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Moisture permeation through porous membranes

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ABSTRACT

Moisture permeation tests were conducted to measure the total moisture transfer resistance including the moisture transfer resistance through membrane and the boundary layer resistances on both sides of the membrane. Special methods were employed to determine the two boundary layer resistances, with the membrane resistance obtained by subtracting these two resistances from the total resistance. The membrane microstructures were observed using a scanning electron microscope. Tests were done on two porous membranes including the PES (poly ether sulfone) and cellulose membranes. The moisture transfer process through each membrane was modeled using a pore flow model, in which the pore sizes were assumed to obey the standard normal distribution and the transmembrane permeation was considered to include the Knudsen and molecular diffusions and the Poisseuille flow. The effects of membrane microstructure on transmembrane permeation were analyzed based on the model, with the moisture permeation test data and SEM observations as a basis. The results show that the membrane resistance decreases with increasing mean pore radius but changes little with the dimensionless standard deviation, further, the membrane resistance is in inverse proportion to the surface porosity to pore tortuosity ratio.

1. Introduction

Membranes used in various membrane technologies have their own morphological structures. Porous membranes have been used in many processes such as membrane distillation [1–3], pervaporation [4,5], ultrafiltration [6,7], and gas separation [8–10]. Since the microstructures of porous membranes have substantial influences on transmembrane permeation, descriptions and measurements of such structures are of practical importance. Membrane structure parameters include the membrane pore size and its distribution, the surface porosity, and the effective thickness. As summarized by Kong and Li [11], the common methods for characterizing membranes are the bubble point technique [12], the scanning electron microscope (SEM) or atomic force microscope (AFM) observation [13–15], the molecular weight cut-off measurement [16], and the gas permeation method [11,17–19].

Many studies have been done on porous membrane characterization and permeability. Mason and Maulinaskas [20] developed the dusty-gas model that was widely used to describe the transport properties of porous membranes. Martinez et al. [21] theoretically and experimentally investigated the effects of membrane structure parameters on transmembrane permeation based on the dusty-gas model. Kong and Li [11] employed both standard normal and log-normal distribution functions to express the pore size distributions of porous hollow fibre membranes and evaluated the membrane microstructures through regression analysis of gas permeation data. Kim and Stevens [18] characterized the pore size distribution and pore densities of track-etched polycarbonate ultrafiltration membranes using image analysis of field emission scanning electron micrographs. Piatkiewicz et al. [19] determined the pore size distribution in microfiltration polypropylene hollow fibres through isopropanol displacement under nitrogen pressure. Tsujita [22] studied the gas sorption and permeation of glassy polymeric membranes from the viewpoint of transport mechanism and the control of microvoids in membranes. Zhang [23] investigated the coupled heat and mass transfer across PVDF porous membranes with finger-line macrovoids based on the SEM observations of membrane surface and cross-sectional structures. Besides, our literature survey also reveals publications on fractal analyses of porous membranes [24–26].

The present research combines the experimental measurements and theoretical analyses. The experiment includes the test of water vapor permeation through membrane and the SEM observation of membrane, which provide a basis for the analyses of membrane microstructures. Tests are done on two membranes including the PES (poly ether sulfone) and cellulose membranes, both of which have a microporous structure. Water vapor permeation tests are carried out to measure the total moisture transfer resistance

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which includes the moisture transfer resistance through membrane and the boundary layer resistances on both sides of the membrane. Special methods are used to determine the two boundary layer resistances, with the membrane resistance obtained by subtracting these two resistances from the total resistance. The membrane microstructures are observed using a scanning electron microscope. In modeling of the moisture transfer process through the membrane, the membrane pore sizes are assumed to meet the standard normal distribution. The transmembrane permeation is considered to include the Knudsen and molecular diffusion and the Poisseuille flow which constitute a combined transport mechanism. The effects of the membrane microstructure on the transmembrane permeation are analyzed based on the measured moisture transfer resistance through the membrane, with the help of SEM observations of the membrane microstructures.

2. Experiment

2.1. Membrane samples

The membrane samples used in the experiments included the PES (poly ether sulfone) and cellulose membranes. Both membranes were provided by the Beijing Beihualiming Membrane Separation Technology Co. Ltd. and had a micro-porous structure. According to the material from the manufacturer, the nominal pore size was 0.45 μm for both membranes. Fig. 1 shows the SEM photos of the PES and cellulose membranes. The membrane thickness was measured based on the SEM observations and the results show that the thickness of the PES membrane was 0.0988 mm and that of the cellulose membrane was 0.1192 mm.

