream is controlled by adjusting the proportions of air mixing. The airflow

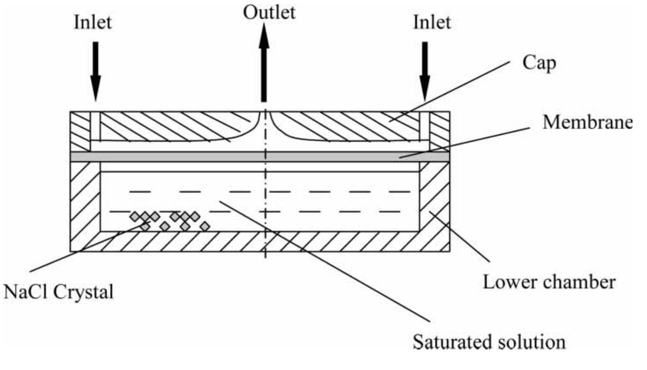

Figure 1. Schematic of the membrane air humidification/dehumidification module.

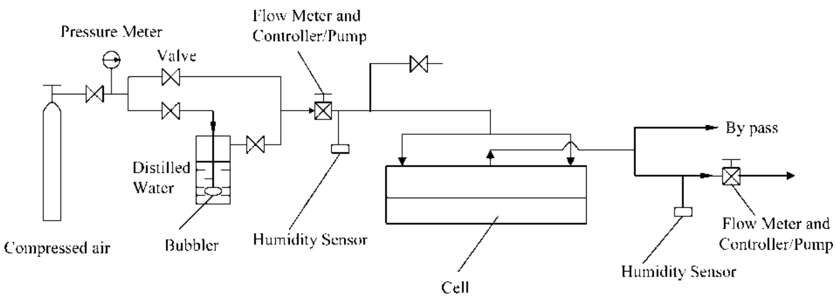

Figure 2. The set-up of the test apparatus.

rates are controlled by two air pumps/controllers at the inlet and outlet of the cell. The humidities and temperatures inside and outside the cell are measured by the built-in RH and temperature sensors, which are installed in the pumps/controllers.

Before each test, the humidity sensors and the flow meters are carefully calibrated with a chilled-mirror dew point meter (accuracy 0.1°C) and a floating ball flow meter (10 ml/min), respectively. Additional NaCl crystals are added to the solution to ensure the solution saturated. Before the test, the cell's outlet and inlet are closed for 24 hours to let the membrane and the cell volume become fully equilibrium with the NaCl solution.

MATHEMATICAL MODEL

Mass Transport in Membrane

The established theory of gas diffusion in such membranes considers three mechanisms: Poiseuille flow, ordinary molecular diffusion, and Knudsen diffusion, or a combination of them.

When Kn (ratio of the pore size to the mean free path) ≥ 10, the Knudsen flow is dominant, the Poisseuille mechanism may be neglected (8). Actually, in most cases for air conditioning industry with microporous membranes, Knudsen number is larger than 10, and Poisseuille flow can be neglected, then the flow is considered to be combined Knudsen and ordinary diffusion.

Ordinary diffusion coefficient of water vapor molecule in air is expressed by (9)

$$D_0 = \frac{C_a T^{1.75}}{P_m \left(v_v^{1/3} + v_a^{1/3} \right)^2} \sqrt{\frac{1}{M_v} + \frac{1}{M_a}} \tag{1}$$

where $C_a = 3.203 \times 10^{-4}$. The terms v_v and v_a are molecular diffusion volumes and are calculated by summing the atomic contributions (9). M_v and M_a are molecule weight of vapor and air in kg/mol. P_m is atmospheric pressure (pa).

Knudsen diffusion coefficient (9)

$$D_K = \frac{d_p}{3}\sqrt{\frac{8RT}{\pi M_v}} \tag{2}$$

where R is gas constant, 8.314 J/(mol K).

The effective diffusivity of combined Knudsen and ordinary flow is (9)

$$D_{KO}^{-1} = \left(D_K^{-1} + D_O^{-1}\right)^{-1} \tag{3}$$

Effective diffusivity in membrane (9)

$$D_{eff} = \frac{\varepsilon}{\tau} D_{KO} \tag{4}$$

Moisture Conservation in Membranes

The schematic of the moisture transport in the cell is represented in Fig. 3. A control volume based mass balance method is employed to obtain the partial differential equations. The model is transient in nature and can be expressed by two-dimensional as

$$\varepsilon \frac{\partial \omega}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(D_{eff}\, r \frac{\partial \omega}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_{eff} \frac{\partial \omega}{\partial z}\right) \tag{5}$$

where r, z are coordinates in radial (m) and thickness (m), t is time (s).

