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Performance analysis of a membrane-based enthalpy exchanger: Effects of the membrane properties on the exchanger performance

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ABSTRACT

A mathematical model was developed to analyze the heat and mass transfer in the core of a membrane-based enthalpy exchanger, and equations for evaluating the thermal and moisture resistances were derived. Calculations were conducted to investigate the effects of the membrane parameters on the exchanger performance. The membrane parameters include the moisture diffusivity, thermal conductivity, moisture sorption constant, and maximum moisture uptake. The calculation results are presented and interpreted in terms of the thermal and moisture resistances. The sensible effectiveness shows a limited change with the membrane parameters because the thermal resistance of the membrane accounts for only a small fraction of the total thermal resistance. The latent effectiveness, basically, change more significantly with the membrane parameters. The enthalpy effectiveness lies between the sensible and the latent effectiveness but locates closer to the latent effectiveness because the latent heat predominates over the sensible heat.

1. Introduction

Forced ventilation is widely used in large buildings where a minimum amount of outdoor air is required for occupant health and comfort [1]. 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. An effective way to reduce the energy consumption is to use a membrane-based enthalpy exchanger to recover energy from the exhaust air (indoor air) to treat the supply air (outdoor air). Since the latent heat of moisture usually accounts for a large fraction of the energy in the exhaust air, recovery of the total heat, which includes the sensible and the latent heat, is of great importance.

A membrane-based enthalpy exchanger (MEE) is an air-to-air heat exchanger with a vapor-permeable membrane core, supply and exhaust airstreams flow through the core and exchange heat and moisture through the membranes. Since the performance of a MEE is largely affected by the moisture permeability of the membrane used to manufacture the core, studies have been conducted to investigate the moisture transport properties of various membranes. As summarized by Ito [2], cellulose triacetate [3], sulfonated poly [4], polyether–polyurethane [5] and siloxane–amido copolymer [6] have been tested for their ability to transfer water vapor. The literature also contains research on the membrane-based enthalpy exchanger. Niu and Zhang [7] developed a theoretical model to predict the performance of a MEE and investigated the effects of the entrance states of the two air streams and the adsorption characteristics of the membranes on the MEE effectiveness. They reported that the entering air humidity greatly affected the exchanger latent effectiveness but had no influence on the sensible effectiveness. Zhang and Niu [8] further developed performance correlations for quick estimates of the enthalpy effectiveness of a MEE, as in Simonson and Besant [9,10] for the rotary energy wheel.

Membrane-based enthalpy exchangers often operate with small temperature differences, which imply the need for accurate energy transfer models. In this research, a mathematical model is developed to analyze the heat and mass transfer in the core of a membrane-based enthalpy exchanger, and equations for evaluating the thermal and moisture resistances are derived. Calculations are conducted to investigate the effects of the membrane properties on the exchanger performance. The calculation results are presented and interpreted in terms of the thermal and moisture resistances.

2. Theoretical model

2.1. Physical model

Fig. 1a shows a schematic of the core of a typical membrane-based enthalpy exchanger [11] while Fig. 1b illustrates the basic physical model for the core. The model consists of a supply stream

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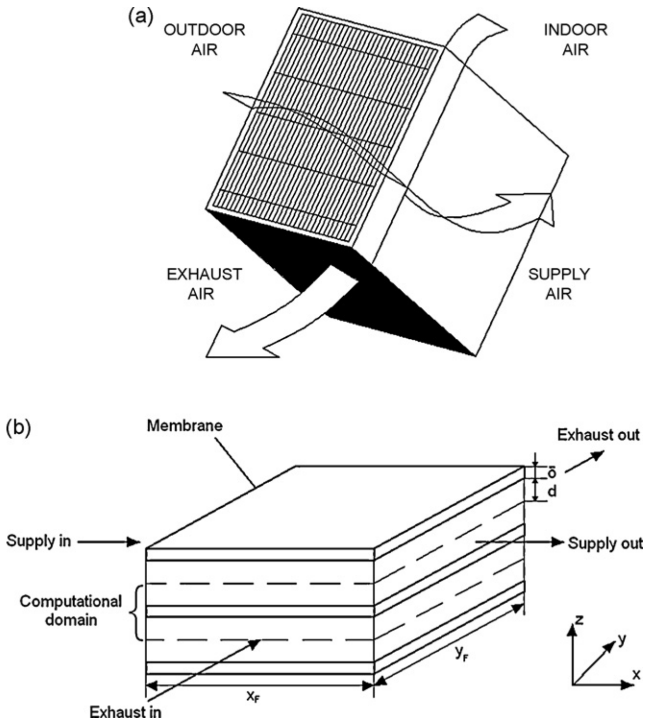

Fig. 1. (a) The core of a typical MEE. (b) Physical model.

channel, an exhaust stream channel and a membrane. The supply air (outside air) and the exhaust air (indoor air or return air) streams flow along the channels in crossflow and exchange heat and moisture through the membrane. Because of symmetry, the computational domain was chosen to include half the volume of the supply airstream, a membrane, and half the volume of the exhaust airstream, as shown in Fig. 1b.

