Phase Change in a Polymer Electrolyte Fuel Cell

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Stable high performance in a polymer electrolyte fuel cell (PEFC) requires efficient removal of product water and heat from the reaction sites. The most important coupling between water and heat transport in PEFC, through the liquid-vapor phase change, remains unexplored. This paper sheds light on physical characteristics of liquid-vapor phase change and its role in PEFC operation. A two-phase, nonisothermal numerical model is used to elucidate the phase-change effects inside the cathode gas diffusion layer (GDL) of a PEFC. Locations of condensation and evaporation are quantified. Operating conditions such as the relative humidity (RH) of inlet gases and materials properties such as the thermal conductivity of GDL are found to have major influence on phase change. Condensation under the cooler land surface is substantially reduced by decreasing the inlet RH or increasing the GDL thermal conductivity. The RH effect is more pronounced near the cell inlet, whereas the GDL thermal conductivity affects the phase-change rate more uniformly throughout the flow length.

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Liquid-vapor phase change, or specifically evaporation/condensation, plays a pivotal role in the coupled water and thermal management of polymer electrolyte fuel cells (PEFCs). Although a large body of literature exists to explore two-phase transport in PEFCs analytically, experimentally, and numerically,1-14 direct examination of the phase change phenomena has been absent. This work sheds light on the physical characteristics of phase-change phenomena and their role in fuel cell operation. Another objective is to prompt the development of in situ and direct measurements of the phase-change rate as an important parameter to the fundamental understanding and design improvement of PEFCs.

In two-phase modeling of PEFCs, local thermodynamic equilibrium is often assumed between the liquid and gas phases at the evaporation/condensation interface. This assumption implies that negligibly small supersaturation of water vapor exists in the gas phase when condensation or evaporation occurs. The chemical equilibrium occurs at the microscale and in the vicinity of an interface. The existence of interfacial equilibrium at a phase-change interface does not mean a zero phase-change rate. Indeed, a finite phase-change rate can coexist with the interfacial equilibrium condition. Analogously, an extremely facile electrochemical reaction yields negligibly small overpotential or an equilibrium condition, but there is still a reaction current occurring at the electrochemical interface. In general, the phase-change rate can be expressed as15,18

\[ r_{H_2O} = H(C_{H_2O} - C_{sat}) \]  \[ \text{[1]} \]

where \( H \) is directly proportional to the area of the interfacial surface where phase change occurs. In porous layers of fuel cells, the liquid-vapor interfacial area is usually sufficiently large that

\[ C_{H_2O} - C_{sat} = \frac{r_{H_2O}}{H} \rightarrow 0 \]

thus yielding equilibrium phase change. If \( H \) is not sufficiently large, there exists nonequilibrium phase change. Wang et al.15 theoretically showed that the coefficient \( H \) is proportional to \( aD_{H_2O}/r_p \), where \( r_p \) is the pore radius, \( a \) is the liquid-vapor interfacial area (proportional to \( 1/r_p \)), and \( D_{H_2O} \) is the water-vapor diffusivity in gas. For a gas diffusion layer (GDL) with a pore radius of 10 \( \mu \)m and water vapor diffusivity on the order of \( 10^{-5} \) m²/s, the \( H \) value is on the order of \( 10^3 \) s⁻¹. Recent calculations by Meng16 clearly indicate that the interfacial equilibrium is reached when \( H \) approaches \( 5 \times 10^3 \) s⁻¹. Therefore, the interfacial thermodynamic equilibrium should be quite valid in PEFCs, particularly in the GDL regions. Mathematicians call this the “big-H normalization.”18 Following the same order of magnitude analysis, the time scale to reach local interfacial equilibrium is found to be only 10 \( \mu \)s (using a characteristic length scale of 10 \( \mu \)m and diffusivity of \( 10^{-5} \) m²/s), sufficiently short to justify the assumption even in transient models that deal with physical events of \( >10 \) ms.19

The presence of liquid water in a PEFC strongly affects heat transfer through the heat pipe effect.20 The porous GDL bridging the hot catalyst layer (CL) and cold land surface creates a heat pipe where the latent heat of water evaporation and condensation greatly assists thermal conduction through GDL fibers. The total heat transfer, thus depending on both GDL heat conduction and heat pipe effect owing to phase change, controls the local temperature profile, which in turn affects the phase change process. As such, there are intricate interactions between water and heat management through the important phase-change phenomena.

