ABSTRACT

Understanding the thermal effects is critical in optimizing the performance and durability of proton exchange membrane fuel cells (PEMFCs). A PEMFC produces a similar amount of waste heat to its electric power output and tolerates only a small deviation in temperature from its design point. These stringent thermal requirements present a significant heat transfer challenge. The heat balance also interplays with the water balance. Although a considerable amount of work has been reported on the experiments and comprehensive thermal models of the fuel cells, the fundamental heat transfer mechanisms in each individual fuel cell component are still not clearly understood. In this work, these thermal transport issues at component level (including polymer, catalyst layers, gas diffusion media and bipolar plates) are reviewed. The current status of PEMFC cooling technology is also reviewed and suggestions for future research are outlined.
INTRODUCTION

Thermal management is a key technical challenge that must be resolved for proton exchange membrane (PEM) fuel cell technology before it can be commercialized (Wang 2004; Faghri and Gao 2005). In this paper the published literature on PEM fuel cell (PEMFC) thermal management is reviewed, the heat transfer issues in individual PEMFC component are outlined, and different practical cooling systems are discussed. After reviewing the current status in these areas specific needs for further research are identified.

BACKGROUND

In this section, the thermal constraints of current PEMFCs caused by using Nafion membranes are first presented. The heat and water transport phenomena within a fuel cell are then outlined. It is followed by a brief discussion on the objectives for developing accurate thermal models.

Thermal Constraints of Current PEMs

Current PEM fuel cells operate in the temperature range of 60 – 80 °C. This range is dictated by the material properties of the PEM. The most commonly employed PEM is Nafion (a trademark of E.I. DuPont de Nemours, Wilmington, DE), which exhibits high proton conductivity only in the hydrated state (Marechal et al. 2007). The hydration requirement of Nafion limits the maximum fuel cell operating temperature to about 80 °C. Above this temperature, the membrane dry out occurs resulting in a decreased proton conductivity. The thermal and mechanical degradation also occurs at elevated temperatures due to the relatively low glass transition temperature ($T_g$) of the hydrated Nafion (in the range of 90 – 120 °C) (Bauer et al. 2005; Young and Mauritz 2001). On the other hand, a cell temperature below 60 °C may lead to water condensation and flooding of electrodes, with a resultant voltage loss caused by added resistance to reactant mass transport. A low operating temperature is also undesirable from consideration of proton conductivity and electrochemical reaction kinetics.

Water and Heat Balance

The main elements composing a PEMFC are: bipolar plates, gas diffusion and microporous layers, catalyst layers and membrane. Figure 1 shows a schematic representation of a PEMFC and the water and heat transport processes within it. The water transport includes contributions from electro-osmotic drag, back diffusion from the cathode to the anode, and diffusion and convection to or from the respective air and hydrogen gas streams. Water is produced at cathode catalyst layer by electrochemical reactions and/or in gas channels due to condensation. An imbalance between production and removal can result in either dehydration of the membrane, or flooding of the electrodes. Both are detrimental to fuel cell performance and durability.

A PEMFC produces an amount of waste heat similar to its electric power output, thus limiting its energy efficiency to about 50% (Wang 2004). Heat production in the PEMFC includes entropic heat of reactions, irreversibilities of the electrochemical reactions and ohmic resistances, as well as water condensation (Wang 2004; Shan and Choe 2005; Weber and Newman 2006). This heat is removed by the cooling system or transferred by conduction-convection across the faces of the stack. The balance of these processes determines the temperature distribution in the PEMFC.

The thermal and water transport in PEMFC are inherently coupled because (i) evaporation and condensation processes are respectively accompanied with absorption and release of latent heat; (ii) water and heat transport occur in conjunction with each other due to heat pipe effect (a temperature gradient induces phase change and net mass transfer of water) (Shan and Choe 2005); and (iii) the saturation vapor pressure is strongly dependent on local gas temperature. The water transport occurs at multiscale, from molecular diffusion of vapor in the CCL to the two-phase flow in the gas distribution channels. Kandlikar (2007) presents a review of current literature on the water transport processes and identifies current research needs in this area.
Thermal Modeling

Due to the complexity and interactions of the water and heat transport processes it is difficult to experimentally measure the temperature distribution inside a fuel cell. Such information is usually obtained through numerical simulation. An accurate thermal model is needed to meet the following objectives:

1. Obtain accurate temperature profiles in the different cell components. Evaluate the effects of temperature on the individual component degradation and durability. Develop a proper heat removal strategy.
2. Provide component-level thermal inputs to assess the part-load, off-design (different inlet gas pressure, temperature and flow rates) and transient performance (fuel utilization, polarization curve, current distribution, etc.) of the stack while integrating with suitable electrochemical and water/gas diffusion (single-phase and two-phase flow with embedded gravity and orientation effects) models.
3. Identify dryout conditions in the membrane and flooding conditions in the cathode side GDL, microporous layer, catalyst layer and gas channels. Predict water transport rates and hydration levels throughout the stack. Project humidity requirements of the inlet gas streams.
4. Provide results from simulations to determine the effects of changing component properties, such as porosity of the GDL, microporous layer structure, surface energies of GDL and the channels, coolant flow rates, channel size and configuration, etc.
5. Develop an overall performance prediction model to allow accurate predictions of the local/average current distributions, maximum temperatures, and water transport and its distribution.

Proper thermal management is critical in the efficient operation of a fuel cell and has been receiving considerable attention, especially in the last five years. Presenting a detailed review of these models itself could be the topic of a separate paper. The present paper is limited to identifying the major challenges in component-level and stack-level thermal issues that still remain unresolved at both microscopic and macroscopic scales.

Fig. 1. Schematic of water balance (left) and heat balance (right) of a PEMFC. NOT TO SCALE.

COMPONENT LEVEL THERMAL TRANSPORT ISSUES

Although there are a large number of publications on thermal management of a PEMFC (e.g. Shan and Choe 2005; Weber and Newman 2006; Fuller and Newman; Nguyen and White 1993; Amphlett et al. 1995; Zhang et al. 2004; Maggio et al. 1996; Djilali and Lu 2002; Faghri and Gao 2005; Hwang 2006; Ju at al 2005a; Muller and Stefanopoulo 2006; Zong et al. 2006; and Xue and Tang 2005), most of these offer an overall
predictive capability without providing a detailed insight into the transport inside individual components. In this section the fundamental heat transfer issues in each individual fuel cell components (membrane, catalyst layer (CL), gas diffusion layer (GDL) and bipolar plate (BPP)) are discussed.

**Proton Exchange Membrane**

The PEM acts as both a protonic conductor and a separator between the anode and the cathode. The most commonly used PEM is perfluorosulfonic acid, in particular Nafion. The proton conductivity is the most important property of Nafion membrane in fuel cell application and is strongly dependent on its water content and temperature (Springer et al. 1991; Zawodzinski et al. 1993). Table 1 lists Nafion’s proton conductivity together with some other properties that are critical in PEMFC application and their variation with temperature and water content.

Table 1. Some properties and their variation with temperature and water content for Nafion 117 membrane

<table>
<thead>
<tr>
<th>Properties</th>
<th>Symbol</th>
<th>Dependence on T and water content</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton conductivity (S/cm)</td>
<td>σ</td>
<td>(0.5139\lambda - 0.326)\exp\left(1268\left(\frac{\lambda}{273+T}\right)\right))</td>
<td>(Springer et al. 1991; Zawodzinski et al. 1993; Yang et al. 2004)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.3 \times 10^{-7}\exp(14\alpha^{0.2}))</td>
<td>at 80 – 140 °C</td>
</tr>
<tr>
<td>Water content</td>
<td>λ</td>
<td>From water vapor:</td>
<td>(Springer et al. 1991; Ju et al. 2005b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.043 + 17.81a - 39.85a^2 + 36.0a^3)</td>
<td>at 30 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.3 + 10.8a - 16.0a^2 + 14.1a^3)</td>
<td>at 80 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>From liquid water:</td>
<td>(Ju et al. 2005b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(8.38 + 0.138 \times T)</td>
<td>at 25 – 130 °C</td>
</tr>
<tr>
<td>Electroosmotic drag</td>
<td>(n_d)</td>
<td>(\frac{2.54}{22})</td>
<td>(Springer et al. 1991)</td>
</tr>
<tr>
<td>Glass-transition temperature</td>
<td>(T_g)</td>
<td>(90 – 120 °C) for hydrated membranes</td>
<td>(Bauer et al. 2005; Young and Mauritz 2001)</td>
</tr>
</tbody>
</table>

Note: 1). Water content \(\lambda\) is defined as the number of water molecules per SO\(_3\)H group; 2). \(n_d\) is defined as the number of water molecules per proton; 3). \(a\) - water vapor activity; 4) \(T\) - temperature (°C).

