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Analytical model of a membrane humidifier for polymer electrolyte membrane fuel cell systems

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ABSTRACT

An analytical model for a membrane humidifier is developed for counter-current flow configuration at steady-state, which is applicable to plate-and-frame as well as shell-and-tube humidifiers. For the first time, the dependence of mass transfer on heat transfer is incorporated in the analytical model and analytical expressions are obtained for the temperature, H_2O concentration and water transfer rate. It is shown that neglecting the effect of mass transfer on heat transfer can result in errors in the predicted temperature and relative humidity. Sensitivity analysis was performed to study the effect of design variables and operating conditions on the humidifier performance. The model predictions were found to be consistent with the literature experimental data for a wide range of operating conditions. Simulations were performed to analyze a system consisting of a humidifier and a fuel cell stack. It was found that high current densities resulted in high water transfer rates but decreased relative humidity at the stack inlet. High operating pressure improved the performance of the humidifier, however, at the cost of increased parasitic losses in the system. The relative humidity at the dry side outlet was found to be dominated by the dry side operating conditions while the water transfer rate and humidifier efficiency were found to be dominated by the wet side operating conditions.

1. Introduction

There is an enhanced focus on development of proton exchange membrane fuel cell (PEMFC) technology. One of the most important components of a fuel cell system is the stack, which generates the required power for running a fuel cell vehicle. Efficient operation of a fuel cell stack occurs within a narrow range of humidity. A low humidity of gases entering the cathode results in reduced ionic conductivity, which is responsible for high ohmic losses [1]. In contrast, high humidity could result in water condensation and channel flooding. If the water produced in the catalyst is not removed effectively, the water residing in the pores of the gas diffusion layer blocks the pathway of reactants, thus resulting in voltage losses [2]. Hence, maintaining the relative humidity of the gases entering the cathode is a crucial aspect of fuel cell system development.

Popular techniques that have been used for humidification include bubbling, direct water or steam injection, using an enthalpy wheel humidifier, or using a membrane humidifier. Amongst these, a membrane humidifier is an attractive candidate for a PEM fuel cell because of reduced parasitic losses as compared to the other methods. Membrane humidifier models having varied degree of details and the accompanying computational effort have been proposed by research groups. Gabelman and Hwang [3] gave a review on hollow fiber membrane contactors, including operating principles, mathematical models, and applications. Park et al. [4] developed a dynamic model for a gas-to-gas shell-and-tube membrane humidifier. They investigated the effect of geometric parameters and operating conditions on the humidifier performance. Kang et al. [5] developed a transient model for a water-to-gas shell-and-tube membrane humidifier. They too studied the various geometric parameters and operating conditions and also investigated various humidifier configurations. Yu et al. [6] proposed a static model for a planar membrane humidifier, which utilized the concept of a planar heat exchanger. Their results showed that the humidity of the wet gas, channel length and membrane thickness are critical parameters which affect the humidifier performance. Chen et al. [7] conducted an experimental and modeling study for a water-to-gas membrane humidifier for PEM fuel cell humidity control. They performed steady-state as well as dynamic tests and showed that under transient conditions, the humidifier showed a non-minimum phase behavior. Min and Su [8] developed a mathematical model for a membrane-based enthalpy exchanger and studied the effect of the membrane parameters on the exchanger performance.

