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Fabrication of a lithium chloride solution based composite supported liquid membrane and its moisture permeation analysis

Li-Zhi Zhang

Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemical and Energy Engineering, South China University of Technology, Guangzhou 510640, China

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Abstract

A novel composite supported liquid membrane has been prepared for ventilation air moisture recovery. The membrane is composed of three layers: two hydrophobic protective layers and a sandwiched hydrophilic support layer in which LiCl solution is immobilized to facilitate water vapor transfer. A test is conducted to measure the moisture permeation rate through the composite membrane. Various resistances in the cell and in the composite membrane are clarified. Linear equilibrium relations between humidity, temperature, and LiCl concentration in the liquid solution layer are obtained to aid in the model set-up. It has been found that the mean moisture permeation rate through the composite membrane is around $1.14 \times 10^{-4}$ kg m$^{-2}$ s$^{-1}$, almost two times higher than that through a solid hydrophilic cellulose acetate membrane with comparative thickness. Further, the supported liquid layer only accounts for 12% of the total moisture transfer resistance in the cell, indicating that there is much potential for further performance improvement.

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1. Introduction

People’s concern on indoor air quality has greatly deepened since the outbreak of the Severe Acute Respiratory Syndrome epidemic (SARS) that devastated South China and some other parts of the world in the Spring of 2003. Increased fresh air ventilation is the most efficient and necessary way to have a better indoor air quality, either in eliminating disgusting odors, diluting VOCs, or decreasing the possibility of being infected by viruses. Increased ventilation rates usually lead to high-energy consumption in air-conditioning. This is because the relative humidity in an occupied building must be controlled to within 40–60% for health and comfort reasons. It has been proved that ventilation air constitutes about 68% of the total moisture load in most commercial buildings [1]. As a consequence, treatment of the latent load from the ventilation air is a difficult and imminent task for HVAC engineers, especially in hot and humid climates.

To save energy in treating fresh air, various techniques for independent air dehumidification have been proposed [2,3]. Among those drawn much attention is one that involves membrane technology—the so called membrane based total heat recovery (MTHR) [4–7]. MTHR is an air-to-air heat exchanger where the two incoming streams (fresh air and exhaust air) exchange heat and moisture simultaneously through membranes. The fresh air represents outdoor air (fresh air intake for a HVAC system). The exhaust air represents stale room air that would normally be exhausted to the outside. The core material of an MTHR ventilator are vapor-permeable membranes, therefore both heat and moisture are transferred between these two air streams when they flow through the unit. Thus, heat and humidity would be recovered from the exhaust stream in winter and excess heat and moisture would be transferred to the exhaust in order to cool and dehumidify the incoming air in summer. In this way, large quantities of energy in HVAC could be saved. Hydrophilic polymer membranes that are permeable to vapor, but impermeable to air, have been considered for MTHR ventilators. Nafion [8,9], regenerated cellulose [10], Cellulose triacetate [11], sulfonated poly(phenylene oxide) [12], polyether-polyurethane [13], siloxane-amido copolymer
Fig. 1. Concept of the composite supported liquid membrane (SLM).

[14], polystyrene-sulfonate [15], polyvinylidene fluoride and polyethersulfone [16], and cellophane [17] are good choices since they have already been used in air dehumidification applications which have similar moisture transfer mechanisms to moisture recovery. However, moisture diffusion coefficients in such polymer membranes are usually very low, in the order of $10^{-12}$ to $10^{-13}$ m$^2$ s$^{-1}$ [11,18], while MTHR ventilators only have limited transmembrane vapor partial pressure difference, consequently performances are quite limited currently.

In contrast to solid membranes, moisture diffusion in liquid membranes ($\sim 10^{-9}$ m$^2$ s$^{-1}$ [19,20], diffusion coefficients) is several orders higher than that in solid membranes. Due to this reason and the inherent high selectivity, in recent years, there has been much effort in progressing the researches of supported liquid membranes (SLM) in various fields: air dehumidification [21], SO$_2$/CO$_2$ separation [22], H$_2$S/CH$_4$ separation [23], wastewater treatment [24], metal ions concentration (uphill transport) [25], separation of isomeric amines between two organic phases [26], to name but a few.

