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Water flux in membrane fuel cell humidifiers: Flow rate and channel location effects

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Abstract

A straight, single channel membrane humidifier was constructed to measure temperature and moisture profiles along both the donor and receiver channels. A persulfonic Nafion membrane was used as the water exchange medium.

We report on results obtained with single-phase vapour-to-vapour, counter flow operation. First, the heat loss to the surroundings was quantified and found to affect the overall performance significantly. Second, the results from varying flow rates indicate that lower flow rates lead to higher outlet dew point values of the receiver stream which can be related to longer residence times. It was also found that moisture transfer is more strongly influenced by the flow rate through the receiver side than the donor side. Finally, five-point dew point profiles for both donor and receiver sides are reported for various temperature conditions. No stream wise variation in moisture flux was observed, and the average flux value increased from 3.3×10^{-5} kg s^{-1} m^{-2} at 30 °C to 2.0×10^{-4} kg s^{-1} m^{-2} at 70 °C under fully humidified donor-side inlet conditions.
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1. Introduction

One of the largest obstacles in the way of proton exchange membrane fuel cells (PEMFC) achieving commercial viability is the cost and size of the system. At least two ways to reduce cost and size are increasing power density (via water management, catalysts, materials, etc.) and trimming balance of plant costs. Reactant humidification subsystems are among the most expensive components in the balance of plant, and in addition can be a key performance enhancer. Technological improvements to reactant humidification will have a beneficial impact on the system power density and cost.

Traditional stack humidification techniques such as saturation bubblers, direct injection, spray injection, etc., are being replaced by smaller, simpler, and more cost-effective solutions. Current stack humidification strategies are enthalpy wheels, self-humidification, and membrane humidifiers. Enthalpy wheels use a motor to rotate a desiccant-coated porous cylindrical core between the wet stream and dry stream. The core absorbs heat and moisture while exposed to the wet stream, and then cools and desorbs the moisture once rotated to the dry stream. This unit is advantageous because it is compact, effective, and has a very low pressure drop, but it is disadvantageous because it has numerous moving parts and seals, is expensive and demands an extra parasitic load to operate the rotary motor.

Self-humidification methods [1,2] attempt to deliver water to the membrane using water or water-producing mechanisms available internally. Watanabe and co-workers have reported on self-humidified PEMFCs using a very thin membranes impregnated with particles of SiO_2, TiO_2, and Pt [1]. The oxides are highly hygroscopic and increase water retention. The noble catalyst enhances water production from $H_{2(g)}$ and $O_{2(g)}$ that diffuse through the thin membrane and react internally. These authors maintain that the parasitic fuel losses are justified by the improved performance of the ionic conductor. However, the effects on membrane longevity and the membrane electrode

Abbreviations: DPAT, dew point approach temperature (°C) or (K); EE, enthalpy exchange effectiveness; LE, latent heat transfer effectiveness; SE, sensible heat transfer effectiveness; WRR, water recovery ratio.

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Nomenclature

A	membrane surface area (m^2)
c_p	specific heat at constant pressure ($J\,mol^{-1}\,K^{-1}$)
h	enthalpy ($J\,kg^{-1}$)
$\bar{J}_{mem,H_2O}$	average water flux across membrane ($kg\,s^{-1}\,m^{-2}$)
L	length of channel, 0.2 m (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
MW	molecular weight ($kg\,mol^{-1}$)
$p^{sat}_{H_2O}$	saturation vapour pressure (Pa)
p	total pressure (101,325 Pa unless specified otherwise) (Pa)
p_{H_2O}	water vapour partial pressure (Pa)
Q	volumetric flow rate (SLPM)
q'	heat transfer rate to surroundings per unit length ($W\,m^{-1}$)
R^2	coefficient of determination
T	temperature (K or °C)
T_d	dew point above liquid water (K)
t_{mem}	membrane thickness (m)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
w	effective perimeter for heat transfer to surroundings (m)
x	distance along channel measured from dry-side inlet (wet-side inlet is at $x = L$) (m)