2.2. Assumptions

The mathematical model of the heat and mass transfer processes in Fig. 1b is based on the following assumptions:

(1) Both the heat and mass transfer are at steady state.
(2) The physical properties of the air fluid and membrane are constant.
(3) Heat conduction and vapor diffusion in the two air streams are negligible compared to the bulk convection.
(4) The adsorption of water vapor on the membrane is in a dynamically equilibrium state, as is the desorption of water vapor from the membrane.
(5) The heat of sorption is constant and equal to the heat of vaporization.

The equations governing the coupled heat and mass transfer process were formulated based on these assumptions.

2.3. Governing equations

Supply air:

$$\rho_s c_{ps} v_s d \frac{\partial T_s}{\partial x} + 2h_s(T_s - T_{ms}) = 0 \tag{1}$$

$$v_s d \frac{\partial C_{ws}}{\partial x} + 2k_s(C_{ws} - C_{wms}) = 0 \tag{2}$$

Exhaust air:

$$\rho_e c_{pe} v_e d \frac{\partial T_e}{\partial y} + 2h_e(T_e - T_{me}) = 0 \tag{3}$$

$$v_e d \frac{\partial C_{we}}{\partial y} + 2k_e(C_{we} - C_{wme}) = 0 \tag{4}$$

Membrane:

$$m_w c_{pw} \frac{\partial T_m}{\partial z} - \lambda_m \frac{\partial^2 T_m}{\partial x^2} - \lambda_m \frac{\partial^2 T_m}{\partial y^2} - \lambda_m \frac{\partial^2 T_m}{\partial z^2} = 0 \tag{5}$$

$$m_w = -D_{wm}\rho_m \frac{\partial \theta}{\partial z} = D_{wm}\rho_m \frac{\theta_{ms} - \theta_{me}}{\delta} \tag{6}$$

where T is the temperature, C_w is the water vapor density in the air streams, v is the velocity of the inlet air streams, m_w is the moisture flow rate through the membrane, ρ is the density, h is the convective heat transfer coefficient, k is the convective mass transfer coefficient, λ_m is the thermal conductivity of the membrane, D_{wm} is the moisture diffusivity in the membrane, θ is the moisture uptake at the membrane surface, and the subscripts s, e, m and w refer to the supply air, exhaust air, membrane and water vapor, respectively.

2.4. Boundary conditions

Supply air:

$$T_s|_{x=0} = T_{si}, \qquad C_{ws}|_{x=0} = C_{wsi} \tag{7}$$

Exhaust air:

$$T_e|_{y=0} = T_{ei}, \qquad C_{we}|_{y=0} = C_{wei} \tag{8}$$

Membrane:

$$\left.\frac{\partial T_m}{\partial x}\right|_{x=0} = 0, \quad \left.\frac{\partial T_m}{\partial x}\right|_{x=xF} = 0, \quad \left.\frac{\partial T_m}{\partial y}\right|_{y=0} = 0, \quad \left.\frac{\partial T_m}{\partial y}\right|_{y=yF} = 0 \tag{9}$$

Membrane surface on the supply side:

$$-\lambda_m \left.\frac{\partial T_m}{\partial z}\right|_{z=0} = h_s(T_s - T_m) + m_w L_w \tag{10}$$

Membrane surface on the exhaust side:

$$-\lambda_m \left.\frac{\partial T_m}{\partial z}\right|_{z=\delta} = -h_e(T_e - T_m) + m_w L_w \tag{11}$$

where L_w denotes the latent heat of moisture.