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Nomenclature

A	total stack area
A_Ω	cross-sectional area of flow
c	molar concentration of water
C_p	specific heat capacity
d_h	hydraulic diameter of the wet side
d_{ti}	inner diameter of tube
d_{to}	outer diameter of tube
D_g	water diffusivity in the gas phase
D_m	diffusivity of water in the membrane
D_s	inner diameter of shell
F	Faraday's constant
Gz_d	Graetz number at the dry side
h_f	individual heat transfer coefficient on the dry/wet side
H	height of channel in a plate-and-frame humidifier
H_f	overall heat transfer coefficient
j	current density
k_c	individual mass transfer coefficient on the dry/wet side
K_c	overall mass transfer coefficient of water
K_p	constant for pressure drop
L	length of humidifier
$\dot{m}_a$	mass flow rate of air
M_w	molecular weight of water
$\dot{N}_a$	molar flow rate of air
$\dot{N}_{H_2O}$	molar flow rate of water
N_t	number of tubes in the shell-and-tube humidifier
$\dot{N}_T$	total molar flow rate
$\dot{N}_{tr}$	molar flow rate of water transfer between wet and dry side
Nu	Nusselt number
p	pressure
$P_{\Omega w}$	wetted perimeter based on the wet side
R_Ω	characteristic transverse length scale
Re	Reynolds number
Sc	Schmidt number
$Sh_{H1,\infty}$	asymptotic Sherwood number
T	temperature of gas
$\bar{u}$	average velocity of gas (air + H_2O)
ω	humidity ratio
W	width of the plate for a plate-and-frame humidifier
x	axial position
x_{dv}	length of flow development region
z	dimensionless axial position

Greek symbols

α	thermal diffusivity
δ_m	membrane thickness
η_h	humidifier efficiency
λ_a	stoichiometric ratio
λ_m	thermal conductivity of the membrane
ϕ	relative humidity
φ	packing fraction in the shell-and-tube humidifier
ρ	density of gas

Subscripts

a	air
ai	air at inlet
d	dry side
di	dry side inlet
do	dry side outlet
h	dimensionless numbers related to temperature
i	inlet
m	dimensionless numbers related to concentration
o	outlet
w	wet side
wi	wet side inlet
wo	wet side outlet

Super-script

*	dimensionless variable

Effectiveness correlations were used by several authors for modeling the humidifier. Zhang and Niu [9] proposed effectiveness correlations for heat and mass transfer processes in an enthalpy exchanger with membrane cores. Zhang [10] proposed an analytical solution to find the effectiveness of a hollow fiber membrane module. The model was used to predict the experimental data within permissible error limits. The effectiveness based method for heat transfer was also used by Yu et al. [6] for modeling a plate humidifier in a counter-current flow configuration. Kadylak et al. [11] discussed the limitations of ε-NTU method for heat and mass transfer. They proposed equations which were solved iteratively to find the flux of water through the membrane.

The detailed models which incorporate the physical phenomenon are usually solved by numerical techniques or by using commercial software. Moreover, these detailed models suffer from a drawback of high computation times. Hence, incorporating these models into a fuel cell system model or a vehicle model is usually not possible. Most of the vehicle models are empirical models or look-up table based models, which are valid over a narrow operating range. Hence, there is a need to develop models which have low computation times, but are still able to retain the essential physics of the underlying process. Park and Oh [12] developed a 1-D analytical model of a water-to-gas humidifier consisting of a Nafion^{TM} membrane. This model was based on the assumption that the partial pressure of water vapor is equal to the saturation pressure at the water side. The analytical expression was used to calculate the relative humidity along the gas flow channel as a function of gas flow rate, length, and height of the gas flow channel. Humidifier models for control have also been proposed by several authors. A low-order, control oriented model of the humidification system was developed by McKay et al. [13]. A physics-based model for a humidifier was proposed by Deng et al. [14], who employed the method of wavelet networks for nonlinear identification.

The correlations proposed in the literature are used to find the effectiveness/water recovery ratio of the humidifier. However, analytical expressions do not exist for the variation of humidity and/or temperature along the humidifier length. In addition, the effect of mass transfer on heat transfer is neglected in the analytical models [10,12]. In this work, we present analytical expressions for the variation of temperature and H_2O concentration along the humidifier. The expressions are validated with experimental data from literature and are found to be consistent for a wide range of operating conditions. Using analytical methods, sensitivity analysis was performed on geometric parameters and the operating conditions, and the results were shown to be consistent with the literature experimental studies. In the present work, we discuss the limitations of the correlation for mass transfer coefficient which is used in the literature studies. We also show that neglecting the effect of mass transfer on heat transfer could result in an incorrect prediction of temperature and humidity. Additionally, the effect of operating pressure and current density is analyzed for a system consisting of a humidifier and a fuel cell stack.