**Dehydration.** The air and hydrogen gas streams are often humidified in order to maintain proper hydration in the PEM. In fact, many fuel cells are operated at or above saturation conditions to ensure that the membrane remains well hydrated. In spite of this, dehydration of Nafion membrane can still occur (Tsushima et al. 2004; Minard et al. 2006; Li and Pickup 2004; Andreaus et al. 2002; Freire and Gonzalez 2001; Buchi and Scherer 2001). Dehydration is most commonly observed on the anode side of the membrane at high current densities (Andreaus et al. 2002; Buchi and Scherer 2001). This is caused by electro-osmotic drag, whereby water
molecules are pulled from anode to cathode by the flow of protons. If water back-diffusion from cathode to anode is insufficient to compensate for the electro-osmotic drag, a reduction in the water content occurs on the anode side of the membrane. This leads to increased proton resistance, and consequently a loss in performance.

Membrane dehydration is sensitive to the operating conditions (such as gas stream relative humidity, temperature, and current density) and the properties of the membrane itself. Generally, thicker membranes are more prone to the anode dehydration because back-diffusion becomes more difficult (Andreaus et al. 2002; Freire and Gonzale 2001). Several approaches have been applied to increase the water back-diffusion and thus overcome the local dehydration of the membrane. Voss et. al. (1995) proposed an anode water removal technique by introducing a large pressure drop in the hydrogen stream (by increasing its flow rate) to draw water through the membrane by back diffusion, thereby reducing the membrane dehydration significantly. This technique significantly impacts the operating conditions of the fuel cell and needs to be carefully evaluated with the overall system performance. Utilizing a thinner PEM can significantly increase the water back-diffusion and thus improve water management (Andreaus et al. 2002; Freire and Gonzale 2001).

Non-uniform temperature distribution. Another important but often overlooked issue is the non-uniform temperature distribution in the membrane. A higher temperature on the cathode side of the membrane has been observed through both experimental measurements (Vie and Kjelstrup 2004) and modeling (Weber and Newman 2006; Nguyen and White 1993; Muller and Stefanopoulo 2006; Zong et al. 2006). This temperature difference, on the order of several degrees C, has considerable impact on the water content of the membrane (Wang and Shi 2006; Yan et al. 2004). These non-uniform distributions are caused by local variations in water content and gas availability at the reaction sites.

Non-uniform temperature distribution also occurs along the flow length. For a typical PEMFC operating under high humidity (75 – 100% RH), a high temperature region (i.e., hot spot) is often observed at the gas inlet resulting from the intense reaction in this area (Shimoi et al. 2004). The hot spot must be avoided for the membrane reliability because the peak temperature of the hot spot may exceed the membrane reliability limit.

Heat transfer consideration. Heat is generated in a PEM from two sources – energy released from the electrochemical reactions, and the ohmic heating due to proton conduction across the PEM. Part of this heat is transferred through the PEM by heat conduction, as the contribution from water transport is minimal. However, the relevant thermal properties (thermal conductivity and heat capacity) of Nafion membrane at various hydration levels are rarely available in literature. Vie and Kjelstrup (2004) estimated the thermal conductivity of a fuel cell membrane by measuring in situ temperature gradients in a fuel cell. An average thermal conductivity of 0.2 ±0.1 W/m.K was obtained for Nafion 115 membrane. Khandelwal and Mench (2006) measured the thermal conductivity of dry Nafion with a steady state measurement method and a value of 0.16 ±0.1 W/m.K was obtained at 30 °C. Various values in the range of 0.1 – 0.95 W/m K have been used in fuel cell modeling (Berning et al. 2002; Maggio et al. 1996). There is a clear need for more accurate measurements of these properties.

New developments in the PEM include high temperature polymer materials and self-humidification membranes. For example PBI based polymers would enable the PEMFC to operate at a temperatures above 120 °C (Labato et al. 2007), and Pt-SiO2-Nafion composite self-humidification membranes would enable the PEMFC to operate at low relative humidity levels (Zhu et al. 2006; Watanabe 1996). This would greatly simplify the water and heat management within the fuel cell. Also the higher operating temperature would improve the heat transfer rate from the device to the coolant.

