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Outdoor air state that may cause moisture condensation in membrane-type total heat exchangers using different membrane materials

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Abstract

Total heat exchanger (THX) is an air-to-air heat exchanger with a heat/moisture exchanging core made of water vapor permeable membrane, it is used to reduce the building energy consumption by recovering both heat and moisture from ventilation air. In hot and humid climate, the membrane surface may get a temperature below the dew point of supply outdoor air, causing moisture condensation at the membrane surface, which may degrade the exchanger performance and increase the health risk. In this research, a mathematical model is built to describe the heat and moisture transfer in the core of a THX, the effects of membrane properties on moisture condensation are analyzed, and the critical outdoor air states for occurrence of the moisture condensation are calculated. The results show that large membrane adsorption constant and large maximum moisture uptake may restrain the moisture condensation, which occurs more easily at the intersection of the supply and exhaust airstreams. The optimal membrane properties are recommended based on a comprehensive consideration of the safety and economy.

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Keywords: Total heat exchanger; Membrane property; Moisture condensation; Outdoor air state

1. Introduction

The building energy consumption accounts for approximately 40% of the global energy consumption, as reported by Omer [1]. With the increasing concern of indoor air quality and energy saving, the membrane-type total heat exchanger (THX), which has a heat/moisture exchanging core made of water vapor permeable membrane that transfers both heat and moisture, is often employed to reduce the building energy consumption associated with the forced ventilation. The core contains numerous alternately stacked flat channels confined by membrane sheets, supply outdoor air and exhaust indoor air flow through the channels and exchange heat and moisture across the membranes. Min and Duan [2,3] compared four different methods to evaluate the performance of a THX, and

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Nomenclature

C	absorption constant of membrane
c_p	specific heat of air ($\text{J kg}^{-1} \text{K}^{-1}$)
D_{wm}	moisture diffusivity in membrane ($\text{kg m}^{-1} \text{s}^{-1}$)
H	enthalpy (kJ kg^{-1})
h	convective heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
d	channel height (m)
J	mass flux ($\text{kg m}^{-2} \text{s}^{-1}$)
k	convective mass transfer coefficient ($\text{kg m}^{-2} \text{s}^{-1}$)
L_w	adsorption heat (J kg^{-1})
Le	Lewis number
m	air mass flow rate (kg s^{-1})
m_{min}	minimum of supply and exhaust air mass flow rate (kg s^{-1})
Nu	Nusselt number
N	number of channels
q	total heat flux through membrane (W m^{-2})
T	absolute temperature (K)
W	humidity ratio (kg kg^{-1})
w_{max}	maximum moisture uptake (kg/kg)
x_F	channel length in x direction (m)
y_F	channel length in y direction (m)

Greek symbols

δ	thickness of membrane (m)
ε	effectiveness
θ	moisture content of membrane surface (kg kg^{-1})
λ	heat conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
ϕ	relative humidity

Subscripts

e	exhaust air
H	total effectiveness
L	latent effectiveness
m	membrane
S	sensible effectiveness
s	supply air
sat	saturation

pointed out that the numerical method with consideration of the adsorption heat was the best method to calculate such performance, especially when the heat and moisture transfer in different directions. Al-Waked et al. [4] investigated the thermal performance enhancement of membrane-based energy recovery ventilators for different numbers of flow channels, flow configurations, airflow rates, and weather conditions. Lee et al. [5] undertook experimental investigations on the characteristics of moisture transfer with a THX core made of different paper membranes. Engarnevis et al. [6] developed a theoretical model for current generation asymmetric composite membranes used in the THX.

On a hot and humid day in the summer, the supply outdoor air has a high relative humidity, so the membrane surface in contact with it is apt to get a temperature below its dew point, causing moisture condensation at the

membrane surface. The condensate water may wet the membrane and change its property, leading to a degraded THX performance. Rafati Nasr et al. [7] state that the problems caused by the moisture condensation in a THX may include: (1) increases in the pressure loss and overall heat/moisture transfer resistances, and (2) increase in the health risk. So, it is necessary to take measures to restrain or even eliminate the possible occurrence of moisture condensation.

