Journal of Membrane Science 367 (2011) 174–181

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Experimental and numerical investigations of moisture permeation through membranes

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ARTICLE INFO

Article history:
Received 25 August 2010
Received in revised form 21 October 2010
Accepted 26 October 2010
Available online 3 November 2010

Keywords:
Membrane dehumidification
Moisture transfer
Membrane parameter
Experiment
Numerical simulation

ABSTRACT

Experimental and numerical combined studies were carried out to investigate the effects of membrane properties and operating condition on water vapor (moisture) permeation through membranes. Experiments were conducted with water vapor transferring from a highly to a less humid air across membrane due to the water vapor concentration difference between the two sides of membrane, and numerical simulations were performed to simulate such process. The transmembrane moisture transfer was characterized using the moisture transfer resistance through membrane as well as the total moisture resistance, which include the membrane resistance and the boundary layer resistance on the two sides of membrane. The uniqueness of this research was a systematic examination of the effects of various membrane parameters and operating condition on the moisture permeation through membranes by combining the experiments and simulations. Tests were done on two membranes including the PVDF and PES membranes. The moisture diffusivities in these membranes were determined by comparing the experimental and numerical total moisture resistances. The results show that the moisture diffusivities in the PVDF and PES membranes are in the order of 10^{-6} kg m^{-1} s^{-1}, with the PVDF yielding a larger diffusivity than the PES membrane. The moisture diffusivity in membrane, the maximum water uptake of membrane, and the sorption constant of membrane all have significant effects on the membrane resistance, with a high diffusivity, a large water uptake, and a proper sorption constant leading to a small membrane resistance, while the effects of the air entering humidity and airflow rate on the membrane resistance are dependent on the sorption constant. These results may help for the selection of the membrane materials.

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1. Introduction

Mass transfer by either molecular diffusion or convection is the transport of one component of a mixture relative to the motion of the mixture and is the result of a concentration gradient [1]. The most important property of membranes, used in separation application, is the ability to control the permeation of different species. A separation is achieved between different species because of differences in the amount of species that dissolves and the rate at which it diffuses [2]. In the process of membrane dehumidification of air, the membrane serves as a barrier between a highly humid air and a less humid air, water vapor transfers from the highly to less humid air through membrane due to the water vapor concentration difference between the two sides of membrane, leading to a dehumidification effect with respect to the highly humid air [3]. A typical application of the membrane dehumidification technology is the membrane-based energy recovery ventilator, which is an air-to-air heat and mass exchanger used to recover both the sensible heat and moisture from the outgoing exhaust indoor air to treat the incoming ventilation outdoor air for an air-conditioned space in summer [4–6]. Min and Su [5] modeled and analyzed the performance of a membrane-based energy recovery ventilator and reported that the heat transfer resistance through the membranes is small compared to the airstream boundary layer resistance on each side of the membranes while the moisture transfer resistance through the membranes predominates over the airstream boundary layer resistance on each side of the membranes. This result suggests that for a membrane-based energy recovery ventilator, the water vapor permeance through the membranes is the key factor controlling the ventilator moisture recovery performance.

It is known that the water vapor permeability of a membrane is determined by the sorption feature and transport property of the membrane. The sorption feature is characterized by the isotherm sorption curves or isotherm sorption equations, while the transport property is represented by the diffusion coefficient. So, in the examination of water vapor permeability, both the thermodynamic (sorption) and kinetics (diffusivity) aspects need to be analyzed [2]. Three basic methods have been used to measure water sorption and transport, they include the mass uptake [7,8], NMR relaxation [9,10], and permeation experiment [11,12]. Different methods may

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doi:10.1016/j.memsci.2010.10.064

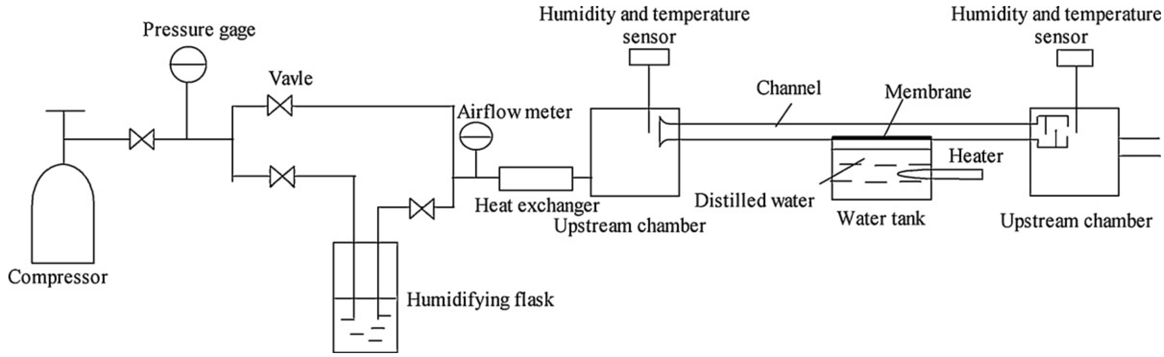

Fig. 1. Experimental apparatus.

