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Experimental and modeling analysis of membrane-based air dehumidification

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ABSTRACT

In this work, a membrane cross flow filtration is studied specifically for the purpose of air dehumidification. A flat sheet composite membrane comprising ceramic and polymeric layers with varied water vapor permeability and selectivity has been developed. Effects of the feed air velocity and humidity, the membrane permeability and selectivity, and the permeate pressure on dehumidification performance (i.e. water vapor removal) and resulting COP (Coefficient of Performance) under a cross-flow flat-sheet setting is systematically studied. Results have shown that the membrane dehumidification performance does not depend on the feed air humidity while its COP does not dependent on the membrane's permeability and the feed air velocity. There exists a tradeoff between the membrane's ability to dehumidify and its achievable COP when both selectivity and permeate pressure are varied.

1. Introduction

In tropical countries, the total energy consumed by the HVAC system is mainly for a direct cooling process by vapor compression chiller. This process is highly inefficient because a significant amount of energy is used for condensing water vapor [1–3]. Hence, it is necessary to remove moisture before cooling the air. Membrane dehumidification has attracted much research interest due to its low cost and low energy consumption [4–13]. Cross flow filtration setup employing flat-sheet membranes (Fig. 1) is highly suitable for air dehumidification because it requires minimal energy to maintain high flow of treated air at atmospheric pressure. A permselective membrane is sandwiched between two chambers. One chamber is continuously fed with a stream of humid supply air at atmospheric pressure. The other chamber is connected to a vacuum pump to produce a transmembrane pressure as a driving force for the filtration process [1–5]. As the humid air stream passes along the membrane, the water vapor is selectively and efficiently sieved out, without any change in air temperature.

To evaluate the performance of a membrane system, both dehumidification performance and dehumidification Coefficient of Performance (COP) are considered. The dehumidification performance in term of percentage of moisture removed can be calculated as:

$$\text{Percentage of water removed} = \frac{\omega_{in} - \omega_{out}}{\omega_{in}} \cdot 100\% \quad (1)$$

where ω_{in} and ω_{out} are the humidity ratios of the feed air before and after treatment. The COP of a dehumidification process can be calculated as follow:

$$\text{COP} = \frac{Q}{W} \quad (2)$$

where Q is the latent heat associated with the amount of water vapor removed. W is approximately the workload of the vacuum pump which can be calculated as follow:

$$W = \frac{nRT}{\varepsilon} \ln \frac{P_{atm}}{P_p} \quad (3)$$

where n is the total moles of gas and vapor pumped by the vacuum pump, R is the ideal gas constant, T is the absolute temperature, P_{atm} is the atmospheric pressure, P_p is the permeate pressure, and ε is the efficiency of vacuum pump. The efficiency of vacuum pump is assumed to be 0.6 [2,3].

In order to create a driving force for water permeation, the permeate pressure must be lower than the partial water vapor pressure in the feed air. Due to the small partial pressure of water vapor in the air, the driving force for water vapor permeation is small. Therefore, in order to obtain significant moisture removal, the membrane must have high water vapor permeance and the permeate pressure must be very low. However, it is important to select an optimal operation pressure at which a reasonable amount

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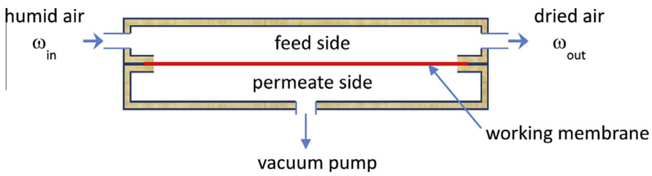

Fig. 1. Cross-flow membrane cell.

of moisture removal is achieved with affordable vacuum pump energy consumption.

Recently, Scovazzo et al. [2] have reported significant dehumidification performance at a permeate pressure much higher than the partial water vapor pressure in the feed air. The researchers extracted some of the air from the output air stream and introduce back into the permeate stream as a sweep gas. In this manner, the concentrated water vapor in the permeate stream is diluted with the sweep air. Therefore, the partial water vapor pressure in permeate stream is reduced significantly, which leads to a higher driving force for water transmission through the membrane. We observe this dilution effect when low selectivity membranes are used. It means that lower membrane's selectivity gives higher dehumidification performance at higher permeate pressure. An interesting question arises if lower selectivity implies higher dehumidification COP?