In this research, a mathematical model is built to describe the heat and moisture transfer in the core of a THX, and the effects of the membrane properties including the membrane adsorption constant and maximum moisture uptake on the moisture condensation are investigated and analyzed. The critical outdoor air states for the occurrence of moisture condensation are calculated and summarized for different membrane properties. The relative humidity contours at the membrane surface are presented, and the optimal membrane properties are recommended based on a comprehensive consideration of the safety and economy.

2. Theoretical model

Fig. 1 shows the basic model for the core of a typical THX. Because of the periodicity and symmetry in geometry, half the volume of the exhaust airstream, half the volume of the supply airstream and intermediate membrane are taken to constitute the computational domain.

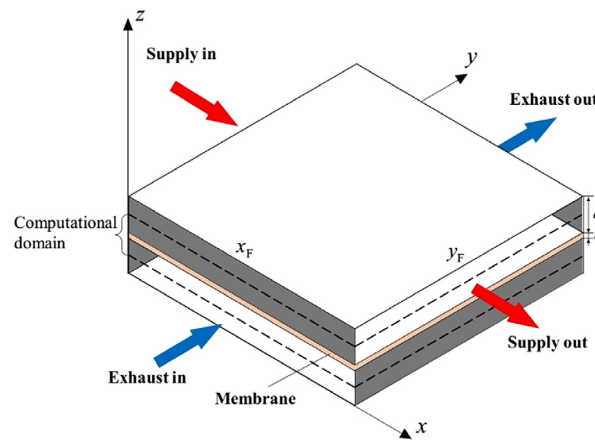


Fig. 1. Basic model.

The model assumes that the physical properties of the air fluid and membrane are constant, and the heat and moisture transfers are both at steady state.

Supply air:

$$\frac{m_s c_p}{N y_F} \frac{\partial T_s}{\partial x} + 2h_s (T_s - T_{ms}) = 0, \quad \frac{m_s}{N y_F} \frac{\partial W_s}{\partial x} + 2k_s (W_s - W_{ms}) = 0 \quad (1)$$

Exhaust air:

$$\frac{m_e c_p}{N x_F} \frac{\partial T_e}{\partial y} + 2h_e (T_e - T_{me}) = 0, \quad \frac{m_e}{N x_F} \frac{\partial W_e}{\partial y} + 2k_e (W_e - W_{me}) = 0 \quad (2)$$

Membrane:

$$q = -\lambda_m \frac{\partial T_m}{\partial z} = \lambda_m \frac{T_{ms} - T_{me}}{\delta}, \quad J = -D_{wm} \frac{\partial \theta_m}{\partial z} = D_{wm} \frac{\theta_{ms} - \theta_{me}}{\delta} \quad (3)$$

further,

$$q = h_s (T_s - T_{ms}) + J L_w = h_e (T_e - T_{me}) + J L_w, \quad J = k_s (W_s - W_{ms}) = k_e (W_e - W_{me}) \quad (4)$$

where m is the air mass flow rate, W is the humidity ratio, h and k are the convective heat and mass transfer coefficients, q and J are the heat and moisture fluxes across membrane, N is the number of channels, x_F and y_F are the channel lengths in the x and y directions, λ_m is the membrane thermal conductivity, D_{wm} is the moisture

diffusivity in membrane, θ is the membrane moisture content, δ is the membrane thickness, and L_w is the heat of adsorption of water vapor on membrane, which is assumed to be equal to the heat of vaporization of water. The subscripts s, e, m and w refer to the supply air, exhaust air, membrane and water vapor, respectively.

The equation describing the moisture adsorption characteristics of water vapor at the membrane surface can be represented by Incropera [8]

$$\theta = \frac{w_{\max}}{1 - C + C/\phi} \quad (5)$$

where ϕ is the air relative humidity, w_{\max} is the maximum moisture content of the membrane material, and C is the membrane adsorption constant, which determines the shape of the adsorption curve. Eq. (5) is widely used to describe the moisture adsorption characteristics of the membrane materials used in a THX, as in Niu & Zhang [9], Min & Su [10–12], and Min & Duan [2,3].