2.5. Mass transfer in the membrane

Both heat and mass transfer occur in a MEE through a moisture permeable membrane. The heat transfer in the membrane obeys the general heat conduction law. However, the mass transfer process is more complicated due to the many parameters and the wide variety of operating conditions. The moisture exchange across the membrane is given by

$$m_w = k_s(C_{ws} - C_{wms}) = k_e(C_{wme} - C_{we}) = D_{wm}\rho_m \frac{\theta_{ms} - \theta_{me}}{\delta} \tag{12}$$

The relationship between the water uptake into the membrane and the relative humidity of the air stream on each side of the membrane can be represented by [9,10]

$$\theta = \frac{w_{max}}{1 - C + C/\phi} \tag{13}$$

where w_{max} is the maximum moisture uptake of the membrane material and C is a constant that determines the shape of the curve and the type of sorption. So, the moisture flow rate through the membrane can be represented by

$$m_w = \frac{D_{wm}\rho_m}{\delta}(\theta_{ms} - \theta_{me}) = \frac{D_{wm}\rho_m w_{max}}{\delta} \times \left(\frac{1}{1 - C + C/\phi_{ms}} - \frac{1}{1 - C + C/\phi_{me}}\right) \quad (14)$$

2.6. Humid air properties

At atmospheric pressure, the temperature, absolute humidity and relative humidity can be related by [9,10]

$$\frac{\phi}{W} = \frac{e^{5294/T}}{10^6} - 1.61\phi \quad (15)$$

where W is the absolute humidity, ϕ is the relative humidity, and T is the temperature in K. The second term on the right side of the equation is very small compared to the other two terms, so it is generally neglected. In this case, Eq. (15) becomes

$$\frac{\phi}{W} \approx \frac{e^{5294/T}}{10^6} \quad (15a)$$

The equation is valid for temperatures of 0–50 °C. The water vapor density and absolute humidity are related by

$$C_w = \rho_a W \quad (16)$$

where ρ_a is the density of humid air.

2.7. Thermal and mass transfer resistances

When heat and mass transfer occur within a MEE, there is not only sensible heat transfer due to the temperature difference, but also latent heat transfer due to mass transfer, so the total heat transfer includes the sensible heat transfer and the latent heat transfer. The sensible heat transfer is given by

$$q_S = h_s(T_s - T_{ms}) = h_e(T_{me} - T_e) \quad (17)$$

The latent heat transfer essentially occurs at membrane surfaces, so the heat transfer across the membrane includes the latent heat due to adsorption on one side and desorption on the other side. Therefore, the total heat transfer through the membrane should be

$$q_{tot} = q_S + q_L \quad (18)$$

where

$$q_L = m_w L_w \quad (19)$$

The equation for the heat transfer across the membrane is

$$q_{tot} = \lambda_m \frac{T_{ms} - T_{me}}{\delta} \quad (20)$$

Therefore, the total thermal resistance can be represented by

$$r_{h,tot} = \frac{1}{h_s} + r_{h,m} + \frac{1}{h_e} = \frac{1}{h_s} + \frac{\delta(1 + k_q)}{\lambda_m} + \frac{1}{h_e} \quad (21)$$

where k_q is the latent-to-sensible heat transfer ratio, given by

$$k_q = \frac{q_L}{q_S} = \frac{m_w L_w}{q_S} \quad (22)$$

Substituting Eqs. (14) and (17) into Eq. (22) yields

$$k_q = \frac{L_w D_{wm}\rho_m w_{max}}{\delta h_s (T_s - T_{ms})}\left[\frac{1}{1 - C + C/\phi_{ms}} - \frac{1}{1 - C + C/\phi_{me}}\right] \quad (22a)$$

From Eqs. (21) and (22a), the thermal resistance of the membrane can be represented by

$$r_{h,m} = \frac{\delta}{\lambda_m}(1 + k_q) = \frac{\delta}{\lambda_m}\left\{1 + \frac{L_w D_{wm}\rho_m w_{max}}{\delta h_s(T_s - T_{ms})} \times \left[\frac{1}{1 - C + C/\phi_{ms}} - \frac{1}{1 - C + C/\phi_{me}}\right]\right\} \quad (23)$$

So, the thermal resistance of the membrane can be considered to be the sum of the intrinsic thermal resistance of the membrane (δ/λ_m) and an additional resistance caused by the latent heat transfer across the membrane ($k_q\delta/\lambda_m$). In Eq. (23), the thermal resistance of the membrane is expressed as a product of the intrinsic thermal resistance and a coefficient that is affected by both the membrane parameter and operating condition. We note that Eq. (23) is different from that given by Niu and Zhang [7], which suggests that the thermal resistance of membrane ($r_{h,m}$) is constant and equals to only the intrinsic thermal resistance of the membrane (δ/λ_m).