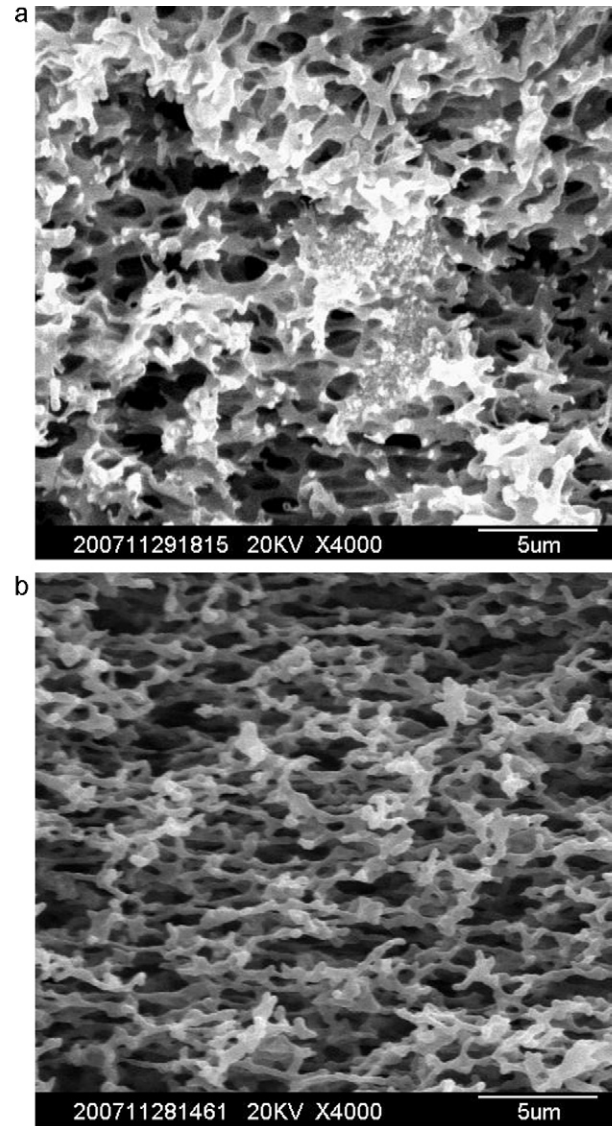

Fig. 1. Microstructures of membranes. (a) PES and (b) cellulose.

2.2. Experimental apparatus

Fig. 2 is a schematic of the experimental setup used to investigate the moisture permeation through membrane. Air fluid is driven by a compressor to flow first in a pipeline and then in a channel. A flask that contains distilled water is used to adjust the air humidity and a heat exchanger is employed to ensure that the air stream has the same temperature as the ambient. The airflow rate is controlled by valves and measured using an airflow meter (Alicat Scientific, Inc., Model: 5LPM) whose precision is 2.5%. The channel has a cross-section of 5 mm × 50 mm and a length of 800 mm. The air humidity and temperature at the channel inlet and outlet are measured using humidity/temperature sensors (ROTRONIC AG Company, Model: Hygrolog NT-3) that are installed in the chambers. The measuring accuracy is 1.5% for relative humidity and 0.3 for temperature.

Fig. 3 shows the test section that consists mainly of an airflow channel, a membrane, and a water tank, with the membrane being sandwiched between the channel and water tank. Both the channel and water tank are made of plexiglas. The channel has a height of 5 mm and a width of 50 mm, while the water tank has a length of 150 mm and a width of 50 mm. The distance from the channel inlet to the water tank is 400 mm and that from the water tank to the channel outlet is 250 mm. An air gap exists between the membrane and water to avoid any possible wetting of the membrane. When air with a relatively low humidity passes over the membrane in the channel, water vapor transfers from the water surface to the air stream through the air gap and membrane. The water tank is equipped with a heater which is used to compensate the heat of vaporization of water. A thermocouple is placed under the water surface to monitor the water temperature. The power of the heater is automatically controlled to ensure that the water surface has the same temperature as the air stream in the channel. The water tank has a L-shape water pouring pipe on its side wall. During test, water can be easily added to the water tank to adjust the air gap thickness.

2.3. Experimental methodology

The purpose of the moisture permeation tests is to determine the moisture transfer resistance through the membrane. The obtained membrane resistance is then used as the basis for the analyses of membrane microstructures. If the moisture transfer from the water surface to the air stream is treated as an one-dimensional process, the total moisture resistance can be represented by the sum of the convective moisture transfer resistance in the channel, the moisture transfer resistance through the membrane, and the moisture transfer resistance caused by the air gap between the membrane and water, i.e.,

$$R_{\mathrm{T}} = R_{\mathrm{c}} + R_{\mathrm{m}} + R_{\mathrm{g}} \tag{1}$$

The membrane resistance can thus be obtained by subtracting the two air layer resistances from the total resistance,

$$R_{\mathrm{m}} = R_{\mathrm{T}} - R_{\mathrm{c}} - R_{\mathrm{g}} = R_{\mathrm{T}} - \frac{1}{k} - \frac{L}{\rho_{\mathrm{a}} D'_{\mathrm{va}}} \tag{2}$$