To improve the performances of MTHR ventilators, in this study, a novel membrane, a composite SLM, which employs LiCl liquid solution immobilized in a porous support membrane to facilitate the transport of moisture, is prepared. To protect the SLM, two hydrophobic polyvinylidene fluoride (PVDF) layers are formed on both surfaces of the SLM. The concept is shown in Fig. 1. The sweep represents exhaust air. Moisture permeation through this membrane is of great interest. Moisture transfer characteristics will be the focus of this study.

2. Experimental work

2.1. Preparation of the supported liquid membranes

Three types of commercial membrane were obtained from a supplier. Very hydrophilic cellulose acetate (CA) membranes with nominal pore diameter 0.22 μm and thickness 50–70 μm are used as the support media to immobilize LiCl solution. Two hydrophobic PVDF membranes (equal nominal pore diameter 0.15 μm, thickness 45 μm) are used as the protective layer. Crystals of LiCl·H$_2$O with laboratory class purity is used as the solute.

Before the preparation of composite membrane, each membrane is experimented and observed for their basic microstructures. Figs. 2 and 3 show the scanning electron micrograph (SEM) graphs of the CA membrane and PVDF membrane, respectively.

Under room temperature, well-stirred LiCl solution with 35% mass fraction is first prepared in a closed glass container. Vacuum degassing is applied for 2 h for the three membranes, after which, the CA membrane is dipped into the LiCl solution. After 24 h, the CA membrane is moved from the solution and placed onto a clean glass plate which is cleaned by alcohol. Surplus LiCl solution on surfaces of CA membrane is blotted off with paper tissue. To be sure that no ionic liquid is removed from the membrane pores, the cleaning procedure is very gentle. At this stage, PVC glue is brushed on one surface of the two PVDF membranes, and at the same time on both surfaces of the CA membrane. After a few seconds, the two PVDF membranes are glued to the CA membrane and are pressed together gently for a few seconds. The prepared composite membrane is placed in a constant-temperature–constant-humidity chamber for another 24 h, before experiment is performed.

For comparison, a composite membrane with no LiCl solution immobilized in the CA membrane is also made with the same procedure. The cross-section SEM views of the two composite membranes are shown in Figs. 4 and 5, respectively. To prevent the microstructure being destroyed by knife crushing when preparing cross-section samples, the membranes are first
Fig. 4. SEM graph of the cross-section of the composite membrane without LiCl solution immobilized, 1000 times magnified.

Fig. 5. SEM graph of the cross-section of the composite membrane with LiCl solution immobilized, 1000 times magnified.

Frozen in liquid nitrogen before they are broken off to see the cross-sections.

As seen from Fig. 4, there are some gaps between different layers. Some big cavities in the support layers are also observed, which are presumed to be imperfections in membrane fabrications. However, they have no adverse effects for this study because during operation, they will be filled with liquid solution. In the preparation process, some thickness of the CA membrane is dissolved by the glue, resulting in a lesser support layer thickness than raw material. Fig. 5 with LiCl solution shows that the CA layer and PVDF layer connect to each other very closely and have a dense and continuum interface. There are more big cavities in the support layer. The reason behind this may be that with LiCl solution soaked, the wetted molecular chains in CA membrane structure become more flexible and they will swell and expand to two sides. The boundaries between different layers are pressed together and linked to each other closely. The final CA layer thickness is 52 μm.

2.2. Moisture transport measurement

The membrane module is a circular cell having an exchange area of 176.7 cm². It is composed of two parts: the lower chamber and the cap, as shown in Fig. 6. 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 that a constant axial air velocity is realized. When flowing across the membrane, the air stream exchanges moisture with the salt solution through the composite
SLM, and is humidified. This test uses NaCl solution since it can ensure outlet humidity not saturated, for the protection of RH sensors.

The whole experimental set-up is shown in Fig. 7. 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 air flow rates are controlled by two air pumps/controllers at the inlet and outlet of the cell. The humidities and temperatures to and from the cell are measured by the built-in RH and temperature sensors, which are installed in the pumps/controllers. A detailed description of the test procedure is given in [27].

In the test, the vapor evaporation is slow, and the cell is well conductive. Therefore, only moisture transfer is considered, by neglecting thermal influences.