Numerical Model

In the present work, we apply a steady-state, nonisothermal, two-phase model of Wang and Wang10 to study the phase-change phenomena in the cathode GDL of a PEFC. Conservation equations of mass, momentum, energy, species, and charge conservation are solved in our model and are presented below:

\[ \nabla \cdot (\rho \vec{u}) = 0 \]  \[ \text{[2]} \]

\[ \text{Momentum:} \quad \frac{1}{\rho} \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla P + \nabla \left( \frac{1}{\kappa} \nabla T \right) + \tau \]  \[ \text{[3]} \]

\[ \text{Energy:} \quad \nabla \cdot (\gamma T \rho C_p) \vec{u} = \nabla \cdot (k_{\text{eff}} \nabla T) + S_{T} \]  \[ \text{[4]} \]

\[ \text{Species:} \quad \nabla \cdot (\gamma \vec{u} \vec{c}) = \nabla \cdot (D^{\text{eff}} \nabla \vec{c}) - \nabla \left[ D^{\text{eff}} \left( \frac{m_f}{M_f} - \frac{\alpha_2}{p_2} \right) \right] \]  \[ \text{[5]} \]

\[ \text{Charge (electrons):} \quad 0 = \nabla \cdot (\sigma_{\text{eff}} \nabla \Phi_e) + S_{\Phi_e} \]  \[ \text{[6]} \]

\[ \text{Charge (protons):} \quad 0 = \nabla \cdot (k_{\text{eff}} \nabla \Phi_p) + S_{\Phi_p} \]  \[ \text{[7]} \]

Details on Eq. 2-7 and their source terms are widely available in the literature.10,19 and also listed in Table I. The liquid saturation is calculated as follows, assuming interfacial equilibrium between the liquid and vapor phases, as justified earlier

\[ s = \frac{C_{H_2O} - C_{sat}(T)}{\rho_l / M_{H_2O} - C_{sat}(T)} \]  \[ \text{[8]} \]
The capillary diffusion flux is defined in terms of the relative mobilities of liquid and gas phases
\[ \dot{j} = \frac{\lambda_l}{\rho g} K \nabla P_c \]  
where \( P_c = \sigma \cos(\theta)/(\varepsilon R)^{1/2} \) and \( J(s) \) is the Leverett function defined as follows:

\[ J(s) = \begin{cases} 
1.417s - 2.120s^3 + 1.263s^5 & \text{for } \theta_c > 90^\circ \\
1.417(1-s) - 2.120(1-s)^3 + 1.263(1-s)^5 & \text{for } \theta_c < 90^\circ 
\end{cases} \]

The species correction factors are described by Eq. 9. Water is the only species that can be present in both liquid and vapor form. Therefore, the correction factor takes into account contributions due to both phases for the water conservation equation. Other species are present only in the vapor phase. The mass conservation equation at steady state could be written for liquid and gas phases as follows:

\[ \nabla (\rho g \vec{u}_l) = \dot{m}_l \]  

\[ \nabla (\rho g \vec{u}_g) = \dot{m}_g \]

Results and Discussion

In the present study, flow stoichiometry is fixed at 2.0 for both the anode and cathode, whereas the cell temperature is fixed at 80°C and average current density at 1.0 A/cm². The cell geometry and other operating parameters are listed in Tables II and III. A mesh consisting of 22,344 computational elements was used to run all simulations, and the mesh sensitivity test has been performed and documented elsewhere. In the simulations to be presented, all species imbalance is <1% and residuals of conservation equations <10⁻⁵. A fully humidified case is considered as the base case. The total heat generation in the cell remains constant due to the fixed current density, and the operating temperature (or land temperature) is also kept constant. Phase change in the cell depends on the relative profiles of local temperature and water vapor concentration. The former is determined largely by the GDL thermal conductivity when the two thermal boundary conditions are fixed, while the latter

\[ \frac{\sigma_{ci} M_i}{n e} \text{, where } M_i = \text{chemical formula of species } k, s_i = \text{stoichiometry coefficient, and } n = \text{number of electrons transferred.} \]
strongly depends on the inlet gas relative humidity (RH). Thus, to explore phase-change effects in the cathode side of a PEFC, we carry out parametric studies of the GDL thermal conductivity and inlet RH.