Initial conditions:

$$t = 0, \quad \omega = \omega_L \tag{6}$$

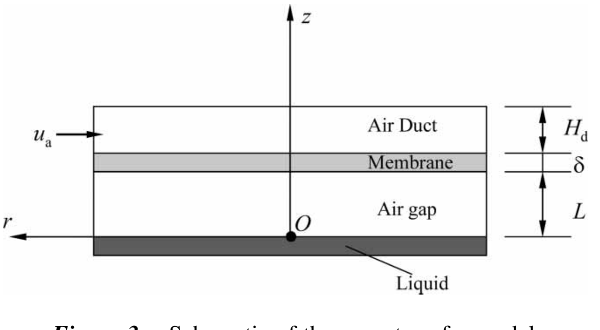

Figure 3. Schematic of the mass transfer model.

Boundary conditions:

$$r = r_0, \quad \frac{\partial \omega}{\partial r} = 0 \tag{7}$$

$$r = 0, \quad \frac{\partial \omega}{\partial r} = 0 \tag{8}$$

$$z = L, \quad D_{\text{eff}} \frac{\partial \omega}{\partial z}\bigg|_{z=L} = D_{\text{va}} \frac{\partial \omega_L}{\partial z}\bigg|_{z=L} \tag{9}$$

$$z = L + \delta, \quad -D_{\text{eff}} \frac{\partial \omega}{\partial z}\bigg|_{z=L+\delta} = k_s(\omega - \omega_a) \tag{10}$$

where ω_L and ω_a refer to air in lower chamber side and air stream side respectively.

Mass Transport in Air Stream

Moisture conservation in air stream is represented by a one-dimensional transient equation:

$$\frac{\partial \omega}{\partial t} + u_a \frac{\partial \omega}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r}\left(D_{\text{va}} r \frac{\partial \omega}{\partial r}\right) + \frac{J_m}{H_d \rho_a} \tag{11}$$

where u_a is air velocity (m/s) in radial, J_m is the local moisture emission rate from the membrane to air ($\text{kgm}^{-2}\text{s}^{-1}$), H_d is height of air stream (m), ρ_a is density of dry air (kg/m^3).

On the membrane upper surface, as shown in Fig. 3, the sweeping side mass flux

$$J_s = k_s \rho_a (\omega_{ms} - \omega) \tag{12}$$

$$J_s = J_m \tag{13}$$

where k_s is the local convective mass transfer coefficient (m/s) between air stream and membrane. The cell is specially designed that a constant air stream radial velocity is realized, when $0.10 < r/r_0 \leq 1.0$. Convective mass transport in the channel can be represented by fully developed laminar flow in duct of parallel plates cross section and is calculated by (10)

$$Sh_L = 7.54 \tag{14}$$

where Sh is Sherwood number, and is defined by

$$Sh = \frac{2 k_s H_d}{D_{\text{va}}} \tag{15}$$

Initial conditions:

$$t = 0, \quad \omega = \omega_L \tag{16}$$

where ω_L is the humidity ratio determined by the saturated NaCl solution and temperature (kg/kg).

Boundary conditions:

$$r = r_0, \quad \omega = \omega_i \tag{17}$$

$$r = 0, \quad \text{stream outlet} \tag{18}$$

Moisture Transport in the Lower Chamber Air Gap

Moisture transport in the lower chamber is governed by gas diffusion. Due to symmetry in angle coordinates, vapor conservation is expressed in two-dimensional by

$$\frac{\partial \omega}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(D_{va} r \frac{\partial \omega}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_{va}\frac{\partial \omega}{\partial z}\right) \tag{19}$$