3. Analysis of transfer resistance

3.1. Total resistance in the cell

Moisture transfer from the saturated NaCl solution to air stream above membrane, is depicted in Fig. 8. Variations of air humidity along the transfer path are shown in Fig. 9 to simplify the mass transfer model. There are totally five resistances that can be clarified: resistance in the lower chamber air gap (1–2); resistance in the first protective layer L1 (2–3); resistance in the supported liquid membrane L2 (3–4); resistance in the other protective hydrophobic layer L3 (4–5); and resistance in the air stream Hg (5–6), as demonstrated in Fig. 10.

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

\[
J = \frac{\Delta \omega}{r_{\text{tot}}}
\]

where \( r_{\text{tot}} \) is the total resistance from the solution surface to air stream and \( \Delta \omega \) is the humidity difference between the solution in lower chamber and air stream above membrane.

\[
\Delta \omega = \omega_L - \omega_D
\]

where subscripts L and D represent solution in lower chamber and air in air duct, respectively.

The mean moisture permeation rate across the whole membrane surface in the cell is calculated by

\[
J_m = \frac{\Delta \omega_{\text{lm}}}{r_{\text{tot}}}
\]

where \( \Delta \omega_{\text{lm}} \) is the logarithmic mean humidity difference between the solution surface and air stream, and it is calculated by

\[
\Delta \omega_{\text{lm}} = \frac{\omega_o - \omega_i}{\ln \left( \frac{\omega_o}{\omega_i} \right)}
\]

where subscripts o and i represent outlet and inlet of air stream, respectively.

The total resistance is comprised of five parts as

\[
r_{\text{tot}} = r_L + r_1 + r_2 + r_3 + r_D
\]

where \( r_L, r_1, r_2, r_3, r_D \) are resistances in air gap, in the first protective layer, in the liquid membrane layer, in the second protective layer, and in air stream, respectively.

3.2. Resistance in the air gap

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

\[
r_L = \frac{L}{\rho_a D_{\text{wa}}}
\]
where $L$ is the height of air gap (m), $\rho_a$ the dry air density (kg m$^{-3}$), and $D_{v,a}$ is the vapor diffusivity in dry air (m$^2$ s$^{-1}$).

### 3.3. Resistance in the composite membrane

Moisture transfer resistance (m$^2$ s$^{-1}$ kg$^{-1}$) in the composite membrane comprises three layers:

$$ r_i = r_1 + r_2 + r_3 $$

where

$$ r_i = \frac{\delta_i}{\rho_a D_{v,a}} $$

where $\delta_i$ is membrane thickness in $i$th layer (m) and $D_{v,a}$ is the equivalent diffusivity of moisture in $i$th membrane, $i = 1, 2, 3$.

### 3.3.1. Resistance in hydrophobic protective layers

The two protective layers on both sides of the liquid membrane are highly hydrophobic. 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.

The governing quantity that provides a guideline in determining which mechanism is operative in a given pore under given operating conditions is the ratio of the pore size to the mean free path $\lambda_i$, which is calculated for a species $i$ using the following expression [28]:

$$ \lambda_i = \frac{k_B T}{\sqrt{2\pi a_i^2 \rho_n}} $$

where $a_i$ is the molecular collision diameter (m), $k_B$ the Boltzmann constant, $1.38 \times 10^{-23}$ J K$^{-1}$, $\rho_n$ the mean total pressure within the membrane pores (Pa), and $T$ is the absolute temperature (K).

For gaseous mixtures of two components, the mean free path and the collision diameters are different from the corresponding quantities for the pure component. The following relationships can be applied for vapor–air mixtures [28]:

$$ \sigma_{i,a} = \sigma_i + \sigma_a \frac{\sigma_i}{2} $$

Under room temperature and atmospheric pressure, calculated $\lambda$ for air is 0.07 $\mu$m; while under vacuum conditions, mean free path for air may be several microns to several meters.

Knudsen number,

$$ Kn = \frac{\lambda}{d_p} $$

where $d_p$ is mean pore diameter (m). When $Kn \geq 10$, the Knudsen flow is dominant, the Poiseuille mechanism may be neglected [28]. Actually, in most cases for HVAC industry with microporous membranes, Knudsen number is larger than 10, and Poiseuille 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 Ref. [29]

$$ D_0 = \frac{C_v T^{1/2}}{P_a(V_a^{1/2} + r_a)^{1/2}} \left( \frac{1}{M_a} + \frac{1}{M_v} \right) $$

where $C_v = 3.203 \times 10^{-4}$. The terms $V_a$ and $r_a$ are molecular diffusion volumes and are calculated by summing the atomic contributions: $V_a = 20.1$, and $r_a = 12.7$ [19]. $M_a$ and $M_v$ are molecular weights of vapor and air in kg mol$^{-1}$. $M$ is 0.018 kg mol$^{-1}$ for water vapor and 0.029 kg mol$^{-1}$ for air, respectively.