The PEFC geometry used for case studies in the present work is shown in Fig. 1. Temperature, saturation, and phase-change rate contours are plotted in the cross section (section A) of the PEFC in the through-plane direction, midway between the inlet and the outlet. The anode and cathode are in counterflow. Thus, near the cathode inlet electro-osmotic drag (EOD) dominates the backflow of water (from the cathode side to the anode side). Along the cathode flow direction as liquid water saturation increases, backflow of water becomes stronger, and near the outlet, it dominates over EOD, resulting in a dry-wet-dry transition along the channel.25 These two opposing mechanisms of water transport are found to balance each other in the middle when cathode and anode sides have a similar level of humidification.26 With nearly zero water crossover through the membrane, all the product water on section A is removed into the cathode channel. Because the current density is kept constant, total water transport from cathode GDL to cathode channel is almost constant at section A for all cases.

<table>
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<tr>
<th>Table II. Cell geometry and properties.</th>
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<td>Cell length</td>
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<td>Gas channel depth</td>
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<tr>
<td>Gas channel width</td>
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<tr>
<td>Land width</td>
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<td>Anode/cathode GDL thickness</td>
<td>0.2 mm</td>
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<tr>
<td>Anode/CCLs thickness</td>
<td>0.01 mm</td>
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<td>Porosity of anode/cathode GDL, (\varepsilon_{\text{gdl}})</td>
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<tr>
<td>Porosity of anode/CCLs, (\varepsilon_{\text{CCL}})</td>
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<tr>
<td>Volume fraction of ionomer in anode/CCLs, (\varphi)</td>
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<td>Hydraulic permeability of anode/ cathode GDL, (K_{\text{gdl}})</td>
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<td>Hydraulic permeability of membrane, (K_{\text{mem}})</td>
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<td>Contact angle of anode/cathode GDL and CCLs, (\theta)</td>
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<td>Anode/cathode inlet pressure, (P_i)</td>
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<td>Cell temperature, (T_{\text{cell}})</td>
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<th>Table III. Simulation parameters.</th>
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<td>Exchange current density × ratio of reaction surface to CL volume in anode side, (a_{\text{C,ref}})</td>
<td>(1.0 \times 10^5 \text{ A/m}^3)</td>
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<td>Exchange current density × ratio of reaction surface to CL volume in cathode side, (a_{\text{Cl,x}})</td>
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<td>Activation energy for oxygen reduction reaction in cathode side, (E_a)</td>
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<td>Reference hydrogen molar concentration, (c_{\text{H,ref}})</td>
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<td>Reference oxygen molar concentration, (c_{\text{O2,ref}})</td>
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<td>Anodic and cathodic transfer coefficients for hydrogen oxidation reaction</td>
<td>(0.18 = \alpha_a = \alpha_c = 1)</td>
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<td>Cathodic transfer coefficient for oxygen reduction reaction</td>
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<td>Hydrogen phase-change rate, (r_{\text{H}})</td>
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<td>Liquid water density, (\rho_l) at (80°C)</td>
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<td>Liquid water viscosity, (\mu_l)</td>
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<td>Effective electronic conductivity in CLs, (\sigma_{\text{CCL}})</td>
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<td>Effective electronic conductivity in GDL, (\sigma_{\text{gdl}})</td>
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<td>Electronic conductivity in current collector, (\sigma_{\text{CL}})</td>
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<td>Catalyst coverage coefficient, (n_i)</td>
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<td>Diffusivity correction factor, (n)</td>
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Figure 1. Schematic of the computational cell showing the sections.

Figure 2. (Color online) (a) Liquid saturation and temperature contours and (b) phase-change rate (kilogram per cubic meter per s) contours in the cathode side, where positive and negative values denote condensation and evaporation, respectively. Base case \([I = 1.0 \text{ A/cm}^2, \text{ stoichiometry} (\text{A/C}) = 2.0, \text{ RH} = 100\%]\) at section A.
Temperature and liquid saturation contours at section A are plotted for the base case in Fig. 2a, whereas Fig. 2b illustrates the phase-change rate contour in the cathode side.

**Effect of inlet RH.**—Because our base case employs the fully humidified condition, the inlet RH is decreased gradually to investigate its effect on phase change. Computations were carried out for inlet RHs of 67% ($T_{dew} = 70^\circ C$), 45% ($T_{dew} = 60^\circ C$), and 25% ($T_{dew} = 50^\circ C$) with other parameters being the same as those in the base case. At lower RH, liquid saturation in the cell is lower.

Temperature and saturation contours at section A for RH = 67% are plotted in Fig. 3a. Here, the temperature range in this case is the same as that in the base case. The range of liquid saturation does not show much difference from that in the base case. The difference from the base case is not apparent in the phase-change rate contours for the RH = 67% case at section A (see Fig. 3b). At section A, gas flow through the cathode channel becomes fully saturated for RH = 67%. Therefore, the contours look very similar to those in the fully humidified base case.