The total mass transfer resistance is

$$r_{m,tot} = \frac{1}{k_s} + r_{m,m} + \frac{1}{k_e} \quad (24)$$

where $r_{m,m}$ denotes the mass transfer resistance in the membrane. From Eq. (12), the moisture resistance of the membrane can be expressed as

$$r_{m,m} = \frac{\delta}{D_{wm}\rho_m}\frac{C_{wms} - C_{wme}}{\theta_{ms} - \theta_{me}} \quad (25)$$

Substituting Eqs. (14), (15a) and (16) into Eq. (25) gives

$$r_{m,m} = \frac{\delta}{D_{wm}}\frac{10^6\rho_a}{\rho_m w_{max}}\frac{(\phi_{ms}/e^{5294/T_{ms}}) - (\phi_{me}/e^{5294/T_{me}})}{1/(1 - C + C/\phi_{ms}) - 1/(1 - C + C/\phi_{me})} \quad (26)$$

So, the moisture resistance of the membrane can be expressed in a form similar to that of the thermal resistance of the membrane, i.e., it can be expressed as a product of the intrinsic moisture resistance and a coefficient that is affected by both the membrane parameter and operating condition.

It is useful to note that Eq. (26) differs from that given by Niu and Zhang [7] in two respects: first, the former uses the humidity ratio difference as the mass transfer driving potential while the latter takes the relative humidity difference as the potential; second, the former uses gradient across membrane while the latter employs gradient at a single side of membrane. Since humidity can change greatly at the two sides of membrane, gradient evaluated at one side of membrane may differ substantially from that across membrane.

The convective heat transfer coefficient can be calculated from

$$h = \frac{Nu\lambda}{d_h} \quad (27)$$

where d_h is the hydraulic diameter, given by

$$d_h = 2d \quad (28)$$

While the Reynolds number is computed from

$$Re = \frac{\rho v d_h}{\mu} \quad (29)$$

For fully developed laminar flow between parallel plates with constant temperature boundary conditions, the Nusselt number is 7.54 [12].

According to the analogy between heat and mass transfer, the heat and mass transfer coefficients can be related by

$$\frac{h}{k\rho c_p} = Le^{2/3} \quad (30)$$

where Le is the Lewis number, which is approximately 0.85 for temperatures of 25–40 °C [13].

2.8. Effectiveness

The sensible heat transfer effectiveness (or the temperature effectiveness) is given by

$$\varepsilon_S = \frac{\rho_s c_{ps} v_s (T_{si} - T_{so}) + \rho_e c_{pe} v_e (T_{eo} - T_{ei})}{2(\rho c_p v)_{\min}(T_{si} - T_{ei})} \tag{31}$$

The latent heat transfer effectiveness (or the moisture effectiveness) is given by

$$\varepsilon_L = \frac{\rho_s v_s (C_{wsi} - C_{wso}) + \rho_e v_e (C_{weo} - C_{wei})}{2(\rho v)_{\min}(C_{wsi} - C_{wei})} \tag{32}$$

The total heat transfer effectiveness (or the enthalpy effectiveness) is given by

$$\varepsilon_H = \frac{\rho_s v_s (H_{si} - H_{so}) + \rho_e v_e (H_{eo} - H_{ei})}{2(\rho v)_{\min}(H_{si} - H_{ei})} \tag{33}$$

3. Numerical computations

The computational domain was discretized into individual control volumes. Since the thickness of the membrane is very small, the numbers of the nodes in the x, y and z directions were set to be 100, 100 and 3, respectively. The forward difference scheme was used for the air streams, with the central difference scheme used for the membrane.

The values specified for the core dimensions and the outdoor and indoor air states are presented in Tables 1 and 2, respectively. They were taken in the light of Niu and Zhang [7] as well as the technical information provided by some MEE manufacturers. Calculations were conducted based on Tables 1 and 2 data. Further, the air flow rate was set to be 0.2 kg/s for both the supply and exhaust air streams, which corresponds to a 2.0 m/s average air velocity in the channel, yielding a Reynolds number of 550.

4. Validation of the calculations

The effectiveness of a crossflow heat exchanger without mass transfer is given by

$$\varepsilon = 1 - \exp\{R_c^{-1}\, NTU^{0.22}[\exp(-R_c\, NTU^{0.78}) - 1]\} \tag{34}$$

$$R_c = \frac{(mc_p)_{\min}}{(mc_p)_{\max}} \tag{34a}$$

$$NTU = \frac{UA}{(mc_p)_{\min}} \tag{34b}$$

where R_c is the heat capacity ratio, NTU is the number of heat transfer units, U is the overall heat transfer coefficient, and A is the heat transfer surface area. The calculation results were verified by calculating the sensible heat transfer effectiveness of the membrane-based enthalpy exchanger with the mass transfer model turned off. For the 0.2 kg/s air flow rate, the calculated effectiveness was 0.670, which is very close to the value of 0.665 given by Eq. (34). The two agree within 1.0%, supporting the reliability of the calculations.

Table 1
Core dimensions.

x_F (mm)	250
y_F (mm)	250
d (mm)	2.0
δ (mm)	0.1
n	180

Table 2
Outdoor and indoor air states.