Initial conditions:

$$t = 0, \quad \omega = \omega_L \tag{20}$$

Boundary conditions:

$$r = r_0, \quad \frac{\partial \omega}{\partial r} = 0 \tag{21}$$

$$r = 0, \quad \frac{\partial \omega}{\partial r} = 0 \tag{22}$$

$$z = 0, \quad \omega = \omega_L \tag{23}$$

$$z = L, \quad D_{va}\frac{\partial \omega}{\partial z}\bigg|_{z=L} = D_{eff}\frac{\partial \omega_m}{\partial z}\bigg|_{z=L} \tag{24}$$

System Performance

The moisture flux from the solution surface to the air stream can be summarized by

$$J = \frac{\Delta \omega_{lm}}{\gamma_{tot}} \tag{25}$$

where γ_{tot} is the total resistance from the solution surface to air stream, $\Delta \omega_{lm}$ is the logarithmic mean humidity difference between the solution surface and air stream, and it is calculated by

$$\Delta\omega_{lm} = \frac{\omega_o - \omega_i}{\ln\left(\frac{\omega_L - \omega_i}{\omega_L - \omega_o}\right)} \tag{26}$$

The total resistance is comprised by three parts as

$$\gamma_{tot} = \gamma_a + \gamma_m + \gamma_L \tag{27}$$

Moisture resistance on the solution side can be represented by the vapor diffusion distance from solution surface to the membrane lower surface.

$$\gamma_L = \frac{L}{\rho_a D_{va}} \tag{28}$$

Moisture transfer resistance (m^2s/kg) across the membrane can be analyzed by

$$\gamma_m = \frac{\delta}{\rho_a D_{eff}} \tag{29}$$

Moisture resistance on air side is

$$\gamma_a = \frac{1}{k_s \rho_a} \tag{30}$$

Convective mass transfer coefficient k_s is calculated by Equations (14) and (15).

A dimensionless parameter, Number of Transfer Units, *NTU*, is defined to characterize the transfer properties of the system as

$$NTU = \frac{A_t K_{tot}}{\rho_a A_c u_a} \tag{31}$$

where A_t is the total transfer area between membrane and air stream (m^2), A_c is the cross-sectional area of air stream, K_{tot} is the total mass transfer coefficient, and it is the inverse of resistance

$$K_{tot} = \frac{1}{\gamma_{tot}} \tag{32}$$

Membrane to total resistance ratio

$$\alpha = \frac{\gamma_m}{\gamma_{tot}} \tag{33}$$

Moisture exchange effectiveness of the system

$$\psi = \frac{\omega_o - \omega_i}{\omega_L - \omega_i} \tag{34}$$

Dimensionless radius

$$r^* = 1 - \frac{r}{r_0} \tag{35}$$

Dimensionless thickness for air gap

$$z^* = \frac{z}{L} \tag{36}$$

Dimensionless thickness for membrane

$$z^* = 1 - \frac{z - L}{\delta} \tag{37}$$

RESULTS AND DISCUSSION

Model Validation

The final set of equations (5), (11), and (19), and the boundary conditions (6)–(10), (16)–(18), (20)–(24) are solved in a coupled way. A program written in FORTRAN language is used. The program is a general one, which can solve 3 dimensional diffusion-convection transient equations with source terms. It is possible to modify all the operating variables, the type of mass transfer mechanisms, and the structural parameters of the membrane.

In calculations, the cell radius is divided into 50 grids, while the membrane thickness and air gap thickness are divided into 20 grids each. Three subroutines corresponding to three components, namely, air gap, membrane, and air stream, are devised to estimate the moisture fields in the cell.

In the experiments and the calculations, the operating parameters are: $L = 2\,\mathrm{mm}$, $H_d = 2\,\mathrm{mm}$, $\omega_L = 0.008\,\mathrm{kg/kg}$, $D_{va} = 2.82\mathrm{e} - 5\,\mathrm{m^2/s}$, operating temperature 20°C, the tested J_m is in the order of $10^{-5}\,\mathrm{kgm^{-2}s^{-1}}$.

Using the parameters of the tested membranes and the operating conditions, the transient response of outlet RH to inlet RH can be modeled. With time lapsing, outlet RH first decreases and then reaches a stable value, indicating that moisture transport becomes stable. This stable value is called the steady state outlet relative humidity. With this value, the moisture exchange effectiveness can be calculated. Figure 4 plots the calculated moisture exchange effectiveness with a comparison with the experimentally obtained values. The discrete dots are test results. As can be seen, good agreements between the calculated and the experimentally obtained are observed. Maximum uncertainty is 6.8%. For all the membranes, the moisture exchange effectiveness decreases with air flow rates, showing a systematic nature.