The difference becomes clearer in the case with RH = 45%. Contours of temperature and saturation at section A for RH = 45% case are plotted in Fig. 4a. The temperature rise in the cell is ~0.5°C lower in this case with respect to the base case. Liquid-saturation contours at section A for this case show that the GDL over the channel is almost dry at this length, but the maximum liquid saturation (which occurs over the land) decreases only slightly. This indicates that liquid shearing at the GDL-channel interface should be low, because part of the GDL is almost dry. The phase-change rate contour at section A (plotted in Fig. 4b) exhibits this trend.

Because of the low humidity of the feed gas, the CL is almost dry under the middle of the channel. Consequently, very little condensation takes place there. As the inlet RH is further reduced to 25%, liquid saturation reduces significantly at section A (shown in Fig. 5a) but the temperature distribution at this section remains about the same. In this case, the membrane electrode assembly and GDL over the land are totally dry under this condition. Hence, the phase-change rate also decreases (shown in Fig. 5b). Under this very low inlet RH, no phase change takes place in the CCL under channel because all the product water could be transported in vapor form by diffusion. Temperature in the CCL is lower under the land, and hence, water condenses in CCL and GDL. Although the heat pipe effect is weakened by lower temperature gradient (also for the case of inlet RH = 45%), water still condenses on the cooler land surface. This liquid evaporates in the GDL near the wet-dry interface.

From the contours of phase-change rate, it is clear that condensation takes place chiefly in two locations in the cathode side, in the CCL and GDL adjacent to it (due to water production) and on the land surface (due to cooler temperature). Variation of phase-change rate and liquid saturation over the land is of special interest because this is a measure of the heat-pipe effect in the cell. Liquid saturation and phase-change rate under the middle of the adjacent land is plotted along the channel for the four cases (RH = 100, 67, 45, and 25%) in Fig. 6. The positive values in Fig. 6b indicate condensation. Because GDL adjacent to the land is cooler, water can only condense there. Therefore, Fig. 6b indicates either condensation or no phase change at this location for all the cases. The fully humidified case shows a high and almost uniform phase-change rate along the channel. For RH = 67%, the phase-change rate under the land de-
creases near the inlet and the exit. For RH = 45%, the GDL is dry near the inlet and outlet. Thus, condensation does not take place under the land for some distance near the inlet and outlet. At the midlength of the channel, the maximum vapor condensation over the land is smaller by 20% with respect to that in the base case due to a smaller temperature difference from cathode CL to cathode bipolar plate.

Liquid saturation and phase-change rate profiles in the in-plane direction yield an important insight. For partially humidified inlet flow, both variables change along the flow direction as shown in Fig. 6. Variations of condensation and liquid saturation on the land surface were investigated at different flow lengths. Three lines are chosen to show these variations, which can be observed close to the inlet ($Y^* = 0.25$), midway between inlet ($Y^* = 0.5$), and close to the outlet ($Y^* = 0.75$). Along these lines, liquid saturation and phase-change rate profiles are plotted for RH = 100, 67, 45, and 25% (Figs. 7a-d, respectively). Liquid saturation is high under the middle of the land and reduces gradually under the channel. The phase-change rate is high under the land as condensation takes place. Under the channel, phase change is almost invisible. In the fully humidified case, the cathode GDL is totally wet. Liquid saturation and phase-change rate are almost uniform along the flow direction (Fig. 6). Therefore, in-plane profiles of these quantities at different flow lengths almost coincide over each other (Fig. 7a). Even for the case of inlet RH = 67%, the cathode GDL becomes totally wet for $0.25 < Y^* < 0.75$ (Fig. 6). Thus, the in-plane profiles of liquid saturation and phase-change rate are almost identical (Fig. 7b). As the inlet RH is decreased to 45%, parts of the cathode GDL near the inlet and exit remain dry. No condensation takes place over the land in these portions (Fig. 6). When the inlet RH is further reduced (45%), the cell becomes drier. The cathode side is not fully wet at section A. Condensation on the land surface starts at 20% of the flow length away from the inlet (Fig 6b). This phase change increases rapidly, reaching maxima at the middle of the flow length, and reduces rapidly after that and dries out at ~80% of the flow length from inlet. The in-plane profiles (shown in Fig. 7c) show this clearly. In the sections close to inlet and exit, liquid saturation is less and condensation takes place only under the center of the land. As the inlet RH is reduced even further (25%), the cell runs in an even more dry condition. Condensation on the cathode land surface occurs at the middle (Fig. 6b), whereas the GDL under the channel is totally dry (Fig. 5b). Near the inlet and exit, the cathode GDL is almost dry, with a trace amount of liquid on the land surface (shown in Fig. 7d).