The convective heat and mass transfer coefficients between the air and membrane are given by

$$h = h_s = h_e = \frac{Nu\lambda}{2d} \quad (6a)$$

$$k = k_s = k_e = \frac{h}{c_p Le^{2/3}} \quad (6b)$$

where d is the channel height, Nu is the Nusselt number, which has a value of 7.54 for fully developed laminar flow between parallel plates with a constant temperature boundary condition [13], and Le is the Lewis number, which is approximately 0.85 for a temperature range of 0–40 °C [14].

The THX performance is evaluated using the sensible, latent and total effectivenesses, given by

$$\varepsilon_S = \frac{m_s (T_{si} - T_{so}) + m_e (T_{eo} - T_{ei})}{2m_{\min} (T_{si} - T_{ei})} \quad (7a)$$

$$\varepsilon_L = \frac{m_s (W_{si} - W_{so}) + m_e (W_{eo} - W_{ei})}{2m_{\min} (W_{si} - W_{ei})} \quad (7b)$$

$$\varepsilon_H = \frac{m_s (H_{si} - H_{so}) + m_e (H_{eo} - H_{ei})}{2m_{\min} (H_{si} - H_{ei})} \quad (7c)$$

The equation for judging the critical air state for no occurrence of moisture condensation is as below:

$$W_{ms} < W_{sat} \quad (8)$$

where W_{ms} is the humidity ratio of supply air, and W_{sat} is the saturation humidity ratio at the membrane surface, which corresponds to a relative humidity of 100%.

3. Results and discussion

The model has already been validated in our previous researches (e.g., Min et al. [15], Min & Duan [2]). The values taken for the THX core dimensions and membrane parameters are presented in Table 1. The indoor air temperature and relative humidity are set as 26 °C and 50%, while the air velocity is set as 2 m/s, which corresponds to an air mass flowrate of 0.2 kg/s.

Table 1. THX core dimensions and membrane parameters.

THX core dimensions		Membrane parameters	
x_F, y_F [m]	0.25	λ_m [W/m K]	0.1
d [mm]	2	D_{wm} [10^{-7} kg/m s]	0.1
N	180	C	0.1–10
δ [mm]	0.1	w_{\max} [kg/kg]	0.15–0.35

Fig. 2 illustrates the critical outdoor air states for the occurrence of moisture condensation for membrane materials with different adsorption constants (C). No moisture condensation takes place if the outdoor air state falls in the lower-left region in Fig. 2a, which is confined by the curve for each adsorption constant. All curves are almost linear and tend to shift towards the upper-right corner when the adsorption constant is increased, implying that a larger

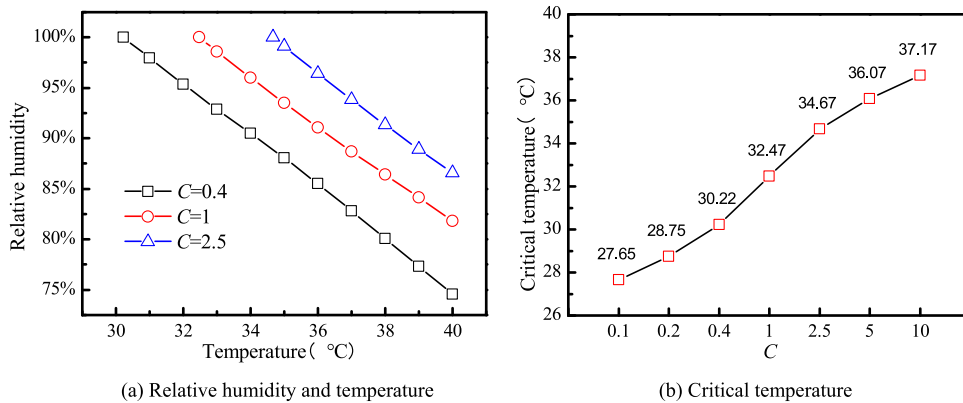


Fig. 2. Critical outdoor air states for different membrane adsorption constants.

adsorption constant allows a higher temperature and relative humidity at which no moisture condensation takes place, so the membrane material with a larger adsorption constant has a better anti-moisture condensation feature. Fig. 2b depicts the critical temperatures corresponding to 100% relative humidity for different adsorption constants in particular, it indicates that the larger the membrane adsorption constant the higher the outdoor air temperature for no occurrence of the moisture condensation.