**Cathode Catalyst Layer (CCL)**

The heat generation in a fuel cell is mainly the result of electrochemical reactions. The entropic heat at standard state is 0.104 J/mol K for the anode and -326.36 J/mol K for the cathode reactions (Lampinen and Fomino 1997). Due to much greater heat generation and water production rates at the cathode than at the anode, the CCL experiences a more severe water and heat management problem. For this reason, the following discussion is focused on CCL.
**Microscopic nature of heat generation and transport in CCL.** Figure 2 shows a schematic of the catalyst layer geometry and its composition. The porous catalyst layers consist of platinum nanoparticles (3-5 nm diameter), carbon nanopowders (10-20 nm diameter) and the ionomer material. Two distinctive pore distributions have been identified in the catalyst layer, namely the primary pores (diameter of 6-20 nm) existing inside the Pt/C agglomerates and the secondary pores (diameter of 20-100 nm) existing between these agglomerates (Uchida et al. 1995; Ihonen 2002; Sun et al.; 2005 and Gloaguen and Durand 1997). The secondary pores offer the major pathway for the transport of reactant gases and product water (Eikerling 2006). Most of the waste heat generated in a PEMFC comes from the electrochemical reactions, which take place on the triple-phase (ionomer - platinum - gaseous reactant) boundaries in the catalyst layer.

![Schematic representation of the catalyst layer structure and its composition. NOT TO SCALE.](image)

The local reactions mainly take place in the secondary pores as will be illustrated in an overall water and heat transport representation in the next section (Fig. 3). In the CCL, oxygen molecules diffuse through the void space in the larger pores and are transported to the catalyst sites as dissolved molecules in the ionomers (Ayad et al. 2004). Protons and electrons transport through the proton conducting ionomers and the interconnected carbon particles, respectively. All these chemical species react on the platinum surface and produce water and heat.

The heat transfer in CCL is coupled with the water transport and phase change dynamics. Although a PEMFC operates above atmospheric pressure and 80 °C, water vapor is favored in the CCL for the following reasons: (a) the nanometer scale of the pores in CCL greatly increases the saturation vapor pressure; (b) the water evaporation is significantly enhanced in these nano-sized pores; and (c) the local high temperature in the CCL further increases the saturation vapor pressure and water evaporation rate. The first point is best highlighted by an example: the equilibrium vapor pressure, calculated from the Kelvin equation (Kaufman 2002), in a micropore with a diameter of 20 nm increases by 11% at 25 °C and by 9% at 80 °C when compared to a flat surface. For the hydrophobic pores in CCL (Yu et al. 2006) the saturation vapor pressure is further increased. As for the second point, Eikerling (2006) has demonstrated that at current density up to 1 A/cm², the evaporation rate in the porous structure is sufficient to convert all the product water from liquid state to vapor phase. From both the thermodynamic and kinetic viewpoints it can be concluded that the catalyst layers are efficient to convert liquid product water into vapor state. According to Eikerling (2006) the fine pores in the catalyst layers promote evaporation of liquid phase and thus allow the water to flow out in the vapor phase and permit reactants to diffuse toward the reaction sites.

The reaction heat in the CCL is also conducted through the GDL and finally removed by the coolant. The effective thermal conductivity of the catalyst layer is an important parameter from a thermal management
perspective. A few experimental measurements exist in the literature. Khandelwal and Mench (2006) measured the combined thermal resistance of an MEA sandwiched between two Toray TGP-H-60 carbon paper diffusion media. By subtracting the thermal resistance of the membrane and the diffusion layers, which were measured independently, the effective thermal conductivity of the catalyst layer was estimated to be $0.27 \pm 0.05$ W/m K. This value is similar in magnitude to that of the diffusion media. At present no attempt has been made to calculate the thermal conductivity of the catalyst layers because of the wide variation in the properties of the component materials, including ionomers and Pt/C particles.

Over the last decade, a few new types of non-conventional catalysts have been developed, e.g. the nanostructured thin film (NSTF) catalysts developed by 3M (Debe et al. 2006) and the non-Pt catalysts (Wang 2005). Since these new catalysts have different compositions and structures as well as different reaction mechanisms, the water and thermal management issues may be quite different from the conventional Pt/C catalyst. This is beyond the scope of this paper.