Figure 5 shows the two-dimensional steady state moisture contours in membrane cross-section. As seen, the contours in membrane are nearly

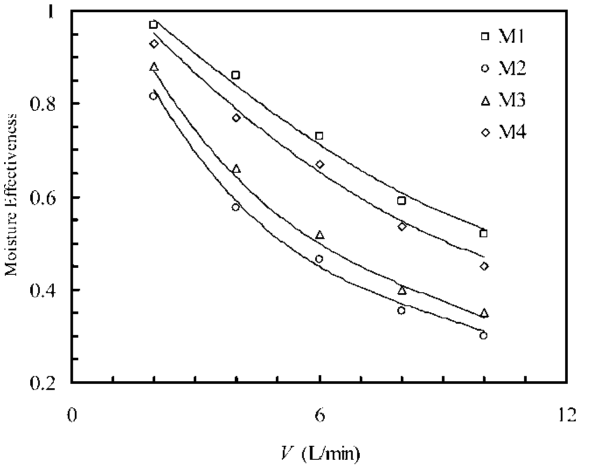

Figure 4. Moisture exchange effectiveness for various hydrophobic membranes, the discrete dots, the experimental; the solid lines, the numerical values.

parallel to diagonal line, indicating a moisture gradient not only in thickness, but also in radius. The gradients are dense near air inlet at $r^* = 0$, but sparsely populated at outlet at $r^* = 1$, showing that membrane exchanges the most moisture neat air inlet. The operating conditions for this case are: inlet humidity 0.0072 kg/kg, air flow rate: 2.4 L/min, membrane, M3. Figure 6 shows the humidity distribution in air stream, membrane (mean in thickness), and in air gap, along the radius, simultaneously. As seen, the variations of change are in phase.

Parametric Studies

With the model, parametric studies can be done. Simulations are performed to investigate the effects of various membrane parameters and operating conditions on system performance. The nominal conditions in the study are: air flow rate, 5 L/min; air gap height, 2 mm; porosity, 0.60; tortuosity, 2.0; thickness, 100 μm; total pressure, 1 atm; temperature, 22.4°C; inlet

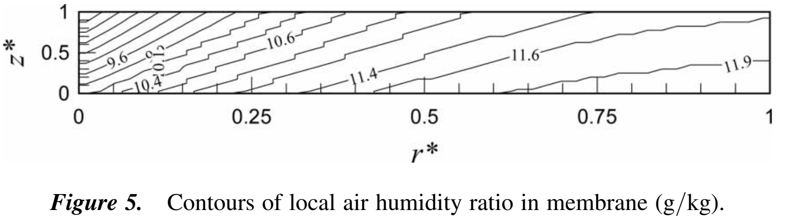

Figure 5. Contours of local air humidity ratio in membrane (g/kg).

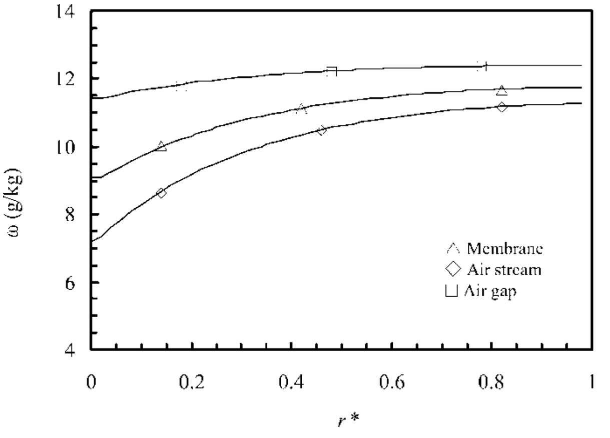

Figure 6. Mean humidity in air gap, membrane and air stream along membrane radius.

humidity, 20%; mean pore diameter, 0.1 μm. One or more characteristics may be changed to reflect the system responses to these changes, but the others are kept unchanged. Though not a direct contacting system, hydrophobic membranes are used because vapor would not condensate in pores of such membranes and the diffusion resistances can be reduced.

