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Material properties and measurements for semi-permeable membranes used in energy exchangers

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ABSTRACT

Over the past decade, semi-permeable membranes that transfer heat and water vapor have been investigated and applied in air-to-air or liquid-to-air energy exchangers. The water vapor diffusion resistance and modulus of elasticity are two of the most important properties of membranes. These properties play significant roles on the design and performance of the membrane-based energy exchangers. In this study, measurement test methods for membrane properties are presented and important factors impacting the test results are evaluated using the test data. It is found that operating conditions and crystals or deposits in membranes influence the vapor diffusion resistances. The elastic modulus can be determined from the elastic deflection of a simply supported membrane subject to a normal pressure difference. Deflections of membranes are known to cause mal-distribution of flows in energy exchangers and this degrades their performance. Some effective methods to reduce deflections of membranes are presented.

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1. Introduction

During the past few decades, semi-permeable membranes have been investigated and applied in several different applications, including desalination of saline water [1], wastewater treatment plants [2], gas separation plants [3], fuel cells [4], clothing [5], etc. The research and applications of semi-permeable membranes that transfer heat and water vapor in energy exchangers for building heating, ventilation, and air-conditioning (HVAC) systems are a new development [6–13]. The semi-permeable membranes are used in both air-to-air energy exchangers [6–9] and liquid-to-air energy exchangers [10–13].

Compared to conventional plate heat exchangers, both the heat and moisture can be transferred in the membrane exchangers simultaneously. Zhang et al. [6,14] studied the heat and mass transfer in a cross-flow air-to-air membrane energy exchanger and evaluated its performance. They and others showed that the membrane-based exchangers were significantly more cost-effective (i.e. about six times) than a sensible-only heat exchangers for energy recovery in hot and humid regions [14]. The results indicated that semi-permeable membrane air-to-air exchangers are a better design option to meet the increasing demands for efficient energy use in buildings. In addition, several research groups have conducted research works on the heat and mass transfer performance of liquid-to-air membrane energy exchangers (LAMEEs) or contactors and their applications have been performed and reported in the past years [10,12,13,15]. Membrane-based liquid-to-air energy exchangers can eliminate the entrainment of liquid desiccant aerosols in air streams, which is generally a critical challenge for some conventional direct-contact liquid desiccant devices (e.g. packed towers or packed beds [16,17]) when they are used as dehumidifiers or regenerators in liquid desiccant air conditioning (LDAC) systems.

The properties of membranes play significant roles for the design and operating performance of the energy exchangers. The water vapor diffusion resistance (VDR) and modulus of elasticity (E) are two of the most important properties for the selections of semi-permeable membranes [18–26]. Niu and Zhang [18] and Min and Su [19] investigated the effects of membrane parameters on the performance of air-to-air membrane energy exchangers. They found that the latent and total effectiveness of the exchangers were largely affected by the moisture permeability of the membranes used to manufacture exchanger cores, while sensible effectiveness was not sensitive to the properties of typical membranes. For the membrane-based liquid-to-air energy exchangers, Larson et al. [22] found that the effectiveness of a run-around

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membrane energy exchanger (RAMEE) system, which mainly consisted of two LAMEEs, decreased as the vapor diffusion resistance of the membrane increases, especially for the *VDR* values greater than 20 s/m.

Since the semi-permeable membranes are flexible, they will deflect under small pressure differences in the energy exchangers during normal operations and create flow channel variations. Variations in the flow channels can create mal-distributed fluid flows and variations in the mass flow and heat and mass transfer coefficients which decreases the total effectiveness of energy exchangers. Larson et al. [23] revealed that moderate pressure difference across membrane in air-to-air membrane exchangers can result in significant membrane deflections. In addition, they found that the membrane deflection is related to the elastic modulus. The lower the membrane modulus of elasticity, the more the membrane will deflect for a given pressure difference. Large membrane deflections cause mal-distribution or non-uniformity in both the supply and exhaust channel flows of the air-to-air exchangers, and, when large enough, degrade the energy performance of these devices. Similar findings were also reported by other researchers for the liquid-to-air membrane energy exchangers (LAMEE) [24–26]. Hemingson et al. [24] found that the total effectiveness of a run-around membrane energy exchanger system, which consisted of two LAMEEs, degraded energy transfer by about 12.5% when the membrane had a peak deflection of 10% of the nominal air channel thickness. Huang et al. [26] studied the heat and mass transfer deteriorations in an elliptical hollow fiber membrane tube bank for liquid desiccant air dehumidification compared with the circular hollow fiber dehumidifier. Up to 35% and 15% deterioration in *Nu* and *Sh* values in both air side and solution side were found. It meant that both the heat and mass transfer in both the air and the solution sides were degraded substantially due to elastic deflections of membranes.