Outdoor air	Dry-ball temperature (°C)	35
	Wet-ball temperature (°C)	29
	Relative humidity (%)	63.8
	Absolute humidity (kg/kg)	0.0231
Indoor air	Dry-ball temperature (°C)	27
	Wet-ball temperature (°C)	19
	Relative humidity (%)	47.3
	Absolute humidity (kg/kg)	0.0104

5. Calculation results and discussion

Fig. 2 shows the variations of the thermal resistance of membrane with the moisture diffusivity in membrane (D_{wm}) for two different thermal conductivities of membrane (λ_m). The calculations used w_{max} = 0.1 kg/kg and C = 2.5. For fixed thermal conductivity, when the moisture diffusivity is increased, the thermal resistance increases because the moisture flow rate through the membrane increases, causing an increased latent heat and consequently an increased latent-to-sensible heat ratio. Further, the thermal resistance increases more slowly as the moisture diffusivity increases. The reason is that a larger moisture diffusivity will lead to a smaller moisture content difference between the two sides of the membrane, which reduces the moisture flow rate through the membrane. For fixed moisture diffusivity, the thermal resistance decreases as the thermal conductivity increases.

In fact, the abovementioned effects of the moisture diffusivity and thermal conductivity on the thermal resistance can be easily understood from Eq. (23), in which the thermal resistance of the membrane is expressed as a product of the intrinsic thermal resistance of the membrane and a coefficient that increases with increasing the moisture diffusivity but decreases with increasing the thermal conductivity of the membrane.

Fig. 3 is a graph similar to Fig. 2, it is for the moisture resistance of membrane. The moisture resistance decreases with increasing the moisture diffusivity but exhibits almost no change with the thermal conductivity. The variation of the moisture resistance with the moisture diffusivity can be explained from Eq. (26), in which the moisture resistance of the membrane is expressed as a product of the intrinsic moisture resistance of the membrane and a coefficient that decreases with increasing the moisture diffusivity of the membrane. Eq. (26) excludes the thermal conductivity of the membrane, however, this does not mean that the moisture resistance has nothing to do with the thermal conductivity. The thermal conductivity has influence on the surface temperatures of the membrane, which affects the moisture resistance of the membrane, although the effect may be very weak.

Fig. 4 presents the variations of the membrane-to-total thermal and moisture resistance ratios with the moisture diffusivity in membrane for two thermal conductivities of membrane. The fig-

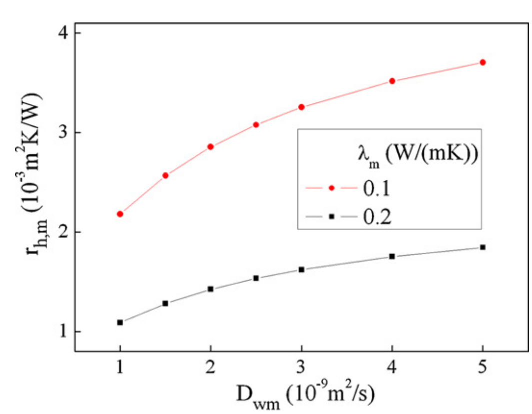

Fig. 2. Variations of the membrane thermal resistance with the membrane transport parameter.

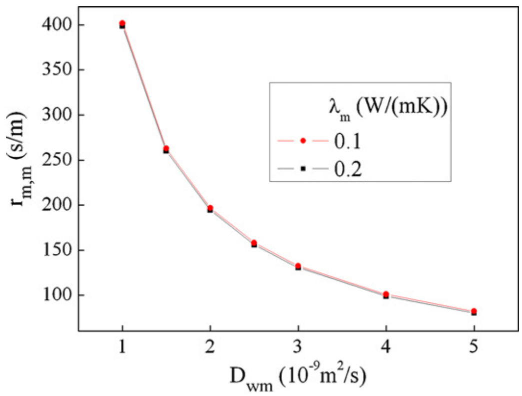

Fig. 3. Variations of the membrane moisture resistance with the membrane transport parameter.

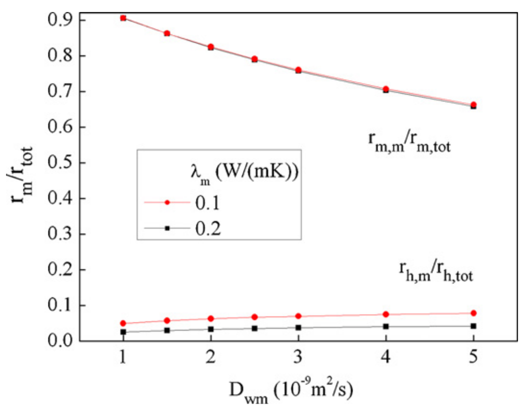

Fig. 4. Variations of the membrane-to-total resistance ratios with the membrane transport parameter.

ure shows that the thermal resistance of the membrane accounts for less than 10% of the total thermal resistance, while the moisture resistance of the membrane accounts for 65–90% of the total moisture resistance. These results support that for a typical membrane-based enthalpy exchanger operating under a typical operating condition, the membrane resistance dominates the mass transfer whereas the convective resistance dominates the heat transfer.