Mean Pore Diameter

For membranes, mean pore diameter is one parameter that characterizes membrane performance. This character is reflected in Fig. 7, which shows the effects of mean pore diameter on moisture exchange effectiveness and the membrane to total resistance ratio. As is observed, with pore diameter increasing, membrane resistance decreases, and moisture exchange effectiveness increases. When the pore diameter is larger than 10 μm, moisture exchange effectiveness can be as high as 1.0, and at the same time, the membrane resistance is so small that it can be neglected, compared to convective resistance on membrane surfaces. When the mean pore diameter is within 0.01 μm to 1.0 μm range, membrane resistance could account for 20% to 80% of the total resistance, depending how large the pores are. Larger pore diameters are better for moisture diffusion, as long as liquid solution does not penetrate into pores.

Porosity

Besides mean pore diameter, membrane porosity is another important parameter that dictates membrane performance. This is in accordance with

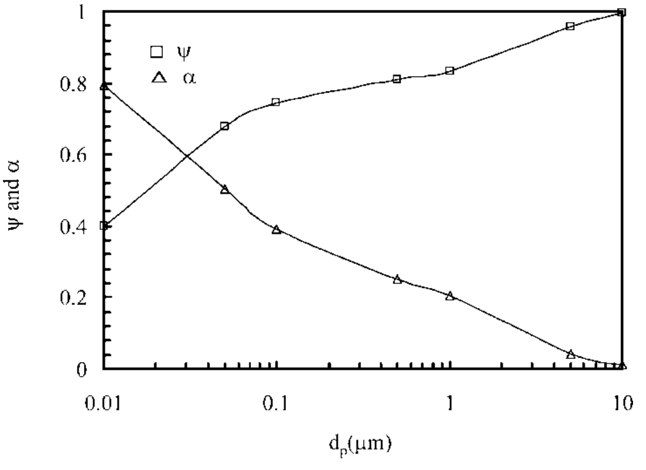

Figure 7. Effects of mean pore diameter on moisture exchange effectiveness and membrane to total resistance ratio.

our observations from Fig. 8. The greater the porosity, the more pores in membrane, and the less the membrane resistance. Membranes with high porosity are beneficial for performance improvement. It should be also mentioned that when the porosity is larger than 0.60, the increase of moisture diffusion with further increase in porosity slows down.

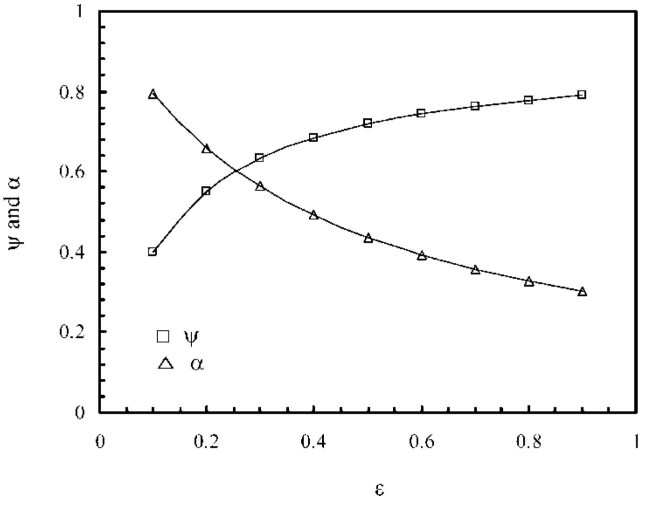

Figure 8. Effects of porosity on moisture exchange effectiveness and membrane to total resistance ratio.

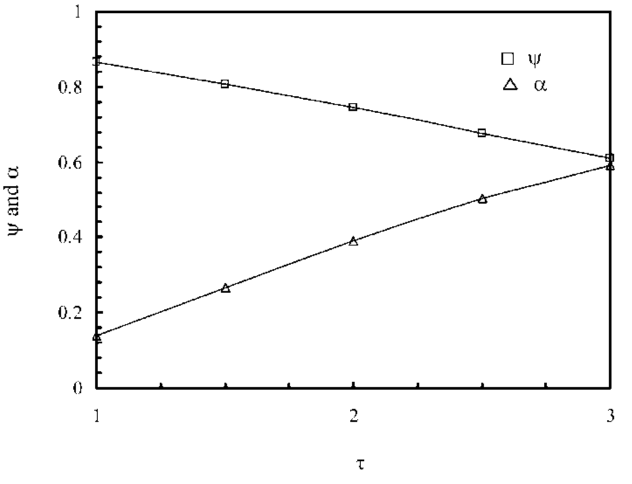

Figure 9. Effects of tortuosity on moisture exchange effectiveness and membrane to total resistance ratio.