In this work, we report the fabrication of composite membranes from stainless steel wire mesh, porous titania and hydrophilic poly(vinyl alcohol) with varied water vapor permeability and selectivity. Based on the characteristics of the synthesized membranes, the feasibility of the membrane-based isothermal dehumidification is systematically investigated. Key factors influencing the dehumidification performance and COP of a membrane system such as permeate pressure, velocity and RH of the feed air, permeability and selectivity of the working membrane are studied through experiments and numerical analysis.

2. Experimental

2.1. Membrane preparation

The membranes comprise a twilled Dutch weave stainless steel mesh scaffold, fine and porous TiO_2 (Degussa P25) and hydrophilic polymer layer made of polyvinyl alcohol (Sigma Aldrich) and lithium chloride (Sigma Aldrich) with a certain ratio. The wet P25 TiO_2 was applied on the stainless steel wire mesh by cast-coating method. The obtained mesh with the intermediate layer of TiO_2 was dried at 80 °C for 10 min and then coated with an aqueous solution containing polyvinyl alcohol and lithium chloride using a dip-coater. After several dips alternated with fast dryings at 80 °C for 10 min, a smooth and bubble-free polymer top layer was formed.

2.2. Water permeability test

Water vapor permeability was estimated using the cup method in accordance to ASTM E96 testing standard. Even though ASTM E96 was developed for the measurement of water fluxes through building materials; such as, fiberboard or gypsum, it can still be employed to obtain data for relative comparison since the present membrane fabrication technique allows the membrane's water permeance to be tuned. A membrane was mounted on the opening of a test cup containing distilled water. The test cup is placed in a chamber with controlled RH and temperature. A constant humidity difference was applied between the two sides of the membrane for water vapor permeation. Water vapor permeance, K^w, in mol m^{-2} s^{-1} Pa^{-1}, was obtained by monitoring the weight changes of the test cup and can be calculated as follows:

$$K^w = \frac{1}{M^w \cdot A \cdot P_s \cdot \frac{\Delta RH}{100}} \cdot \frac{dm}{dt} \quad (4)$$

where M^w is the water molar mass (kg mol^{-1}), A is the tested area of the membrane (m^2), P_s is the water vapor saturation pressure at the testing temperature (Pa), and ΔRH is the difference in relative humidity across the membrane and dm/dt is mass change of the cup in unit time (kg s^{-1}).

2.3. Air permeability test

Air permeability measurements were conducted according to ISO 15105-1 standard. A membrane is mounted in a gas transmission cell so as to form a sealed barrier between two chambers. The lower-pressure chamber is evacuated, followed by evacuation of the higher-pressure chamber. Dry air is then introduced to the evacuated higher-pressure chamber and permeates into the lower-pressure chamber. The amount of gas which permeates through the specimen was determined by the increase in pressure on the lower-pressure side. Air permeance, K^a in mol·m^{-2} s^{-1} Pa^{-1} was calculated as follow

$$K^a = \frac{V}{R \cdot T \cdot A \cdot P_h} \cdot \frac{dp}{dt} \quad (5)$$

where V is the volume of the low-pressure chamber (L), R is the gas constant = 8.31 · 10^3 L Pa K^{-1} mol^{-1}, T is the test temperature (K), A is the transmission area of the membrane (m^2), P_h is the pressure of the gas in the high-pressure chamber (Pa), and dp/dt is the change in pressure per unit time in the low-pressure chamber (Pa s^{-1}) at pseudo-steady state part of the dp/dt curve.

2.4. Dehumidification test

The membranes were tested in an experimental setup as shown in Fig. 2. The thickness of each chamber in the membrane cell is 2.5 mm. The dimensions of the effective area of the membranes were 10 cm in length and 2 cm in width. As the humid air passed over the membrane, water vapor is removed and the drier air is obtained. Dehumidification performance was calculated based on humidity ratio values as shown in Eq. (1).

3. Modeling

A 2D simulation for the experimental dehumidification setup, with dimension of 0.25 cm x10 cm in each channel, was developed employing the COMSOL Multiphysics 4.3b platform. The working membrane was modeled as a thin permeable barrier between a feed air chamber and vacuum permeate chamber. The developed membrane model was used to analyze the membrane performance in a designed experimental setup operating at room temperature and under various controllable variables such as permeate pressure, velocity and RH of the feed air, and permeability and selectivity of the membrane.

3.1. Assumptions

The following assumptions were made when developing the model:

1. Humid air is an ideal gas containing two components, water vapor and air.
2. The fluid flow of air stream in air chamber is laminar, steady and incompressible