Another interesting observation from Fig. 7 is the existence of a distinct peak in the phase-change rate profile under land for RH = 100 and 67% cases. Cathode GDL is totally wet in these cases. Liquid saturation is maximum under the middle of the land in all cases and minimum under the middle of the channel. Therefore, resistance to gas flow due to the heat-pipe effect toward the land is greater under the middle of the land (because a greater portion of the
pores are blocked by liquid). However, the in-plane variation of temperature in the land is negligible. Thus, the driving temperature difference for the heat-pipe effect remains almost the same while the resistance to flow path increases under the middle of the land. Therefore, the maxima of the phase-change rate shifts toward the channel following the path of least resistance as shown in Fig. 8. For the lower inlet RH cases, however, this peak is less pronounced (RH = 45%) or even nonexistent (RH = 25%). In these cases, liquid saturation is much lower and the maxima of phase-change rate occurs under the middle of the channel.

**Effect of GDL thermal conductivity.**—The other parameter that has a strong effect on phase change rate is the GDL thermal conductivity. In the base case, the GDL thermal conductivity is 3 W/mK. As the GDL thermal conductivity is reduced by one-third to 2 W/mK, cell temperature increases with little change in the liquid-saturation profile (shown in Fig. 9a). Although production and transfer of heat in this case is the same as in the base case, a fractional increase in temperature is less than a fractional reduction in thermal conductivity. The phase-change rate contours (shown in Fig. 9b) show a much higher level of condensation on the cathode land surface, which indicates a stronger heat-pipe effect with decreasing GDL thermal conductivity.

The same trend is observed in Fig. 10a and b, where the GDL thermal conductivity is decreased to 1 W/mK. Condensation on the

![Figure 7](image-url)

**Figure 7.** (a) RH = 100, (b) 67, (c) 45, and (d) 25. Liquid saturation and phase-change rate profiles in the GDL near land and channel at different along-channel locations. [i = 1.0 A/cm², stoichiometry (A/C) = 2.0].

![Figure 8](image-url)

**Figure 8.** Least-resistance path for the heat pipe.
cathode land increases substantially. This shows that yet a greater fraction of total heat transfer is through the heat-pipe effect.

Increase in condensation under the cathode land is shown in Fig. 11b. The liquid saturation close to the cathode land along the flow direction does not change appreciably with decreasing GDL thermal conductivity (Fig. 11a). Because the inlet RH is 100% in these cases, conditions are almost identical in the flow direction. Therefore, variation of both the liquid saturation and phase-change rate is very small along the channel. The same could be found from the in-plane profiles of liquid saturation and phase-change rate at different locations in flow direction (shown in Fig. 12).

Energy balance can be performed near the GDL-land interface in the normal direction. In the presence of very small advection, conductive heat flux and heat release due to condensation of water is balanced near the GDL-land interface in the normal direction. Considering these fluxes on an elemental volume at $x$ (close to the GDL-land interface with $x$ through plane direction) of dimension $\Delta x$, we get

$$
\left. k_{gdl} \frac{\partial T}{\partial x} \right|_x - h_{fg} M_{H_2O} D_{fg,H_2O} \frac{\partial C_{H_2O}}{\partial x} = 0
$$

[18]

Applying the Taylor series approximation with $\Delta x \to 0$, and assuming constant liquid saturation ($s$), porosity ($e$), and considering that $\partial C_{H_2O}/\partial x = (\partial C_{H_2O}/\partial T)(\partial T/\partial x)$, we can obtain

$$
\frac{\partial}{\partial x} \left( k_{gdl} + h_{fg} M_{H_2O} D_{fg,H_2O} \frac{\partial C_{H_2O}}{\partial T} \right) \frac{\partial T}{\partial x} = 0
$$

[19]

From Eq. 19, it is clear that the heat-pipe effect increases the total heat transfer of the GDL. Also, we can define an effective thermal conductivity due to phase change. Summation of the GDL thermal conductivity and phase-change thermal conductivity gives a total thermal conductivity

$$
k_{eff} = k_{gdl} + h_{fg} M_{H_2O} D_{fg,H_2O} \frac{\partial C_{H_2O}}{\partial T} = k_{gdl} + k_{total}
$$

