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Effectiveness correlations for heat and mass transfer in membrane humidifiers

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ABSTRACT

The latent effectiveness and the latent number of transfer units (NTUs) for mass transfer in membrane humidity exchangers were applied to proton exchange membrane fuel cell (PEMFC) membrane humidifiers. We report on two limitations that cause deviations in the theoretical outlet conditions reported previously: (1) using a constant enthalpy of vaporization derived from the reference temperature in the Clausius–Clapeyron equation; and (2) simplifying the relationship between relative humidity and absolute humidity as linear. These limitations are alleviated by using an effective mass transfer coefficient U_{eff}. The constitutive equations are solved iteratively to find the flux of water through the membrane. The new procedure was applied to three types of membrane and compared to the curves of ε_L and NTU_L found using Zhang and Niu's method, which is normally applied to energy recovery ventilators (ERVs).

1. Introduction

While a PEM fuel cell may be operated with dry streams of air and hydrogen, Rajalakshmi et al. [1], among other researchers [2–4], have shown that the fuel cell power output increases if the reactant streams are humidified. Fig. 1 illustrates a typical implementation at the cathodes: dry air is pumped from a compressor or blower. As the dry stream passes over the membrane heat and mass are transferred from the wet stream at the fuel cell cathode exhaust.

The effectiveness-number of transfer units (ε-NTU) method is well known in heat exchanger design for determining the properties of the unknown outlet fluid streams, or for setting the geometrical and flow parameters to achieve the required composition at the outlets [5,6]. Heat transfer and mass transfer of water are coupled in an enthalpy exchanger for attaining the outlet conditions.

In this paper, the formulations by Zhang and Niu of latent effectiveness ε_L and number of transfer units for moisture transfer NTU_L [7] were extended for use in a membrane heat and humidity plate-and-frame exchanger. The effect of extended conditions, such as elevated temperatures, used in operating fuel cells was evaluated for the mathematical model used in energy recovery ventilator (ERV) systems. Some of the simplifications and assumptions made during the mathematical derivation by Zhang and Niu are analyzed for the situation in proton exchange membrane fuel cell (PEMFC) membrane heat and humidity exchangers. The results of an alternative approach were compared with results using the method proposed by Zhang and Niu.

2. Current latent effectiveness derivations

Niu and Zhang derived a latent effectiveness and number of transfer units (NTU_L) which closely resembles the sensible heat effectiveness and number of thermal units (NTUs) method commonly used in heat exchanger design. They show that the deduction of effectiveness correlations for moisture is of the same form as sensible effectiveness [7]. Heat and humidity exchangers, such as energy (or enthalpy) recovery ventilators (ERVs) commonly have their effectiveness measured with both sensible energy transfer and latent energy transfer. The same effectiveness measures can be applied to humidifiers used in fuel cell applications due to their similar configurations and operating principles.

The latent effectiveness ε_L can be defined as

$$\varepsilon_L = \frac{(\dot{m}c_p)_d(\omega_{di} - \omega_{do})}{(\dot{m}c_p)_{min}(\omega_{di} - \omega_{wi})} \quad (1)$$

The absolute humidity, ω, is used for latent transfer, where dry-bulb temperature is used in the form corresponding to sensible heat transfer. The outlet condition can then be determined by rearranging Eq. (1)

$$\omega_{do} = \omega_{di} - \varepsilon_L \frac{(\dot{m}c_p)_{min}}{(\dot{m}c_p)_d}(\omega_{di} - \omega_{wi}) \quad (2)$$

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Nomenclature

A	membrane surface area (m^2)
B	width of humidifier (m)
C	constant parameter for sorption curve equation
c_p	specific heat capacity at constant pressure ($J\,kg^{-1}\,K^{-1}$)
d	channel depth (m)
D_{wm}	diffusivity of water in membrane ($kg\,m^{-1}\,s^{-1}$)
h_M	convective mass transfer coefficient, or conductance ($kg\,m^{-2}\,s^{-1}$)
Δh_{vap}	heat of vaporization ($J\,kg^{-1}$)
J	water flux ($kg\,s^{-1}\,m^{-2}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
l	length of channel (m)
M	number of plates (levels) in humidifier
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
n	number of channels in humidifier plate
P	pressure (Pa)
Q	volumetric flow rate (STP m^3/s)
R	universal gas constant ($J\,kg^{-1}\,K^{-1}$)
R_L	ratio of mass capacity
T	temperature (K)
t_{mem}	membrane thickness (m)
U_L	overall mass transfer coefficient ($kg\,m^{-2}\,s^{-1}$)
U_{eff}	effective mass transfer coefficient ($kg\,m^{-2}\,s^{-1}$)
w	width of channel (m)