Knudsen diffusion coefficient [29]

$$ D_k = \frac{dp}{\lambda} \frac{3RT}{\pi M_i} $$

where $R$ is gas constant, 8.314 J mol$^{-1}$ K$^{-1}$.

The effective diffusivity of combined Knudsen and ordinary flow is [29]

$$ D_{eq} = (D_k^{-1} + D_0^{-1})^{-1} $$

Moisture flux (kg m$^{-2}$ s$^{-1}$) is expressed by

$$ J = \frac{\rho_v e_i D_{eq} \Delta \varphi}{T_0} $$

where $\Delta \varphi$ is humidity difference between the two sides of L1 or L3. Consequently,

$$ D_{eq} = \frac{\rho_v e_i}{T_0} D_{eq,i} \quad i = 1, 3. $$

### 3.3.2. Resistance in supported liquid layer

Water transfer in liquid membrane [22]:

$$ J = \frac{C_0}{T_0} \frac{\Delta C_w}{\Delta t} $$

where $D_{w,i}$ is water diffusivity in liquid membrane (m$^2$ s$^{-1}$) and $\Delta C_w$ is the difference of water concentration in liquid membrane solution (kg m$^{-3}$) between the two sides of liquid membrane.

Water vapor partial pressure, temperature, and LiCl solution concentration are governed by a thermodynamic equation [30]

$$ \log p_v = A(m) + \frac{B(m)}{T} + \frac{C(m)}{T^2} $$

$$ A(m) = A_0 + A_1 m + A_2 m^2 + A_3 m^3 $$

$$ B(m) = B_0 + B_1 m + B_2 m^2 + B_3 m^3 $$

$$ C(m) = C_0 + C_1 m + C_2 m^2 + C_3 m^3 $$

where in this equation $p_v$, is in kPa, $T$ in K, and $m$ is molality of the electrolyte (mol LiCl/kg water).

$$ m = \frac{x}{0.0425(1-x)} $$
where \( x \) is mass fraction of solute (kg LiCl/kg solution). The constants in Eqs. (19)–(21) are given by Ref. [30] 
\[
\begin{align*}
A_0 &= 7.323350, & A_1 &= -0.0623661, & A_2 &= 0.0061613, & A_3 &= -0.001042 \\
B_0 &= -1718.1570, & B_1 &= 8.2255, & B_2 &= -2.2131, & B_3 &= 0.0246 \\
C_0 &= -97575.680, & C_1 &= 3839.979, & C_2 &= -421.429, & C_3 &= 16.731
\end{align*}
\]
Water concentration in solution is 
\[
C_w = (1 - x)\rho_{sol}
\]
where \( \rho_{sol} \) is solution density (kg m\(^{-3}\)), and it is calculated by the following equation [30]: 
\[
\rho_{sol} = \rho_w \sum_{i=0}^{3} \phi_i \left( \frac{x}{1 - \tau} \right)^i
\]
where \( \rho_w \) is pure water density at temperature \( T \), and \( \phi_i \) are given below [31]: 
\[
\phi_0 = 1, \quad \phi_1 = 0.540966, \quad \phi_2 = -1.303792, \quad \phi_3 = 0.100791
\]
In moist air, water vapor partial pressure is calculated by Ref. [7] 
\[
p_v = \frac{\omega P}{\omega + 0.622}
\]
Humidity ratio in ambient air is in the range of 0.005–0.035 kg/kg, therefore the above equation can be simplified to 
\[
p_v = 1.60860P
\]
As can be seen, the relations between the air humidity and water concentration in solution are rather complicated and need iterations to find solution. Calculations of thermodynamic equilibrium chart of LiCl solution with Eqs. (18)–(24) found that under isothermal conditions, a linear equation similar to Henry’s sorption law can be used to express the water concentration in the solution as 
\[
C_w = k_p p_v + C_{w0}
\]
where \( k_p \) is called the Henry coefficient (kg m\(^{-3}\) Pa\(^{-1}\)) and \( C_{w0} \) is a constant (kg m\(^{-3}\)). Table 1 lists the curve regressed values of \( k_p \) and \( C_{w0} \) under different temperatures. 
This table gives the following correlations to estimate \( k_p \) and \( C_{w0} \) from temperature: 
\[
k_p = 0.2625 - 0.0093T + 9.0 \times 10^{-3}T^2
\]
\[
C_{w0} = 739.9 - 1.1T
\]