Fig. 5 illustrates the variations of the sensible, latent, and enthalpy effectivenesses with the moisture diffusivity in membrane for two thermal conductivities of membrane. As the moisture diffusivity increases, the sensible effectiveness decreases very slightly while the latent effectiveness increases considerably, the enthalpy effectiveness lies between the sensible and the latent effectiveness and shows a variation similar to that of the latent effectiveness. Although the moisture diffusivity in membrane has a significant effect on the thermal resistance of the membrane (Fig. 2), the thermal resistance of the membrane accounts for only 10% of the total thermal resistance (Fig. 4), resulting in a minimal effect of the moisture diffusivity on the sensible effectiveness. The quick increase of the latent effectiveness corresponds to the rapid decrease of the moisture resistance of the membrane (Fig. 3), which accounts for 65–90% of the total moisture resistance (Fig. 4). The thermal conductivity of the membrane has an insignificant effect on the sensible effectiveness because the thermal resistance of the membrane accounts for only 10% of the total thermal resistance. The thermal conductivity of the membrane has almost no influence on the latent effectiveness because it has little influence on the moisture resistance of the membrane. The enthalpy effectiveness locates closer to the latent effectiveness and exhibits a variation similar to that of the latent effectiveness. The reason is that the latent heat is generally greater than the sensible heat, e.g., for $D_{wm} = 3 \times 10^{-9}$ m^2/s, the latent-to-sensible heat ratio, k_q, takes a value of about 2.5. Since the thermal resistance of the membrane has a linear relationship with the latent-to-sensible heat ratio (Eq. (23)), the variation of the thermal resistance of the membrane (Fig. 2) actually reflects that of the latent-to-sensible heat ratio.

Fig. 6 presents the variations of the thermal resistance of the membrane with the sorption constant of membrane (C) for two different maximum moisture contents of membrane (w_{max}). The calculations used $\lambda_m = 0.1$ W/mK and $D_{wm} = 2.5 \times 10^{-9}$ m^2/s. For fixed maximum moisture content, when the sorption constant is increased, the thermal resistance initially increases, after attaining to a maximum at a certain sorption constant, turns to decrease. The thermal resistance shows a relatively complicated change with the sorption constant because it is a more complicated function of the sorption constant, as seen in Eq. (23). For fixed sorption constant, the thermal resistance increases with increasing the maximum moisture content. It can be inferred from Eq. (23) that the effect of the maximum moisture content of membrane should be similar to that of the moisture diffusivity in membrane.

Fig. 7 is a graph similar to Fig. 6, it is for the moisture resistance of membrane. For fixed maximum moisture content, as the moisture diffusivity increases, the moisture resistance first decreases, after reaching a minimum, turns to increase. The variation of the moisture resistance with the sorption constant is complicated, because the function of the moisture resistance with respect to the sorption constant is complicated, as seen in Eq. (26). For fixed sorption constant, the moisture resistance decreases with increasing the maximum moisture content.

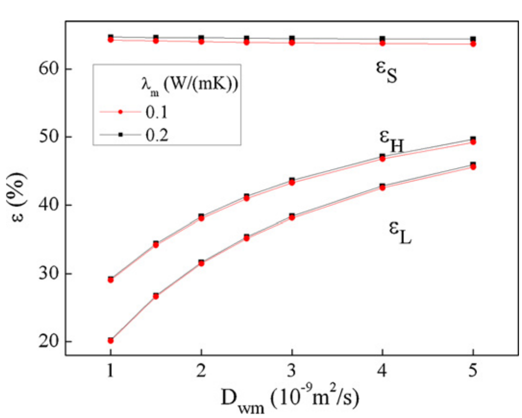

Fig. 5. Variations of the sensible, latent and enthalpy effectivenesses with the membrane transport parameter.

