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Performance of a cross-flow humidifier with a high flux water vapor transport membrane

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HIGHLIGHTS

- Fabricated composite membranes with PFSA ionomer and microporous ePTFE layers.
- Measured the permeance of composite membranes in dynamic and pseudo-static tests.
- Optimized the membranes for high permeance, adequate durability, and low cost.
- Built and tested full-scale cross-flow humidifier using the composite membranes.
- Developed a model to determine the operating conditions for high transport fluxes.

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ABSTRACT

Water vapor transport (WVT) flux across a composite membrane that consists of a very thin perfluorosulfonic acid (PFSA) ionomer layer sandwiched between two expanded polytetrafluoroethylene (PTFE) microporous layers is investigated. Static and dynamic tests are conducted to measure WVT flux for different composite structures; a transport model shows that the underlying individual resistances for water diffusion in the gas phase and microporous and ionomer layers and for interfacial kinetics of water uptake at the ionomer surface are equally important under different conditions. A finite-difference model is formulated to determine water transport in a full-scale (2-m^2 active membrane area) planar cross-flow humidifier module assembled using pleats of the optimized composite membrane. In agreement with the experimental data, the modeled WVT flux in the module increases at higher inlet relative humidity (RH) of the wet stream and at lower pressures, but the mass transfer effectiveness is higher at higher pressures. The model indicates that the WVT flux is highest under conditions that maintain the wet stream at close to 100% RH while preventing the dry stream from becoming saturated. The overall water transport is determined by the gradient in RH of the wet and dry streams but is also affected by vapor diffusion in the gas layer and the microporous layer.

1. Introduction

Most of the polymer electrolyte fuel cell stacks for automotive applications currently require that the inlet cathode air be humidified for extended durability and acceptable performance [1–4]. External humidification becomes even more essential as the automotive manufacturers attempt to increase the stack temperature to above 90 °C in order to satisfy heat rejection requirements [5]. Extensive research effort is being dedicated to develop high-temperature polymer membranes that have acceptable proton conductivity under dry conditions, but formidable technical and material issues remain to be overcome [6,7]. Some manufacturers have successfully practiced internal humidification for water management but the stack temperatures are generally lower than 90 °C [8,9].

Both active and passive methods have been employed for external humidification of the cathode air [10–12]. Active methods involving direct injection of liquid water with spray nozzles are not considered attractive since they require either carrying consumable

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water on-board the vehicle (unacceptable) or using a condenser to recover water formed in the fuel cell which adds to the system complexity [1,2].

Enthalpy wheel humidifier is an example of the passive humidification method [11]. It consists of a thin-walled, desiccant-coated (400 or more cells per square inch) monolith that is rotated at 10–60 rpm (revolutions per minute) to contact the dry inlet air and wet depleted cathode exhaust at different times during a single revolution. The desiccant absorbs moisture as it contacts the wet stream and releases moisture as it contacts the dry stream. Perfluorosulfonic acid (PFSA) based membrane humidifiers have also been built [12]. In one such device tested, the humidifier required 7000 hollow Nafion fibers of 1-mm internal and 1.2-mm external diameter (100 μm fiber thickness) for an 80-kW fuel cell system. Mirza [13] measured the performance of this membrane module and reported that 20–35% of water in the inlet wet air at 2.3 atm and 80 °C (<80% relative humidity) could be transferred to the dry air at 2.5 atm and 80 °C. Under similar conditions, the water transfer rates in the enthalpy wheel humidifier were considerably higher (50–70%).

Compactness (high transport flux), ease of packaging (planar rather than circular geometry), cost and durability are some of the requirements for water transport membranes and modules for automotive fuel cells. Whereas PFSA membranes fulfill most of these requirements for the water transport media, they fall short primarily on cost, and secondarily on durability, especially when they are made thin to increase performance and lower cost. Recently, Johnson et al. [14,15] have developed a composite water vapor transport membrane that overcomes both of these limitations. The basic composite structure shown in Fig. 1 consists of a very thin ionomer layer sandwiched between two microporous polymer layers. The ionomer layer provides the active water transport and acts as an impermeable barrier to prevent gas crossover. The water transport rate can be engineered to be very high either through the use of a material that has very high inherent water transport rates (e.g., PFSA polymers), or by making it extremely thin (e.g., <5 μm). The microporous layer provides three critical features: first it protects the thin ionomer layer from mechanical damage during handling; second, it confers strength to the thin layer allowing it to be more durable during use; and third, it offers a strong, protective support layer for placement of a macroporous gas diffusion layer.