Tortuosity

Tortuosity is a parameter that reflects the zigzag nature of membrane pores. Its effects on moisture diffusion can be seen from Fig. 9. The performance is improved with lower pore tortuosity. This is reasonable considering that the higher the tortuosity, the more likely that vapor molecules collide with pore walls, and the higher the membrane resistance.

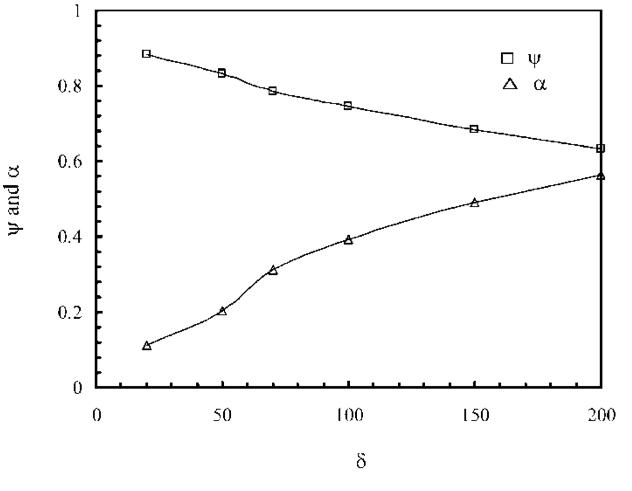

Figure 10. Effects of membrane thickness on moisture exchange effectiveness and membrane to total resistance ratio.

Membrane Thickness

Membrane thickness directly determines the membrane performance. As shown in Fig. 10, the membrane resistance is inversely proportional to membrane thickness, and is proportional to moisture exchange effectiveness. Therefore, thinner membranes are beneficial for system improvement. However, in real applications, membrane with a certain thickness is necessary to ensure the mechanical strength of the unit. Optimization needs to be performed to have a balance between the moisture diffusion and durability.

Air Gap Thickness

Figure 11 shows the effects of air gap height on moisture exchange effectiveness and membrane to total resistance ratio. Both the performance and the membrane to total resistance ratio decrease with air gap distance. The reason is that moisture is first diffused from the solution surface to membrane lower surface. The shorter the diffusion distance, the less the total resistance and the higher the performance. That is the reason why most real applications use direct contact membrane systems in which the membrane are in direct contact with the water or salt solution. This situation corresponds to $L = 0$ in Fig. 10.

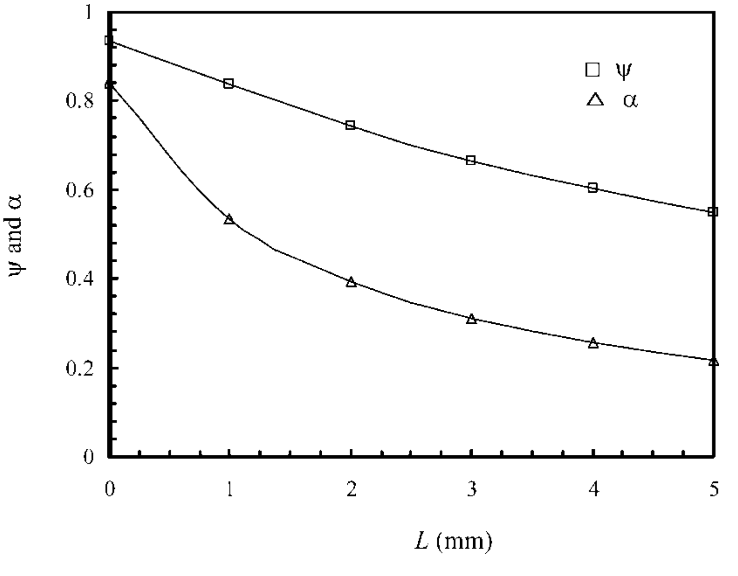

Figure 11. Effects of air gap height on moisture exchange effectiveness and membrane to total resistance ratio.