The Gas Diffusion Layer (GDL) and Microporous Layer (MPL)

The most commonly used gas diffusion layer (GDL) materials for PEM fuel cells are carbon cloth and carbon paper. These materials are highly porous to allow gas transport to the catalyst layer, as well as liquid water transport from the catalyst layer. In order to facilitate the removal of liquid water, these fibrous materials are usually further hydrophobicized with a polytetrafluoroethylene (PTFE) coating. GDLs also serve as the main medium to conduct heat from the catalyst layers to the flow-field plates. A fine microporous layer (MPL), consisting mainly of carbon powders and PTFE particles, has been widely used by fuel cell researchers to improve the performance of a PEMFC (Pasagullari et al. 2005; Qi and Kaufman 2002; Jordan et al. 2000; Kong et al. 2002; Beattie et al. 1999).

GDL flooding, caused by liquid water accumulating in the pores of the GDL and consequently hindering oxygen transport to the catalyst sites, is one of the most common issues in proper water and thermal management. Flooding may occur when a PEMFC is operated at moderate or high current densities and/or with fully humidified reactants. GDL flooding is usually described by “water saturation”, which is expressed as the ratio of volume of water-filled pores to the total volume of pores in a GDL. According to Nam and Kaviany (2003), the water saturation in a GDL is dominated by the condensation/evaporation processes. Generally, the oxygen depletion due to the electrochemical reaction results in water condensation, while the total pressure drop along the gas channel leads to water evaporation. The phase change inside the GDL is also strongly affected by the temperature distribution. The heat production due to both the electrochemical reactions in the CL and the ohmic heating in the GDL increases the temperature in the GDL, thus increasing the water vapor saturation pressure. Both modeling results (Berning and Djilali 2003) and experimental data (Vie and Kjelstrup 2004) indicate that significant temperature gradients (~5 °C) exist across the GDL.

The heat transfer within the GDL occurs by conduction and convection mechanisms. Heat is conducted through both the solid carbon fiber matrix and the liquid water, whereas convection is mainly through the gas phase. The thermal conductivity of the GDL is an important parameter and has been measured by Khandelwal and Mench (2006). The thermal and electrical conductivity of GDL are likely anisotropic, which complicates the thermal measurements and heat transfer modeling (Pharaoh et al. 2006). Another complication comes from the temperature difference between the fluids and the solid matrix in the GDL. Hwang et al. (2007) showed that the local fluid and matrix temperatures have considerable influence on the current density distribution.

The presence of a microporous layer has been shown to improve the fuel cell performance by a number of investigators, although the exact mechanism is not clearly understood. Several authors (Qi and Kaufman 2002; Beattie et al. 1999) have demonstrated that the MPL improves the humidification of the membrane at the anode side, thus improving the water management. Jordan et al. (2000) and Kong et al. (2002) concluded that the MPL enhances oxygen diffusion by reducing flooding in the cathode. Owejan et al. (2007) conducted experiments on cracked and crack-free MPLs with the same GDL material and found a significant reduction in the resistance to water flow in the cracked case during ex-situ experiments. However, there was no difference in the electrochemical performance between the two MPLs, indicating that during the PEMFC operation, the water flow through the MPL may not be in the liquid form. In addition they looked at the effect of MPL position on
the GDL. Based on their experiments, they further concluded that the vapor capillary effects within the GDL have an insignificant effect on mass transport overpotential, and the Darcy flow in the catalyst layer has little influence in the transport process. As noted by some investigators, introducing an MPL also improves electrical contact between GDL and catalyst layers thereby improving the fuel cell performance (Qi and Kaufman 2002).

**Coupled heat and water transport mechanisms in CCL, MPL and GDL**

The local temperature profiles and water vapor partial pressures play a crucial role in the transport processes in these regions. As discussed under CCL section above, the favorable state of water in the CCL is vapor phase. At low and moderate current densities, the particular pore structure in the catalyst layer favors water in vapor phase, benefiting the water and heat management. At high current densities, when water production rate increases beyond the evaporation capability of the porous catalyst layer, catalyst flooding will occur. A detailed review of the transport mechanisms of water is given by Kandlikar (2007). The role of microporous layer is critical in water management as it acts like a surface tension based gate that prevents the backflow of water from GDL into the CCL, while facilitating flow of water away from CCL into GDL. The local temperature is another key element in ascertaining that the condensation occurs in the GDL.