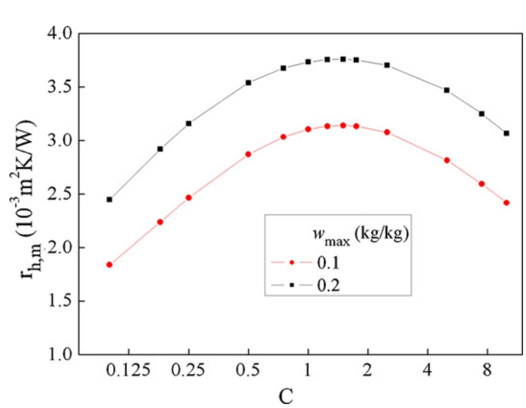

Fig. 6. Variations of the membrane thermal resistance with the membrane sorption parameter.

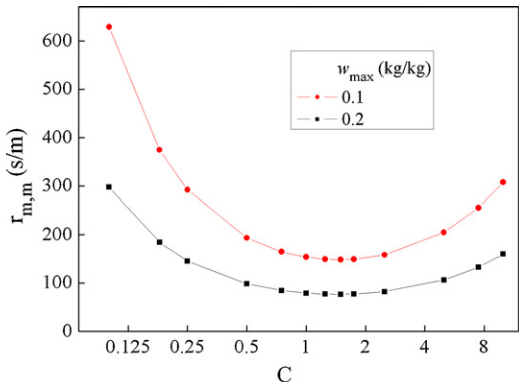

Fig. 7. Variations of the membrane moisture resistance with the membrane sorption parameter.

The membrane-to-total thermal and moisture resistance ratios are plotted against the sorption constant for two different maximum moisture contents in Fig. 8. The thermal resistance of the membrane accounts for 10% or less of the total thermal resistance, while the moisture resistance of the membrane accounts for 65–95% of the total moisture resistance. So, the membrane resistance dominates the mass transfer while the convective resistance dominates the heat transfer.

The variations of the sensible, latent, and enthalpy effectivenesses with the sorption constant of membrane are presented for two maximum moisture contents of membrane in Fig. 9. As the sorption constant increases, the sensible effectiveness maintains almost unchanged, whereas the latent effectiveness initially increases, after attaining to a peak, turns to decrease. As the maximum moisture content increases, the sensible effectiveness shows little change while the latent effectiveness tends to increase. The sensible effectiveness shows almost no change with the sorption constant and maximum moisture content, because the thermal resistance of the membrane accounts for only 10% or less of the total thermal resistance. The variations of the latent effectiveness with the sorption constant and maximum moisture content correspond to those of the moisture resistance of the membrane (Fig. 7). The enthalpy effectiveness locates closer to the latent effectiveness and shows a variation similar to that of the latent effectiveness, because the latent heat predominates over the sensible heat.

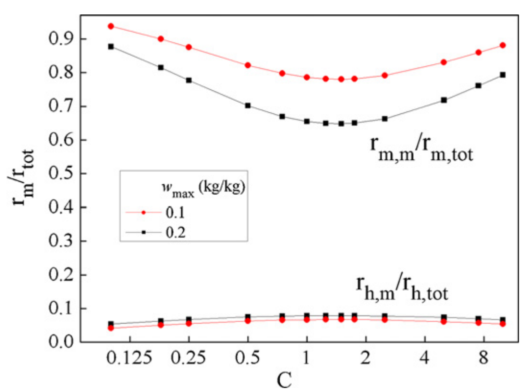

Fig. 8. Variations of latent-to-sensible heat ratio with the membrane sorption parameter.

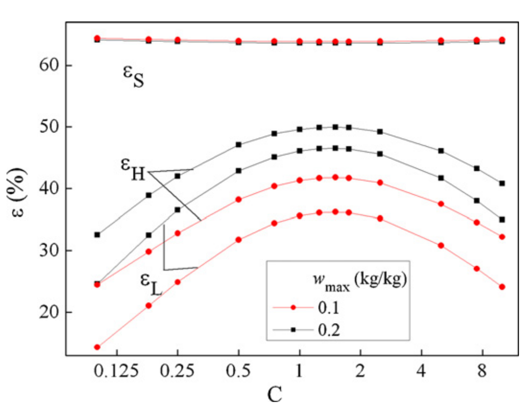

Fig. 9. Variations of the sensible, latent and enthalpy effectivenesses with the membrane sorption parameter.

6. Conclusions

(1) A mathematical model was established to predict the performance of a membrane-based enthalpy exchanger, and equations for evaluating the thermal and moisture resistances were derived. The effects of the membrane parameters on the exchanger performance were investigated systematically and the results were presented and interpreted in terms of thermal and moisture resistances.

(2) As the moisture diffusivity in membrane increases, the sensible effectiveness maintains almost unchanged because the thermal resistance of the membrane accounts for only a small fraction of the total thermal resistance while the latent effectiveness increases considerably because the moisture resistance of the membrane decreases considerably, the enthalpy effectiveness lies between the sensible and the latent effectiveness and shows a variation similar to that of the latent effectiveness because the latent heat predominates over the sensible heat. The thermal conductivity of the membrane has an insignificant influence on all effectivenesses.

