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Response surface methods for membrane humidifier performance

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HIGHLIGHTS

- First report of a designed experiment to evaluate humidifier performance.
- Passive, planar humidifier performance for proton-exchange membrane fuel cells.
- Response surface model is an adequate tool for predicting humidifier performance.

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ABSTRACT

A designed experiment employing a response surface model was created to evaluate the performance of a passive, planar humidifier intended for the use in PEMFC applications. The performance of this humidifier was analyzed in terms of relative humidity and water transfer rate. For this analysis, a central composite design with four numeric factors was chosen. These four factors were inlet temperature and flow rates on each of two inlet streams. The performance criteria for an acceptable humidifier required air flow from humidifier to fuel cell to be at 80%–100% relative humidity and a temperature between 60 and 80 °C in order to allow for optimal operation of the fuel cell. This experimental design was implemented with a modified fuel cell test station, and humidifiers with two separate membrane types compared. The results of the analysis demonstrate the response surface model to be an adequate tool for evaluating and predicting the tested humidifier's performance. The factors chosen and their interactions show mixed results on humidifier performance.

1. Introduction

Reactant humidification subsystems contribute significantly to the complexity and cost of polymer electrolyte membrane fuel cell (PEMFC) products. One remaining technical challenge in PEMFC development is the management of water inside the fuel cell stack. A dry membrane can not only become limiting for the overall fuel cell performance; it can also damage the membrane electrode assembly itself. For example, membrane swelling that takes place upon hydration can increase the membrane's dry volume by 10–20% [1,2]. Repetitive volume changes can introduce mechanical stresses which may cause permanent damage or failures, such as membrane rupture [3,4]. Excess liquid water on either the anode or the cathode side of the MEA will decrease the electrode area available for the fuel cell reaction to occur and potentially block the reactant transport to the active sites, increasing the mass transport losses associated with the reaction. For optimal performance, it is therefore necessary for to maintain the operating conditions, particularly relative humidity, in the fuel cell stack within a narrow range of operating conditions which causes neither dehydration nor flooding.

Numerous methods have been developed to investigate and improve the water management within the fuel cell stack [5–10]. Numerical and experimental analyses for external, gas-to-gas membrane humidifiers with planar geometry have been carried out demonstrating effective performance in PEMFC applications [11–13]. Humidifiers with cylindrical geometry have also been proposed for PEMFC systems [14–17]. However, it is challenging to generalize the results of these experimental or modeling efforts over the broad range of fuel cell operating conditions.

The great modeling challenge of membrane humidifiers is the presence of two-phase flow. This leads to two regions of heat and mass transfer throughout the humidifier: the region of membrane in contact with humidified air, and the region in contact with liquid water. This liquid water distribution is irregular and complicates performance predictions. Kadylak et al. [13] avoid this complication

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Nomenclature

Symbol and description

A	membrane area
C	volumetric concentrations of membrane matrix contacting a fluid
D	vapor transfer coefficient
G	vapor molar mass
$\dot{m}$	mass transport
M	membrane equivalent weight
n	number of factors
k	order of a response
R^x	resolution of a design (x in Latin numerals)
t	membrane thickness
T	temperature
x	factor levels in a regression equation

Greek symbols

α	location of star points
β	regression coefficients
λ	water content
ρ	membrane density
ϕ	relative humidity

Subscripts

λ	characteristic of water content
dry	for dry membrane
j	indices indicating factors referred to in regression equation
m	membrane
min	minimum
max	maximum
x	indicates fluid type (air or water)

Abbreviations

PEMFC	proton exchange membrane fuel cell
MEA	membrane electrode assembly
DoE	design of experiment
WTR	water transport rate
RSM	response surface methods
CCD	central composite design

by modeling only with conditions resulting in non-condensing flows, either isothermal or low humidity. Work such as that by Chen et al. [14], which models heat and mass transfer between liquid and dry gas streams through a Nafion membrane, illustrates the difficulty of analytical models in modeling the complex phenomena present in membrane humidifiers. Their equation for water transport,

$$\dot{m}_{1,\mathrm{v,tr}} = D_{\mathrm{w}}\frac{C_2 - C_1}{t_{\mathrm{m}}}G_{\mathrm{V}}A \tag{1}$$

contains three terms dependent on water content and phase on either side of the membrane. C_x, the volumetric concentrations of the membrane matrix in contact with air ($x = 1$) or water ($x = 2$), is given by

$$C_x = \frac{\rho_{\mathrm{m,dry}}}{M_{\mathrm{m,dry}}}\lambda_x \tag{2}$$

Chen et al. demonstrate that λ_1 can be obtained from a curve fit depending on ϕ_1 and indicate that λ_2, which can take any value from 14 to 22, must be determined based on experimental data. Finally,

$$D_{\mathrm{w}} = D_{\lambda}e^{E_0\left(\frac{1}{303} - \frac{1}{T}\right)} \tag{3}$$

where D_{λ} has a piecewise-linear equation depending on the membrane water content λ_{m}, in turn dependent on ϕ_2, approximated by Chen et al. as the arithmetic mean of dry and wet side relative humidities.

λ_x, λ_{m}, and T are all local quantities, subject to significant change between inlet and outlet, or from layer to layer for a planar humidifier such as the ones in this paper, for a humidifier operating under fuel cell conditions. An accurate calculation of heat and mass transport across the full range of operating conditions must take into account the variation of these quantities, as well as the two-phase nature of the flow. The computational expense of modeling this for a full-scale humidifier is prohibitive; work to date has focused on modeling simplified humidifiers under simplified conditions [11–17]. The present work addresses this limitation in the existing literature with an empirical model.

A reliable approach for developing an empirical model of humidifier performance is provided by the design of experiments (DoE) methods. Designed experiments have the ability to cover a full range of operating conditions and assess the effects of interactions between chosen factors. These methods are of particular use in complex systems affected by numerous factors, and are commonly used in the practice of chemical engineering. Recently, the literature shows a growing body of work using DoE methods for the study of PEM fuel cells, which are themselves complex systems [18–24]. A broad range of DoE techniques have been used in PEMFC research [21,24–30], but only Cave and Mérida have used a designed experiment – a 2^k full factorial – in characterizing humidifiers [31].

In this paper, the DoE method is applied to the study of a planar membrane humidifier intended for use on the cathode side of a 10 kW PEMFC system. A discussion of the humidifier system is used to select an appropriate design and factors. The operating range and desired outputs are based on the operating range of a PEMFC. The resulting designed experiment is executed and data analysis performed to produce a response surface for a test humidifier with respect to the humidification requirements of a PEMFC. The results of this study are discussed with respect to previous research.

2. Creating empirical models using response surface methodology

Response surface methods and analysis, also known as response surface methodology (RSM), is a selection of statistical and mathematical techniques used to develop, improve and optimize processes [32,33]. In most cases, multiple regression is used to develop the empirical models. A simple, general equation for a second-order response surface model describes a response y in terms of two variables x_1, x_2:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11}x_1^2 + \beta_{22}x_2^2 + \beta_{12}x_1 x_2 + \varepsilon. \tag{4}$$

The parameters β_j are regression coefficients that will be determined during the model fitting, ε represents the statistical