Greek letters

ε	effectiveness [0,1]
γ_{mem}	membrane conductivity ($W\,m^{-1}\,K^{-1}$)
λ	stoichiometric ratio
ξ	relative humidity [0,1]
ω	humidity ratio, or specific humidity ($kg_{H_2O}\,kg^{-1}_{dry\ air}$)

Subscripts

H_2O	water vapour
air	air
WI	wet-side channel inlet (also used as an abbreviation)
WO	wet-side channel outlet (also used as an abbreviation)
DI	dry-side channel inlet (also used as an abbreviation)
DO	dry-side channel outlet (also used as an abbreviation)
surr	surroundings
wet	wet-side channel
dry	Dry-side channel
x	all probe locations along channel

assembly response to sudden changes in current density are not clear.

Although several conditioning schemes have been proposed to run PEMFC stacks on dry reactants, these schemes are only effective for low power applications (<5 kW) working at low temperatures (<60 °C) [3]. Larger power applications require direct reactant humidification almost without exception. The reasons behind this requirement are not restricted to operational constraints, and they can be explained by the fundamental properties of humidified gas mixtures. Larminie and Dicks considered a PEMFC operating on dry reactants [3]. They treated the water vapour and the exiting streams as perfect gases, and assumed that all the product water was evaporated. With these assumptions, they calculated the partial pressure of water in terms of the total pressure at the cathode outlets, and the flow stoichiometry of dry air. Mérida reviewed these calculations [4] and used the resulting expressions to generate the curves in Fig. 1. These calculations illustrate that the stringent water requirements within a PEMFC restrict operation to a very narrow range (i.e., a range for which $\xi = 1 \pm \delta\xi$, where $\delta\xi$ is small). Operating temperatures higher than 60 °C (which are desirable to minimise activation losses) correspond to very drying conditions for all practical flows at low pressures.

A third type of humidification subsystem is a membrane humidifier. These passive devices recover humidity from the cathode exhaust and transfer it through a hygroscopic membrane to the cathode inlet stream (dry air). Two architectures are currently in use, both derived from compact heat exchanger designs. In the shell and tube design, the dry stream flows inside a bank of small membrane tubes while the wet stream flows over and around the bank of tubes. The plate and frame architecture consists of membranes stacked on top of each other with a flow field plate separating the layers to allow flow. Membrane humidifiers are capable of a high moisture transfer capability at a reasonable pressure drop. This work characterizes a single channel version of a membrane humidifier.

While humidifiers can be constructed with other membranes, Nafion membranes are the standard heat and mass transfer medium in a commercial membrane humidifier. The under-

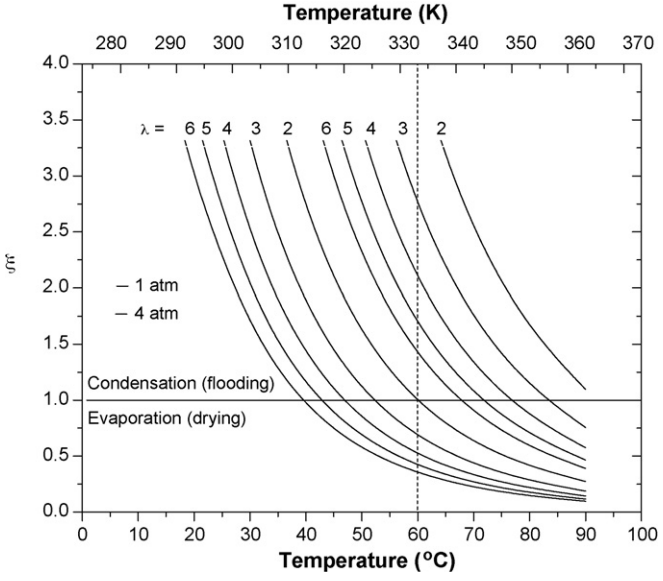

Fig. 1. The variation of relative humidity at the cathode outlets as a function of temperature, stoichiometry, and operating pressure [4], adapted from [3].

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