(3) As the sorption constant of the membrane increases, the sensible effectiveness maintains almost unchanged whereas the latent effectiveness initially increases, after attaining to a maximum, turns to decrease. As the maximum moisture content increases, the sensible effectiveness shows little change while the latent effectiveness increases significantly, the enthalpy effectiveness locates closer to the latent effectiveness and exhibits a variation similar to that of the latent effectiveness.

Acknowledgement

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Nomenclature

A	heat transfer surface area (m^2)
C	constant in sorption equation
C_w	water vapor density in the air (kg/m^3)
c_p	specific heat (J/kg K)
D	diffusivity (m^2/s)
d	channel height (m)
d_h	hydraulic diameter (m)
h	convective heat transfer coefficient (W/m^2 K)
H	specific enthalpy (J/kg)
k	convective mass transfer coefficient (m/s)
k_q	latent-to-sensible heat ratio
Le	Lewis number
L_w	moisture latent heat (J/kg)
m	air flow rate (kg/s)
m_w	moisture flow rate through the membrane (kg/m^2 s)

n	number of channels
NTU	number of heat transfer units
Nu	Nusselt number
q	heat flux (W/m^2)
r	thermal resistance (m^2 K/W), or moisture resistance (m^2 s/kg)
Re	Reynolds number
T	temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
v	velocity (m/s)
W	absolute humidity (kg/kg)
w_{max}	maximum moisture uptake of membrane (kg/kg)
x, y, z	coordinates
x_F, y_F	channel length (m)

Greek symbols

δ	thickness (mm)
ε	effectiveness
θ	moisture uptake at membrane surface (kg/kg)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
ϕ	relative humidity

Subscripts

a	air
e	exhaust
h	heat
H	enthalpy
i	inlet
L	latent
m	membrane or moisture
s	supply
S	sensible
o	outlet
tot	total
w	water vapor

References

[1] ASHRAE, ASHRAE Handbook-Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 1993 (Chapter 23.1).

[2] A. Ito, Dehumidification of air by a hygroscopic liquid membrane supported on surface of a hydrophobic microporous membrane, J. Membr. Sci. 175 (2000) 35–42.

[3] C.Y. Pan, C.D. Jensen, C. Bielech, H.W. Habgood, Permeation of water vapor through cellulose triacetate membranes in hollow fiber form, J. Appl. Polym. Sci. 22 (1978) 2307–2323.

[4] H. Fu, J. Jia, J. Xu, Studies on the sulfonation of poly(phenylene oxide) (PPO) and permeation behavior of gases and water vapor through sulfonated PPO membranes. II. Permeation behavior of gases and water vapor through sulfonated PPO membranes, J. Appl. Polym. Sci. 51 (1994) 1405–1409.

[5] L. DiLandro, M. Pegoraro, L. Bordogna, Interaction of polyether–polyurethane with water vapor and water–methane separation selectivity, J. Membr. Sci. 64 (1991) 229–236.

[6] K.L. Wang, S.H. McCray, D.D. Newbold, E.L. Cussler, Hollow fiber air drying, J. Membr. Sci. 72 (1992) 231–244.

[7] J.L. Niu, L.Z. Zhang, Membrane based enthalpy exchanger: material considerations and clarification of moisture resistance, J. Membr. Sci. 3 (189) (2001) 179–191.

[8] L.Z. Zhang, J.L. Niu, Effectiveness correlations for heat and mass transfer processes in an enthalpy exchanger with membrane cores, ASME J. Heat Transfer 5 (122) (2002) 922–929.

[9] C.J. Simonson, R.W. Besant, Energy wheel effectiveness. Part 1—development of dimensionless groups, Int. J. Heat Mass Transfer 42 (1999) 2161–2170.

[10] C.J. Simonson, R.W. Besant, Energy wheel effectiveness, Part 2—correlations, Int. J. Heat Mass Transfer 42 (1999) 2171–2185.

[11] ASHRAE, ASHRAE Handbook-HVAC Systems and Equipment, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 2000 (Chapter 44.7).

[12] F.P. Incropera, D.P. DeWitt, Fundamentals of Heat and Mass Transfer, 4th ed., John Wiley & Sons, New York, 1996, p. 450.

[13] T.H. Kuehn, J.W. Ramsey, J.L. Threlkeld, Thermal Environmental Engineering, 3rd ed., Prentice Hall, Upper Saddle River, NJ, 1998, pp. 245–246.