Fig. 3 shows the variations of various effectivenesses with the membrane adsorption constant. With increasing adsorption constant, the sensible effectiveness changes slightly while the latent and total effectivenesses first increase, after experiencing a slow change stage, turn to decrease. The maximum appears at an adsorption constant that is larger than but very close to the value of unity.

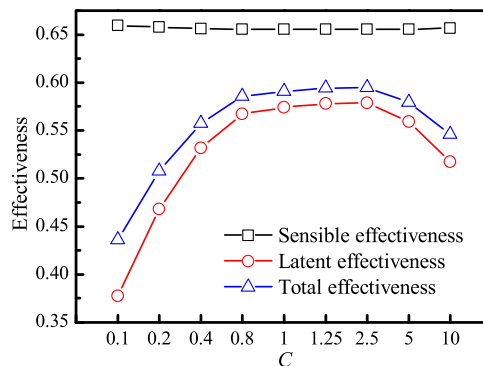


Fig. 3. Various effectivenesses for different membrane adsorption constants.

Comprehensive consideration of Figs. 2 and 3 results suggests that $C = 2.5$ would be a good choice for the membrane adsorption constant, because the relevant membrane yields not only a good anti-condensation performance but also a high effectiveness.

Figs. 4 and 5 are similar to Figs. 2 and 3, they are for the maximum moisture uptake of the membrane. The results in Fig. 4 look very similar to those in Fig. 2, a larger maximum moisture uptake yields a higher relative humidity and temperature at which no moisture condensation takes place, meaning that the membrane material with a larger maximum moisture uptake has better anti-condensation performance. Fig. 5 shows that, as the maximum moisture uptake increases the sensible effectiveness decreases very slightly while the latent and total effectivenesses increase significantly, so the increase in the maximum moisture uptake may contribute to the economic improvement in general. Comprehensive consideration of Figs. 4 and 5 suggests that a larger value should be taken for the maximum moisture uptake in order to get a better effectiveness performance and less health risk.

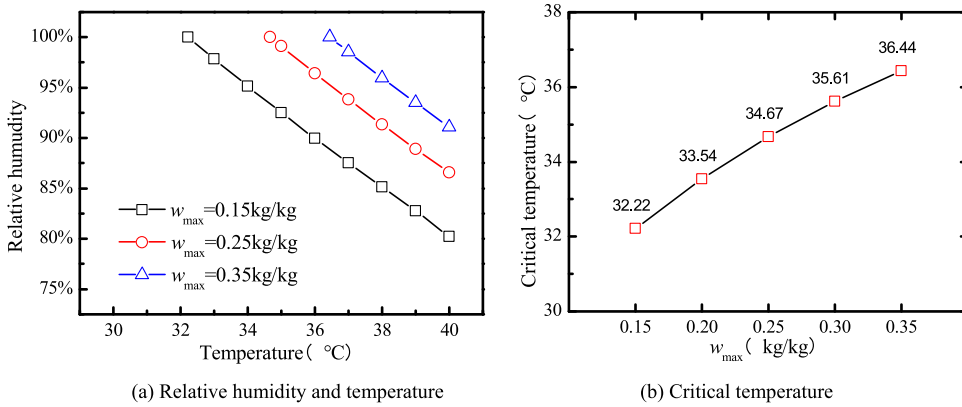


Fig. 4. Critical outdoor air states for different maximum moisture uptakes.