| \( T \) (°C) | \( k_p \) (kg m\(^{-3}\) Pa\(^{-1}\)) | \( C_{w0} \) (kg m\(^{-3}\)) |
|-------------|-----------------|-----------------|
| 15          | 0.1434          | 727.8           |
| 25          | 0.0665          | 706.4           |
| 35          | 0.0493          | 700.2           |
| 45          | 0.0293          | 691.2           |

The moisture diffusion resistance in the liquid membrane layer can be expressed by 
\[
r_2 = \frac{2k_p D_{el}}{\rho_k D_{el}}
\]
where the equivalent diffusion coefficient of vapor in liquid membrane is 
\[
D_{el} = 1.60860P \rho_k D_{el}
\]

3.4. Convective resistance in air stream

Convective moisture resistance on air stream side is 
\[
r_D = \frac{1}{k_v}
\]
where \( k_v \) is convective mass transfer coefficient (m s\(^{-1}\)).

Convective mass transport in the cell has been investigated by the author and co-workers previously [32] and is expressed in terms of a correlation by 
\[
Sh = 0.3359ReSc \left( \frac{\nu}{2H_a} \right)^{-0.834}
\]
where \( Sh, Re, \) and \( Sc \) are Sherwood number, Reynolds number, and Schmidt number, respectively. They are defined as 
\[
Sh = \frac{2k_H D_{el}}{\nu}
\]
\[
Re = \frac{2\nu D_{el}}{\nu}
\]
\[
Sc = \frac{\nu}{D_{el}}
\]
where \( \nu \) is the kinematic viscosity of air (m\(^2\) s\(^{-1}\)), \( r \) is the radial coordinate (m), \( r_0 \) the radius of the cell (m), and \( \omega_a \) is the air velocity (m s\(^{-1}\)) in radial direction.

3.5. Moisture distribution in air stream

Moisture conservation in air stream is represented by a one-dimensional steady-state equation: 
\[
\frac{\partial \omega}{\partial t} - \frac{1}{H_a} \frac{\partial}{\partial r} \left( H_a \omega \frac{\partial \omega}{\partial r} \right) = 0
\]
Boundary conditions: 
\[
r = r_0, \quad \omega = \omega_a
\]
\[
r = 0, \quad \text{stream outlet.}
\]
Table 2
Parameters used in the test and analysis

| Symbol | Value |
|--------|-------|
| T (°C) | 26.0  |
| δ₁, δ₃ (μm) | 45    |
| δ₂ (μm) | 52    |
| δ₄ (μm) | 0.15  |
| δ₅ (μm) | 0.22  |
| r₀ (mm) | 75    |
| H₀ (mm) | 1.0   |
| Dₑ₁ (× 10⁻⁹ m² s⁻¹) | 3.0    |
| τ₁, τ₂ | 0.65, 0.51 |
| τ₃ | 2.0   |
| V (L min⁻¹) | 10.0 |
| L (mm) | 0.1   |

* From Ref. [20]. Others are from manufacturer’s specifications.

3.6. Moisture permeability

Mean moisture permeability across the whole membrane surface (kg m⁻² s⁻¹)/(kg/kg), is calculated by

\[
\text{Pe} = \frac{u_a \rho_a A_c (\omega_o - \omega_i)}{A_t \Delta \omega_{lm}} \tag{40}
\]

where \( A_c \) is the cross-section area of air duct (m²) and \( A_t \) is the transfer area of membrane in the cell (m²). The permeability \( \text{Pe} \) here represents moisture transfer rate (kg s⁻¹) for unit area of membrane under unit transmembrane humidity difference (kg vapor/kg dry air). It reflects the performance of membrane. Dimensionless radius

\[
r^* = 1 - \frac{r}{r_0} \tag{41}
\]

4. Results and discussion

4.1. Moisture permeability

Table 2 lists the values of operating conditions and system configurations. For each test, several minutes are needed for the system to become steady state. After outlet RH reaches steady state, water vapor permeability can be calculated with Eq. (33). This is the experimental data. The outlet RH can also be predicted with Eq. (30). This is the model prediction. In calculations, the cell radius is divided into 50 grids.