generate quite different results. Extensive studies have been made on water transport properties of Nafion membranes because of their extraordinarily high water permeability and wide application in electrochemical processes [13,14]. Majsztrik et al. [15] summarized most of the measured diffusivities of water in Nafion reported in literature and reported that their values varied by more than three orders of magnitude. Rivin et al. [11] stated that reliable values of the diffusion coefficient for water or alcohols in Nafion can not be determined directly from the sorption or permeation kinetics, they can be obtained from combined steady state permeation and equilibrium solubility measurements under continuous flow conditions, with proper attention to corrections for the boundary layer effects in the permeation measurements. Liu et al. [16] investigated the water vapor permeation through a silicone rubber-PSF (polysulfone) composite membrane and analyzed the resistance of this asymmetric composite membrane to the permeation of water vapor on the basis of a serial resistance model. Larson et al. [17] studied the elastic and moisture transfer properties of polyethylene and polypropylene membranes intended for use in liquid-to-air energy exchangers. Gibson et al. [18] investigated the transport properties of electrospun nanofiber based porous membranes and reported their water vapor diffusion and air permeability as well as aerosol particle penetration. Zhang [19,20] performed a series of studies on the water vapor permeation through polymer membranes, he used a standard field and laboratory emission cell as the test chamber to investigate the water vapor diffusion coefficients of the membranes.

In this research, an experimental study was carried out to investigate the effects of membrane properties and operating condition on the water vapor permeation through membranes with different parameters. A numerical simulation was also conducted to complete and extend the investigation. Experiments were executed to provide a base for simulations while the simulations were implemented to enrich and broaden the contents of the experiments. The uniqueness of this research was a systematic examination of the effects of various membrane parameters and operating condition on the transmembrane water vapor (moisture) transport characteristics by combining the experiments and simulations. The membrane parameters include the sorption constant and maximum water uptake and the operating condition includes the airflow rate and air entering humidity. The transmembrane moisture transfer was characterized by the moisture transfer resistance through membrane as well as the total moisture resistance, which includes the membrane resistance and the boundary layer resistances on both sides of membrane. Tests were conducted on two membranes including the PVDF (poly vinylidene fluoride) and PES (poly ether sulfone) membranes. The moisture diffusivities in these membranes were determined by comparing the measured and calculated total moisture resistances, that indirectly offered a method to evaluate the moisture diffusivity in a membrane [21].

2. Experiment

Fig. 1 is a schematic of the experimental apparatus used to investigate the water vapor permeation through a membrane. Air fluid driven by a compressor flows in a pipeline and then in a channel in which water vapor transports from the surface of the water in a water tank embedded in the channel to the air stream across the membrane under test. When the air flows in the pipeline, it is split into two streams, one of them is humidified through a flask of distilled water and then re-mixed with the other air stream. The desired humidity of the mixed air stream can be obtained by adjusting the ratios of the two air streams. The airflow rate is controlled by valves and measured using an airflow meter (Alicat Scientific, Inc., Model: 5LPM) whose precision is 2.5%. Before the air enters the upstream flow stabilizing chamber, it exchanges heat with ambient air through an air-to-air heat exchanger to ensure that the air stream has the same temperature as the environment. The channel has a trapezoid-shaped entrance used to reduce the entrance length of the flow and a baffle-type exit whose role is to uniform the moisture in the air stream. The channel has a cross-section of 5 mm × 50 mm and a length of 800 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. The channel, chambers and water tank are all made of plexiglas. 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

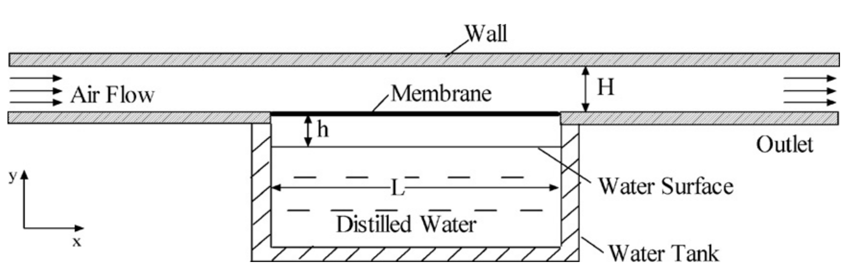

Fig. 2. Test section.

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