Figure 3 shows a proposed transport model for water from its generation at CCL to its removal in the gas channels. When the high temperature water vapor in the CCL passes through the microporous layer and the GDL, it is cooled and partly condensed into liquid water. Condensation in the MPL with finer pores is less desirable than in the GDL which has a coarser pore structure. If the local saturation condition results in the condensation in the MPL, it may lead to flooding. A condensation front therefore is expected to exist under optimum conditions somewhere at the interface between the MPL and the GDL or within the GDL as shown in Fig. 3, depending on the local temperature. The flow of vapor from the reaction sites and its subsequent condensation inside the GDL also enhances the heat transfer due to release of latent heat during condensation. The thermal gradients within the GDL thus play a significant role in the water vapor transport toward the gas channels and its condensation within the GDL matrix.

![Fig. 3. A proposed CCL water transport mechanism showing the electrode reaction and the transport of product water in a catalyst layer. NOT TO SCALE.](image)

**Bipolar Plates**

The bipolar plates constitute the mechanical backbone of a fuel cell stack. They conduct current between cells and provide conduits for reactant gases and coolant. They are commonly made of graphite composites due
to their high corrosion resistance and low surface contact resistance. Considerable attempts are being made to replace the BPP made from graphite composites with metals due to their high mechanical strength, better durability to shocks and vibrations, and much superior manufacturability and cost effectiveness (Tawfik et al. 2007). In order to prevent the corrosion of metal in the harsh acidic and humid environment inside the PEMFC, metals are usually coated with an anti-corrosion coating. The main challenge however is that the anti-corrosion coating or the passivating oxide layer on the metal surface usually causes an undesirable contact resistance.

The removal of waste heat is a major function of the bipolar plates. Due to the high inlet water vapor pressure, only a small amount of heat is removed in the form of latent heat by the gas stream. Most of the heat is carried away as the sensible heat by the coolant stream. A significant cooling duty is therefore required in a PEMFC with a rather small temperature difference between the cooling stream and the fuel cell. In addition to a higher operating temperature desired from the electrochemical perspective, a higher operating temperature is favorable from a cooling perspective as well. Recent developments in the cooling systems are reviewed in a separate section.

In addition, the temperature distribution along the gas channel is often non-uniform. Several variations occur along the gas channel, including (i) dilution of oxygen by the addition of water vapor into gas stream, (ii) water condensation caused by oxygen depletion from inlet to outlet, and (iii) water evaporation caused by the pressure drop along the channel (Berning and Djilali 2003). A comprehensive heat transfer model therefore needs to accurately track the electrochemical reaction and evaporation/condensation processes in various regions of a fuel cell. Such issues become even more important during dynamic operation (Yan et al. 2007).

**Temperature Distribution in PEMFC Components**

The balance between the heat generation and heat removal determines the steady-state operating temperature of a PEMFC. The relevant terms for each of the heat transfer component are described below:

1. Heat production due to electrochemical reaction: \( Q_{rxn} = \sum h(\eta_h + \Pi_h) \), where \( h \) is the current, \( \eta_h \) is overpotential, \( \Pi_h \) is Peltier coefficient of an electrode reaction, and \( h \) represents either the anode or cathode. The first term on the right side represents the irreversible heat due to overpotential, and the second one represents the reversible entropic heat. The Peltier coefficients for the hydrogen-oxidation reaction (HOR) and the oxygen-reduction reaction (ORR) have been measured experimentally. Averages are -13 mV for HOR (Sun et al. 2005; Gloaguen and Durand 1997) and -240 mV for ORR (Pasaogullari et al. 2005) at 25 °C.

2. Heat generation due to ohmic heating: \( Q_{ohm} = \int \frac{i^2}{\sigma(y)} dy \), where \( \sigma \) represents the proton conductivity or electronic conductivity. This conductivity is generally a function of thickness due to the varying composition.

3. Heat generation/consumption due to water vaporization/condensation: \( Q = \Delta H_{vap} r_{v,c} \), where \( \Delta H_{vap} \) is the heat of vaporization and \( r_{v,c} \) is the rate of vaporization or condensation. The local temperature and humidity ratio are interlinked with the release of the latent heat and the location of the condensation front as shown in Fig. 3.

4. Heat transfer due to convection and conduction: \( hA_{conv}\Delta T, kA_{cond}\frac{dT}{dy} \), respectively, where \( h \) is the heat transfer coefficient, \( A_{conv} \) the convective area, \( \Delta T \) the temperature difference, \( k \) the thermal conductivity, \( A_{cond} \) the conduction area and \( \frac{dT}{dy} \) is the temperature gradient in the heat flow direction.