Fig. 11 plots the relative humidity of outlet air under different air flow rates. The model predictions are also plotted in the figure. They are in agreement. Maximum difference is 3%.

Fig. 12 shows the distributions of equivalent air relative humidity on both surfaces of liquid membrane and in air stream, along cell radius. \( r^* = 1 - r/r_0 \). Surface 1: on air gap side. Surface 2: on air stream side.

Fig. 13 plots the distributions of equilibrium mass fraction of LiCl in liquid on both surfaces of liquid membrane, along cell radius. \( r^* = 1 - r/r_0 \). Surface 1: on air gap side. Surface 2: on air stream side.
surrounding air relative humidity has been set-up. As a result, LiCl concentration in the liquid membrane re-distributed and forms a non-uniform mass fraction field. Under the gradients of LiCl (or water) concentrations, moisture is transferred from the lower gap to the air stream. The liquid solution layer also acts as a barrier to air transfer since little air is dissolved in LiCl solution.

Fig. 14 shows the local vapor emission rate along cell radius. As seen, the emission rate exhibits a non-uniform distribution on membrane surface. It decreases from $3 \times 10^4 \text{ kg m}^{-2} \text{s}^{-1}$ at air inlet to $2.4 \times 10^{-5} \text{ kg m}^{-2} \text{s}^{-1}$ at air outlet. The mean moisture emission rate is $1.14 \times 10^{-4} \text{ kg m}^{-2} \text{s}^{-1}$, which is two times higher than the performance of CA membranes in our previous study with the same system ($3.8 \times 10^{-5} \text{ kg m}^{-2} \text{s}^{-1}$) [32]. The resulted mean permeability is $0.043 (\text{ kg m}^{-2} \text{s}^{-1})/(\text{ kg/kg})$.

4.2. Resistance analysis

With models just proposed, various resistances in moisture transfer can be estimated. Fig. 15 shows the percentages of various resistances to total resistance, $3.5 \text{ m}^2 \text{s}^{-1} \text{ kg}^{-1}$. As seen, the current cell fluid dynamics has a relatively larger convective moisture transfer resistance, accounting for 23% of the total resistance. The two protective layers account for 28% of the total resistance each. The air gap diffusion resistance amounts to less than 10% of the total resistance. In real applications in MTHR ventilators, only membrane resistance and convective resistance are considered. As a result, to further improve performances in future, the resistances in protective layers and flow channels should be lowered as a priority. One efficient measure may be to lower the thickness of protective layers to a dozen micrometers, for instance. Using turbulent flow arrangement such as cross-corrugated parallel plates may be the good way to lower resistance in flow channels.

5. Conclusions

A composite supported liquid membrane for moisture recovery has been developed. The supported liquid layer and the two protective layers are in good contact, from SEM observations. The microstructure and the performances are good, though there are some undesired cavities formed in the support layer. The measured water vapor permeation rates are two times higher than a hydrophilic solid membrane with comparative thickness. Various resistances in the composite membrane and in the test cell have been clarified. It is found that the liquid layer only accounts for 12% of the total resistance, therefore there should be much potential for further performance improvement in future, by decreasing other resistances. That is the direction currently being pursued.

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Nomenclature

- $A$: area (m$^2$)
- $c$: concentration (kg m$^{-3}$)
- $d$: pore diameter (m)
- $D$: diffusivity (m$^2$ s$^{-1}$)
- $H$: duct height of air stream (m)
- $J$: emission rate (kg m$^{-2}$ s$^{-1}$)
- $k$: convective mass transfer coefficient (m s$^{-1}$)
- $k_B$: Boltzmann constant (1.38 $\times$ 10$^{-23}$ J K$^{-1}$)
- $k_p$: Henry constant (kg m$^{-3}$ Pa$^{-1}$)
- $K_n$: Knudsen number
- $L$: height of air gap (m)
- $m$: molality of electrolyte (mol LiCl/kg water)
- $M$: molecule weight (kg mol$^{-1}$)
- $p$: partial pressure (Pa)
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