Greek symbols

γ	moisture diffusive resistance ($m^2\,s\,kg^{-1}$)
ε	effectiveness [0,1]
θ	water uptake (kg H_2O/kg dry membrane)
θ_{max}	maximum water uptake capacity (kg H_2O/kg dry membrane)
ϕ	relative humidity
ω	absolute humidity (humidity ratio) (kg H_2O/kg dry air)

Subscripts

air	air species
d	referring to the dry (or sweep) side
di	dry-side channel inlet
do	dry-side channel outlet
H_2O	water
L	latent or moisture
mem, m	membrane
min	minimum
ref	reference state
sat	value at saturation
v	vapor
w	referring to the wet (or feed) side
wi	wet-side channel inlet
wo	wet-side channel outlet

Analogous to the expression for number of thermal units used for heat transfer in heat exchangers, a total number of transfer units for latent heat with overall mass transfer coefficient U_L is defined as

$$\mathrm{NTU_L} = \frac{AU_L}{\dot{m}_{min}} \tag{3}$$

for the total area of transfer A being equal on both sides. As is done for sensible heat, the latent effectiveness can be determined as a function of $\mathrm{NTU_L}$ and another dimensionless parameter, $R_L = \dot{m}_{min}/\dot{m}_{max}$. For unmixed cross-flows considered in the present work [6]:

$$\varepsilon_L = 1 - \exp\left[\frac{\exp\left(-\mathrm{NTU_L^{0.78}}R_L\right) - 1}{\mathrm{NTU_L^{-0.22}}}R_L\right] \tag{4}$$

Other effectiveness correlations are used for different exchanger configurations [5,6]. The latent effectiveness can therefore be substituted into Eq. (2) to determine the outlet moisture content. The total moisture transfer conductance U_L has been calculated by Niu and Zhang.

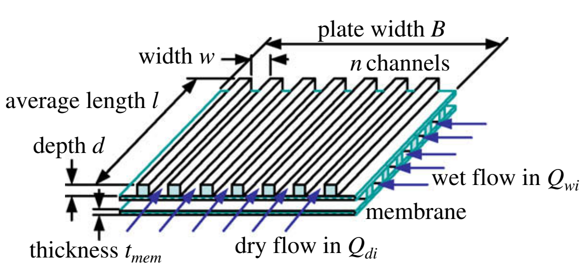

Fig. 1. Schematic of layered humidifier plates in cross-flow arrangement.

Water flux through the membrane at steady state was modeled with Fick's first law and incorporating membrane water uptake characteristics:

$$\dot{m}_{H_2O} = \frac{D_{wm}}{t_{mem}}\frac{\partial\theta}{\partial\phi}\bigg|_{mw}(\phi_{mw} - \phi_{md}) \tag{5}$$

To obtain the overall mass transfer coefficient U_L, the relative humidities must be changed into the driving force of absolute humidity ω, from a linear relation between the two parameters. Substituting the Clausius–Clapeyron equation into the relationship between relative humidity and absolute humidity based on vapor partial pressure, Zhang and Niu (from Simonson and Besant [8]) arrive at the following relation after substituting for the pressure at standard atmosphere:

$$\frac{\phi}{\omega} = \frac{e^{5294/T}}{10^6} - 1.61\phi \tag{6}$$

The second term on the right-hand side is ignored in order to simplify the equation to a linear relationship, assumed to have an effect of less than 5%

$$\phi = \frac{e^{5294/T}}{10^6}\omega \tag{7}$$

Therefore, Eq. (5) can now be written in terms of the driving force of absolute humidity

$$\dot{m}_{H_2O} = \frac{D_{wm}}{t_{mem}}\frac{\partial\theta}{\partial\phi}\bigg|_{mw}\frac{e^{5294/T}}{10^6}(\omega_{mw} - \omega_{md}) \tag{8}$$

Some algebraic manipulations lead to the water transfer in terms of the difference in absolute humidity as the driving force [9]:

$$\dot{m}_{H_2O} = \left(\frac{1}{h_{Mw}} + \gamma_m + \frac{1}{h_{Md}}\right)^{-1}(\omega_w - \omega_d) \tag{9}$$

Therefore, the overall mass transfer coefficient U_L to be used in Eq. (3) has been found as