The balance between heat generation and various heat transport mechanisms determines the temperature distribution in a PEMFC. A schematic of the anticipated temperature profile across a PEMFC having cooling channels in each bipolar plate is shown in Fig. 4. A peak temperature is expected within the CCL due to the large amount of heat generation from the electrochemical reaction. This has been verified by experimental measurements (Vie and Kjelstrup 2004) and various thermal models (Wang 2004; Weber and Newman 2006; Hwang 2006). The thermal conductivity of each component and their thickness are listed from experimental measurements (Khandelwal and Mench 2006). Also shown in Fig. 4 are the heat generated in each component due to reaction and/or ohmic heating is estimated for a 50 cm² single fuel cell operating at 1 A/cm². A cell
A voltage of 0.6 V is assumed in estimating the irreversible heat generation in the CCL due to the overpotential ($\eta$). To limit the stack thickness, its weight and cost, cooling channels are usually not provided in each bipolar plate. The temperature profile is accordingly modified. Developing accurate thermal models is therefore quite challenging as it needs to account for all the heat transfer terms along with the water relative humidity, concentrations of various species and phase distribution (liquid or vapor phase of water) to accurately predict the thermal profile.

**CURRENT STATUS OF PEMFC COOLING SYSTEMS**

Two factors are critical in designing a cooling system for PEM fuel cells: First, the nominal operating temperature of a PEMFC is limited to about 80 °C. This means that the driving force for heat rejection is far less than that in a typical internal combustion engine cooling system. Second, nearly the entire waste heat load must be removed by an ancillary cooling system, unlike a combustion process where a significant fraction of the heat is carried out of the engine with the reaction product streams, or dissipated internally. These two factors account for the need to have relatively large radiators in automotive fuel cell systems, and providing space for the radiators and the associated air handling ducts represents a significant design challenge (Ashley 2006).

A common fuel cell stack cooling method involves design of the bipolar plate such that there are internal cooling channels between the anode and cathode, an example of which is shown in Fig. 5. The channels on all plates are connected through a common header which is formed when the plates are assembled into the “stack”. With this approach, the channel geometry is designed to accommodate the heat transfer medium of choice.

For some smaller fuel cell systems (up to 2 – 5 kW in electrical power output) it is possible to use air as the heat transfer fluid, and thus rely on a relatively inexpensive blower for coolant delivery. The 1.2 kW Mark 1020 system offered by Ballard is an example of this approach (Fuels Cells Bulletin 2006). The coolant air can simply be exhausted to ambient, removing the need for a radiator. For fuel cells with power output in excess of about 100 W, use of a single air stream would require extremely high cathode stoichiometric ratios, resulting in
unacceptably dry operating conditions (Larminie and Dicks 2003). For automotive and many stationary fuel cell systems, the waste heat loads are large enough that a closed cooling loop, comprised of a liquid heat transfer fluid, coolant pump, and radiator, is required. Various liquids have been used, with differences related mostly to cooling capacity, cost, corrosion control, or adjustment of electrical conductivity. Electrical conductivity of coolants must be as low as possible to avoid electrical current loss through the cooling subsystem. Aside from the glycol-based coolants typical of internal combustion systems, some variations that have been patented include:

- A low-cost fluid based on kerosenic hydrocarbons or kerosene-water mixtures (Abd Elhamid et al. 2004)
- Maintaining low fluid conductivity by incorporation of an ion exchange medium into the coolant loop (Imaseki 2006).
- Addition of carboxylic salts to the heat transfer fluid, to maintain electrical conductivity less than 100 μS/cm (Meas and Lievens 2007).
- Improving durability of glycol-water coolants by incorporation of a filter to remove oxidation products (Matsuzaki 2007).
- Control of the coolant loop pressure to enable phase change, thereby increasing the effective heat transfer coefficient, and reducing the total amount of coolant required (Lee and Skala 2005).
- Reducing the size of the coolant system by use of a refrigerant fluid (Yoshii et al. 2006).

![Membrane electrode assembly](image)

Fig. 5. Typical fuel cell bipolar plate design in which coolant channels are formed by joining anode and cathode flow fields. In this example, the individual plates are fabricated from corrugated metal (Wilkinson and Vanderleeden 2003).