The composite membrane has been incorporated in an innovative pleated planar membrane humidifier that is able to achieve automotive water transport and pressure drop requirements [15]. The pleated design utilizes existing low-cost, high-volume pleating equipment that is used to manufacture air filters for automotive and heating, ventilation and air conditioning applications. Although the pleated humidifier is a proven technology, further improvement in humidifier size, cost and performance is possible through the use of the composite membrane and optimizing the flow field channel design to take full advantage of its intrinsically high transport fluxes.

The purpose of this paper is to present a model that has been developed to characterize the performance of the composite membrane and the planar cross-flow humidifier assembled using this membrane. The emphasis here is on mechanisms and rates of water transport rather than cost and durability that are equally important. We use the model to identify first the sources of water transport resistances in the membrane and then the optimum operating conditions for achieving maximum transport flux in the humidifier module.

2. Experimental

2.1. Composite membranes (Gore)

Composite membranes of silicone, low equivalent weight perfluorosulfonic acid (PFSA), divinyl benzene styrene polymer, polyvinyl alcohol, and polyurethane were prepared in multiple thicknesses using different types of expanded polytetrafluoroethylene (ePTFE) reinforcements in the composite structure [15]. Additionally, in order to reduce the material cost and improve performance, approaches were investigated to reduce the content of the expensive ionomer in the composite structures. Thicknesses of the ionomer layer in the composite ranged from as thin as ~1 μm up to about 10 μm. The optimal thickness appeared to be on the order of 5 μm, which uses a small amount of ionomer thus reducing cost, while simultaneously allowing acceptable processing. Although thinner layers are possible, it may be difficult to maintain a continuous hole-free layer with the required quality when ionomer layers are thinner than 3–5 μm or so. Samples of 18 μm GORE-SELECT® membrane were obtained for use as a control.

The use of a macroporous backer with the composites made in this study may or may not be essential but it is advantageous for handling. A range of potential macroporous backer materials were explored and a light, open polyester non-woven backer was identified as ideal. Its cost is low, it is very open so does not impact water transport significantly, it withstands the temperature excursions expected in the application, and can be readily laminated to the composite membrane. This material, an open PET (polyethylene terephthalate) nonwoven fabric, shows acceptable water transport performance. Durability testing in the module indicated that this material has little impact on either durability or water transport behavior, and, therefore, it was used in all module tests.

2.2. Membrane characterization (Gore)

The membranes were characterized by measuring multiple properties including air permeance in wet and dry conditions, hot soak durability, and RH cycling durability. The water vapor transport rate was the primary screening tool for all samples.

Membrane samples were placed in a specially-designed dynamic test apparatus shown in Fig. 2a that minimizes pressure loss, and all resistances to water transport except that of the membrane. At a fixed temperature, a high humidity gas stream was applied to

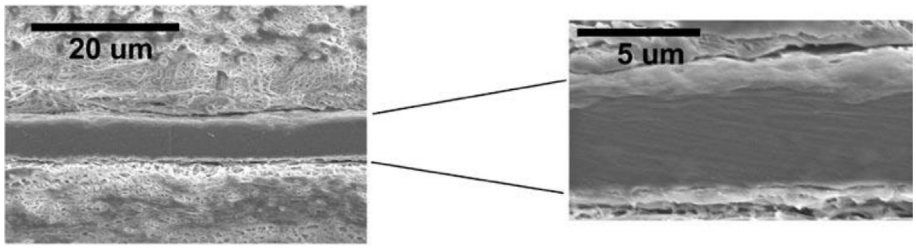

Fig. 1. Ionomer sandwiched between microporous layers to form an optimized humidification membrane.