Measurement methods and devices for the vapor diffusion resistance and elastic modulus of semi-permeable membranes have been reported by Larson et al. [22] and other researchers [27,28]. However, they mainly showed the physical principles of their measurements, but some important factors that may impact the measurement results or material properties were not considered and discussed. In this paper, a new modified measurement method for the vapor diffusion resistance is presented. Some measured changes of the membrane vapor diffusion resistance are presented for slightly different test conditions. As well, effective methods to reduce the deflection of membranes used in exchangers are presented.

2. Vapor diffusion resistance (VDR)

The vapor diffusion resistance value of a membrane used in an energy exchanger is critical to the latent and total effectiveness of the exchanger. Moisture flux varies directly with vapor content difference and inversely with VDR (i.e. for a given operating condition, the latent and total effectiveness of an exchanger improves if a membrane with lower VDR is used).

A new modified measurement device for the vapor permeability of membrane is introduced in this section. In addition, some significant factors which may impact the VDR values of membranes are also presented and discussed.

2.1. Vapor diffusion resistance measurement

There are several devices and methods available to measure the water vapor permeability of membranes [27,29–31], and it is important to test the membranes using a method and test conditions that the membranes would experience in practical applications [29]. In this particular laboratory, the Permatran-W® 101K device [32] has been used to measure the water vapor transmission rate (WVTR) of the highly permeable membranes. This device uses a modified ASTM E96BW standard (inverted cup with a guard membrane) to measure the WVTR of a membrane [31,32]. Permatran-W® 101K device has 6 test cells to sequentially test the membrane WVTR on 6 different membrane areas to reduce the precision uncertainty. This is an advantage compared with other devices or methods that use only one membrane area for testing.

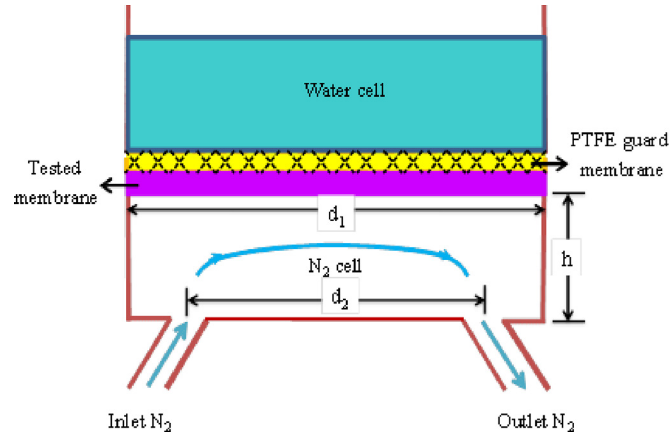

Fig. 1. Schematic of a test cell in Permatran-W® test apparatus [32]. The dimensions of the N_2 cell are: $h=3.10\pm0.02$ mm, $d_1=34.97\pm0.05$ mm, and $d_2=21.12\pm0.07$ mm.

A schematic of the Permatran test cell and the nitrogen gas flow in the test cell are shown in Fig. 1 [32]. There is a water reservoir on the top of the test cell which contains distilled water. A PTFE guard membrane is used on the bottom of the reservoir which allows water vapor to transfer through the guard membrane but prevents liquid water to directly contact the membrane under test. The properties of this guard membrane are very stable under different testing conditions (i.e. different temperature and humidity conditions) and it can effectively reduce deformations of the membrane during the testing process. The tested membrane, for which the WVTR is calculated, is located on the bottom of the PTFE guard membrane in the Permatran test cell. Dry nitrogen gas ($\sim$0% RH) with constant supply pressure (~ 15 psi or 103 kPa) flows continuously into the bottom of the test cell cylindrical cavity and flows out of the test cell cavity through a tube located 180° from the inlet. For each test cell in the Permatran, it records the data for the nitrogen flow rate, temperature and outlet relative humidity (RH) of the nitrogen gas, which are then used to calculate the mass flow of the water vapor through a membrane. The Permatran is used to calculate the WVTR at steady-state conditions. For this purpose, it compares the recent calculated WVTR for a cell to the previous two or more measurements of the same cell, and if they agree within 1%, the measurement for that membrane is complete and the WVTR is recorded for the membrane.

The entire vapor permeability test for membranes consists of two steps, the calibration step and the membrane test step. Prior to measuring the membrane WVTR in the second step, the WVTR value of test cell under calibration condition (without tested membrane) is measured to determine the calibration VDR, as shown in Eq. (1). The calibration VDR includes the nitrogen boundary layer resistance, the water boundary layer resistance, and the guard membrane resistance. When the tested membrane is installed in the membrane test process, the total VDR can be calculated by the recorded WVTR value through tested membrane, which should be higher than the calibration VDR value. The

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