[20]

As the GDL thermal conductivity is decreased, the fraction of total heat transferred through the heat pipe increases. This increases the temperature gradient, and ultimately, the cell temperature rises. The effective diffusivity of water vapor decreases as the liquid saturation increases.\textsuperscript{7} The relation between effective diffusivity of water vapor and liquid saturation is shown as follows

$$
D_{fg,H_2O} = D_{fg,H_2O} e^{-s^3 x^3 - s^4}
$$

[21]

Therefore, as the liquid saturation increases, the heat-pipe effect weakens. For the same reason, for fully (or highly) saturated conditions, the heat-pipe effect shifts toward the channel (as was found in Fig. 7), although minimum temperature occurs under the middle of land.

Conclusions

Phase change in PEMFCs has been quantified as an important link between water and heat management. It is shown that phase change in fuel cells is controlled primarily by two sets of parameters: operating conditions (e.g., RH of inlet gases) and material thermophys-
The inlet RH effect is felt along the channel as low humidity results in the dry length near the inlet and outlet. For fully humidified conditions, the maximum condensation takes place about midway between the middle of the land and channel-land interface. High resistance due to liquid saturation under the middle of the land results in this shift. Under lower inlet RH, maximum condensation coincides with the maximum liquid saturation at the middle of the land. GDL thermal conductivity does not change the shape of the phase-change rate profile. Lower thermal conductivity results in a greater temperature gradient in the cathode GDL, and consequently, the cell temperature increases. The heat transfer coefficient due to phase change remains relatively constant; hence, the phase-change heat transfer becomes a larger fraction of the total heat transfer, and condensation under the land increases significantly at lower GDL thermal conductivity.

Work is underway in our laboratory to develop in situ, direct measurements of phase-change rates in an operating fuel cell. The mechanism of phase-change-driven removal of product water and heat from a PEFC, as elaborated in this work, is a paradigm shift from the more conventional view of capillary-driven removal of liquid water. In this mechanism, thermal properties of fuel cell materials or components and cell temperature play decisive roles, whereas surface wettability and two-phase flow properties, such as capillary pressure and relative permeability, are controlling factors in the conventional mechanism.

Acknowledgments

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List of Symbols

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<thead>
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<th>Symbol</th>
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<tr>
<td>$A$</td>
<td>area</td>
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<tr>
<td>$a$</td>
<td>catalyst surface area per unit volume, m$^2$/m$^3$</td>
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<tr>
<td>$C_i$</td>
<td>local concentration of species $i$, mol/m$^3$</td>
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<td>$c_p$</td>
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<td>$F$</td>
<td>Faraday constant</td>
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\( \dot{i} \) current density, A/m\(^2\)
\( \dot{i} \) superficial current density, A/m\(^2\)
\( j \) transfer current density, A/m\(^3\)
\( j \) mass flux, kg/m\(^2\) s
\( K \) permeability of a porous medium
\( k \) relative permeability
\( M \) molecular weight
\( m_f \) mass fraction of species \( k \) in liquid
\( m \) liquid-gas interfacial mass transfer rate, kg/m\(^3\) s
\( n \) normal direction; number of electrons
\( n_{el} \) electro-osmotic coefficient, H\(_2\)O/H\(^+\)
\( P \) pressure, Pa
\( r \) radius
\( S \) source term in the governing equations
\( s \) liquid water saturation
\( T \) temperature, K
\( U_{eq} \) equilibrium potential
\( u \) velocity
\( V \) volume
\( x \) \( x \) coordinate, \( \mu \)m
\( y \) \( y \) coordinate, \( \mu \)m
\( z \) \( z \) coordinate, \( \mu \)m

Greek
\( \alpha \) net water transport coefficient
\( \gamma \) correction factor
\( \varepsilon \) porosity
\( \phi \) phase potential
\( \eta \) surface overpotential, V
\( \mu \) viscosity
\( \nu \) kinematic viscosity
\( \kappa \) electrolyte conductivity, S/m
\( \lambda \) relative mobility
\( \rho \) density
\( \tau \) shear stress
\( \sigma \) surface tension, N/m; electronic conductivity, S/m
\( \delta \) gas stoichiometry at the inlet (anode or cathode)

Subscripts and superscripts
avg average
\( c \) convective; capillary
e electrolyte phase
eff effective
fg phase change
g gas phase
H\(_2\)O water
in inlet
l liquid species
mem membrane
O\(_2\) oxygen
ph phase
r relative
s solid phase
sat saturation
T thermal

References