Additional concepts have been proposed which rely on evaporative processes to facilitate fuel cell stack cooling. In one embodiment, a dispersed liquid droplet stream is introduced into the reactant flows to provide both the humidification of PEM and evaporative cooling (Brambilla and Mazzucchelli 2004). Other approaches involve heat pipes or heat pumps which rely on combined evaporation and condensation processes within a separate subsystem to extract heat generated within the stack and reject it to the ambient environment. In another example, a wicking structure is used on the cathode side to form the flow field channels, facilitate internal distribution of liquid water, and simultaneously provide cooling and gas humidification (Goebel 2005).
A noteworthy departure from the internally cooled plate design illustrated in Fig. 5 is the concept advanced by UTC Power, in which the bipolar plates are fabricated from a porous, hydrophilic material. This allows direct water exchange with the cathode side of the MEA (Meyers et al. 2006). To maintain water balance in the system, some of the product water must be returned to the stack, by directing the cathode exit stream through a condenser, which is either the primary radiator of a fuel cell vehicle, or an intermediate heat exchanger coupled to the primary radiator (Fig. 6). The overall volume of cooling water required is reduced by relying on the heat of vaporization. A vent above the fuel cell stack ensures that the liquid water pressure is equilibrated with the ambient. This pressure difference and capillary force pulls water into the porous plate, maintaining even water distribution with no moving parts (Reiser et al. 2006).

An important consideration is that in order to meet long-term performance and material durability requirements it is essential that the rate of cooling be reasonably uniform across the fuel cell active area. Large temperature gradients in the fuel cell materials introduce significant in-plane stresses that can lead to premature failure. Moreover, for automotive fuel cell systems in particular, the stringent cost targets make it difficult to introduce additional components or subsystems, even for concepts that may offer improvements in heat transfer effectiveness and/or uniformity. Therefore, it is reasonable to expect that internally liquid-cooled bipolar plates will be widely used in early introduction of large stationary and automotive PEM fuel cell systems.

**CONCLUDING REMARKS**

Thermal management is a key design consideration for PEMFCs, from the microscopic scale of the catalyst particles (nanometer scale) and microporous layer, the component level gas diffusion layers and bipolar plates, to the integration of the fuel cell stack with various external subsystems. The temperature and water vapor pressure profiles within the membrane-electrode assembly dictate the phase of water present in various regions and its transport from the PEM to gas channels. In this sense, fuel cell thermal and water transport mechanisms are intimately interlinked, and one cannot study the fuel cell performance without considering the heat transfer.

As fuel cells continue to develop toward commercialization, there are a number of critical research needs related to thermal management. Some of the important needs identified in the above review are:

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*Fig. 6. Evaporatively-cooled stack design, using porous bipolar plate technology (Meyers et al. 2006)*
1. Accurate experimental data for the thermal conductivity and contact resistance of different components (e.g. proton exchange membranes, catalyst layers, gas diffusion layers and bipolar plates) are needed for thermal and water transport modeling. Particular focus is needed on understanding multi-dimensional effects in components which are highly anisotropic.

2. New materials are desired for certain individual components. For example: a new PEM that can operate at high temperature and low relative humidity, a new catalyst material or design that provides better mass and heat transport properties, a new GDL that further mitigates water accumulation, and a new BPP that combines the advantages of metal and graphite.

3. A clear understanding of the fundamental water and heat transfer mechanisms in each component is needed. A variety of fundamental phenomena, such as membrane dehydration, liquid water production in CL, anode-cathode water balance, water saturation and transport in the microporous layer and GDL, and the non-uniform distributions of temperature and current density along the gas channel, all need further investigation.

4. Defining a set of easily measurable and rigorously meaningful thermal parameters for the catalyst layer, microporous layer and GDL is critical in developing better models.

5. Most currently used equations for description of transport phenomena in the GDL are derived for granular porous materials. Their extension to porous media in PEMFC (including CL and GDL) is open to question. Better transport models are needed to describe the water transport in the GDL.

6. The transient heat transfer problems, such as the start-up, shut-down, and freeze-thaw cycling, need to be accurately modeled for developing appropriate control algorithms, especially in the case of automotive systems which encounter highly dynamic load profiles.

**NOMENCLATURE**

- $a$ Water activity (dimensionless)
- $n_d$ Electro-osmotic drag (dimensionless)
- $h$ Convection heat transfer coefficient (W/cm$^2$ K)
- $\Delta H$ Change of enthalpy (J/mol)
- $i$ Current density (A/cm$^2$)
- $Q$ Heat (J)
- $T_g$ Glass transition temperature (°C)
- $T$ Temperature (°C)
- $\sigma$ Electrical conductivity (S/cm)
- $\lambda$ Water uptake (dimensionless)
- $\eta$ Overpotential (V)

**REFERENCES**


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