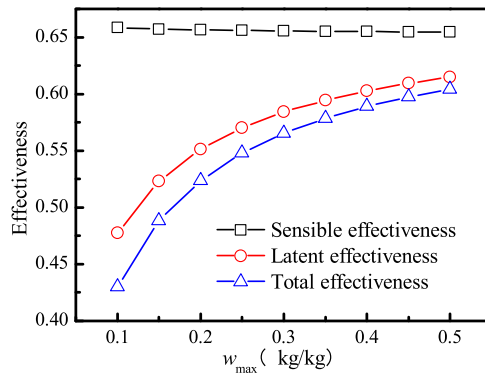


Fig. 5. Various effectivenesses for different maximum moisture uptakes.

Fig. 6 illustrates the relative humidity contours at the membrane surface for 35 °C outdoor air temperature and 70% outdoor air relative humidity for two different membrane materials. One membrane has a property of $C = 1$ and $w_{max} = 0.25$ kg/kg, called the normal membrane, and the other has a property of $C = 2.5$ and $w_{max} = 0.35$ kg/kg, called the recommended membrane. For both membranes, the zone with a higher relative humidity appears in the lower-left region, which is the intersection of the supply outdoor and exhaust indoor airstreams, at which

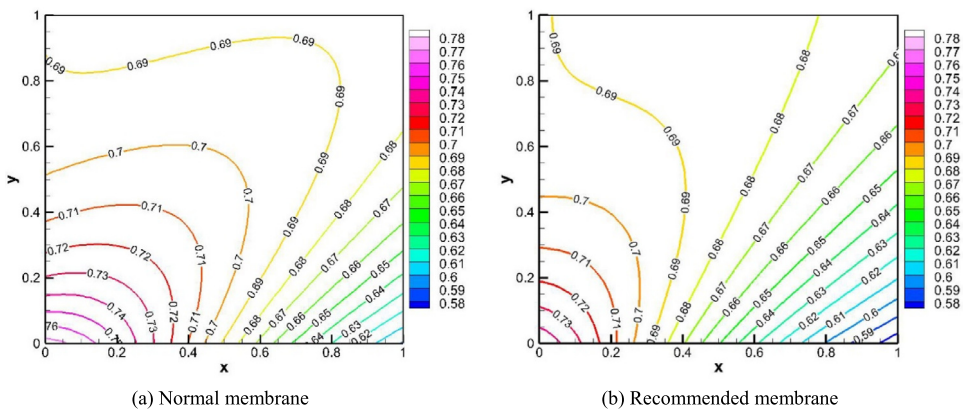


Fig. 6. Relative humidity contours at the membrane surface.

the moisture condensation occurs more easily because of the higher relative humidity. Comparison of Figs. 6a and 6b suggests that the recommended membrane has reduced humidities as compared with the normal membrane, implying that the moisture condensation occurs more difficultly at the recommended membrane surface than at the normal membrane surface, which may interpret the reason why the membrane with a larger adsorption constant and a larger maximum moisture uptake have a better anti-condensation performance. Further, the effectivenesses of the THX using the two different membrane materials are also calculated and the results show that the recommended membrane yields almost the same sensible effectiveness as the normal membrane but gives 3.7 percentage point higher latent effectiveness and 2.9 percentage point higher total effectiveness than the normal membrane.

4. Conclusions

- The outdoor air relative humidity and temperature ranges for no occurrence of moisture condensation for different membrane properties are provided, it is found that the larger the membrane adsorption constant and maximum moisture uptake the better the anti-moisture condensation performance.
- The membrane that has a moderate adsorption constant and a large maximum moisture uptake may yield not only a good anti-moisture condensation performance but also a high effectiveness performance. The recommended membrane that has a property of $C = 2.5$ and $w_{\max} = 0.35$ kg/kg can not only restrain the occurrence of moisture condensation but also give a good economy as compared to the normal membrane that has a property of $C = 1$ and $w_{\max} = 0.25$ kg/kg.
- The moisture condensation takes place more easily at the intersection of the supply and exhaust airstreams because of the higher relative humidity in that region.

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