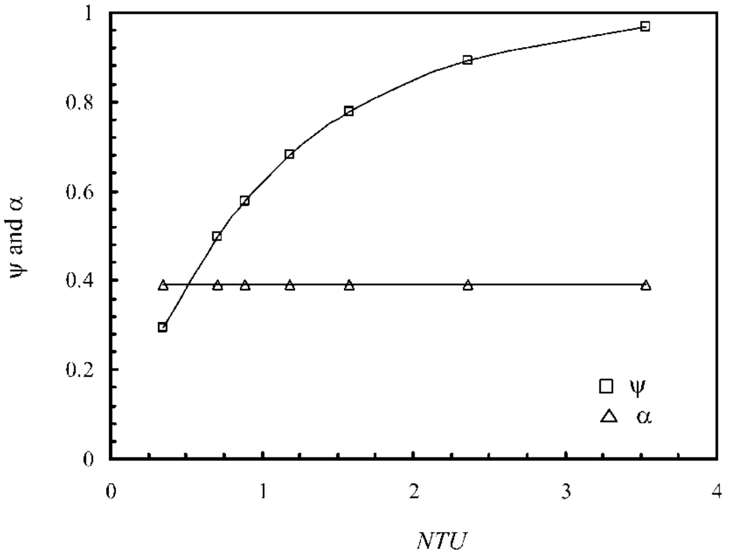

Figure 12. Effects of *NTU* on moisture exchange effectiveness and membrane to total resistance ratio.

NTU

Number of Transfer Units (NTU) is a parameter summarizing membrane resistance, convective resistance and air flow rates. The effects of varying *NTU* on moisture exchange effectiveness and membrane resistance is shown in Fig.12. In this figure, the air flow rate is changed to have a varying *NTU*, from 2 L/min to 12 L/min, therefore the total resistance and the membrane to total resistance ratio changes little. The membrane itself accounts for 40% of the total resistance. The moisture exchange effectiveness rises with *NTU*. A correlation can be fitted to govern this relation as:

$$\psi = 0.5748 NTU^{0.5135} \tag{38}$$

CONCLUSIONS

The mass transfer process for membrane based air humidification and/or dehumidification is investigated. With a detailed two-dimensional transient model, the effects of membrane characteristics and operating conditions on the performance of hydrophobic membrane humidification/dehumidification processes are investigated. It has been found that the mechanisms for mass transfer in membrane pores are co-determined by membrane characteristics and operating conditions. Membrane porosity, mean pore diameter, tortuosity, and thickness are the determining factors influencing membrane moisture diffusion. A correlation has been obtained to reflect the relations between the moisture exchange effectiveness and Number of Transfer Units. A number of transfer units can be used to govern the moisture exchange effectiveness. Another choice for better moisture diffusion is to use direct contact arrangement.

NOMENCLATURE

A_c	cross-sectional area (m^2)
A_t	total transfer area between membrane and air stream (m^2)
D	vapor diffusivity (m^2/s)
d_p	pore diameter (m)
H_d	duct height of air stream (m)
J	emission rate ($kgm^{-2}s^{-1}$)
k	convective mass transfer coefficient (m/s)
k_B	Boltzmann constant (1.38×10^{-23} J/K)
K_{tot}	total mass transfer coefficient ($kgm^{-2}s^{-1}$)
L	Height of air gap (m)
M	molecule weight (kg/mol)
P_m	mean atmospheric pressure in pores (atm)
R	gas constant, 8.314 J/(mol K)
r	radius coordinate (m)
r_0	cell radius (m)
Sh	Sherwood number
T	temperature (K)
t	time (s)
u_a	air bulk velocity (m/s) along radius
v	molecular diffusion volume
V	Volumetric air flow rate (m^3/s)
z	coordinates in membrane thickness (m)

Greek Letters

ρ	density (kg/m^3)
ψ	effectiveness
ω	humidity ratio (kg moisture/kg air)
τ	pore tortuosity
ε	porosity
γ	resistance (m^2s/kg)
α	membrane to total resistance ratio
δ	thickness (μm)

Superscripts

*	dimensionless

Subscripts

a	air
eff	effective
i	inlet
k	Knudsen
L	lower chamber
m	mean, membrane
o	outlet, ordinary
s	surface
v	vapor

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