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In situ-polymerized wicks for passive water management in proton exchange membrane fuel cells

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ABSTRACT

Air-delivery is typically the largest parasitic loss in PEM fuel cell systems. We develop a passive water management system that minimizes this loss by enabling stable, flood-free performance in parallel channel architectures, at very low air stoichiometries. Our system employs *in situ*-polymerized wicks which conform to and coat cathode flow field channel walls, thereby spatially defining regions for water and air transport. We first present the fabrication procedure, which incorporates a flow field plate geometry comparable to many state-of-the-art architectures (e.g., stamped metal or injection molded flow fields). We then experimentally compare water management flow field performance versus a control case with no wick integration. At the very low air stoichiometry of 1.15, our system delivers a peak power density of 0.68 W cm^{-2}. This represents a 62% increase in peak power over the control case. The open channel and manifold geometries are identical for both cases, and we demonstrate near identical inlet-to-outlet cathode pressure drops at all fuel cell operating points. Our water management system therefore achieves significant performance enhancement without introducing additional parasitic losses.

1. Introduction

Presently, the transportation sector relies on petroleum for 95% of total energy used. As a result, transportation accounts for a considerable portion of global greenhouse gas emissions (24% in 2004). [1] Over the past decade, increased research and development has gone toward transportation technologies which exploit alternative energy sources. These technologies include bio fuel combustion, hybrid, plug-in hybrid, electric, and fuel cell vehicles. Of these technologies, market penetration models and technological advancement forecasts suggest that fuel cell vehicles may have the most promise for long-term CO_2 emission reduction [2,3]. Key disadvantages remain, however, which prevent near-term implementation and deployment of fuel cell vehicles. Some disadvantages include current cost of catalyst materials and manufacture, long-term durability issues, and the necessity of a fueling infrastructure [2,4].

Proton exchange membrane (PEM) fuel cells are favored for transportation due to their high efficiency, low operating temperature, and high power density [5]. A persistent challenge in PEM fuel cell systems, however, is water management [6]. Membrane humidity must be maximized to ensure good ionic conductivity [7], while excess product water must be removed to prevent electrode, gas diffusion layer (GDL), and flow field channel flooding [6]. Flooding has multiple impacts on fuel cell performance. At the very least, flooding reduces gas permeability in the GDL and, in effect, the limiting current [8–10]. In addition to GDL flooding, flow field channel flooding can lead to mal-distribution of reagent delivery, localized fuel starvation, and significant spatial non-uniformity in reaction rates [11–14]. These flooding events not only introduce large efficiency losses, but also lead to electrode and long-term performance degradation [4]. Flooding poses additional challenges in stacks, where cell flow fields are manifolded in parallel. In such systems, flooding in a single cell has minimal impact on overall inlet-to-outlet pressure drop. As a result, product water can continue to accumulate. This leads to non-uniformity in cell-to-cell potentials, and, in severe cases, cell reversal [15].

Effective water management, therefore, is critical for stable and long-term reliable performance [16,17]. This is often addressed by using fully humidified inlet gas streams and incorporating serpentine channel cathode flow fields for air-delivery [18]. The long channel length and reduced air channel cross-sectional area of serpentine designs lead to increased pressure drop and increased air velocities, which advectively remove excess product water. Although stable performance is achieved, this approach results in large parasitic power losses (as high as 35% of stack power) and increased system complexity [18–20]. Required auxiliary compressor and gas humidification systems also reduce power density through increased system size, sometimes accounting for up to 20% of total fuel cell system volume [21].

Parallel channel cathode flow field architectures are appealing, as they require minimal pressure differentials to deliver

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reactants. They offer reduced air compression and delivery parasitic power. These architectures are often impractical, however, as they typically require high stoichiometric air-flow rates to achieve flood-free, stable performance [13,22].

Several groups have proposed novel methods to minimize air stoichiometry requirements while maintaining effective water management. We here first review largely passive and then active water management strategies. Voss et al. removed excess product water through the anode by enforcing a cathode-to-anode membrane water saturation gradient [23]. This saturation gradient was realized through careful control of anode and cathode gas humidification. In another study, Inoue et al. developed cooling water channel designs to strategically impose thermal gradients, and by extension, saturation pressure gradients. This resulted in approximately uniform relative humidity [24]. Similarly, Li et al. leveraged in-channel pressure gradients to maintain gas streams precisely at saturation [18]. As air pressure decreases with distance downstream, water carrying capacity increases. Li et al. used this effect to develop a simple cathode channel design model which matches increased water carrying capacity with water production rate. Although these methods have shown effective water management, they significantly constrain system design and geometry, and are often not compatible with parallel channel, low-pressure differential, flow field designs.

An alternative approach is to use active flood mitigation for parallel flow field architectures. Yi et al. employed hydrophilic, porous carbon water transport plates as cell separators [25]. These water transport plates remain fully saturated and internally humidify undersaturated gas streams, while a pressure differential applied between gas and internal water transport channels removes excess product water. Buie et al. integrated an electroosmotic (EO) pump directly into a fuel cell cathode [26] and applied an electric field to drive liquid water from the GDL to an external reservoir. Litster et al. extended this idea by externally coupling an EO pump with a porous carbon cathode flow field [27,28]. In their design, an EO pump generated pressure gradient removed excess product water absorbed by the porous carbon flow field. These active water management strategies all enabled stable, flood-free performance in parallel channel flow field architectures, at significantly reduced air stoichiometries.

Although both passive and active water management strategies have resulted in considerable performance enhancements, concerns remain related to fuel cell cost, manufacturability, and power density, specifically in the transportation sector. Separator plates typically account for 80% of stack weight and a significant portion of the total stack cost. State-of-the-art separator plates leverage injection molding or stamping manufacture procedures to minimize cost and weight [29]. To the best of our knowledge, current flood mitigation techniques are very difficult to integrate into these new flow field designs, specifically those which utilize parallel channels. In the present work, we develop a passive water management system that enables stable performance in parallel channel flow field designs at extremely low air stoichiometries, and can be integrated with state-of-the-art flow field architectures. We leverage an *in situ*-polymerized wick design which can conform to the shape of existing flow field plates and be used to provide water management while minimizing pressure drop.

2. Material and methods

2.1. Water management flow field design overview

We *in situ*-polymerized 200 μm thick polymer wicks on the channel walls of a 19 parallel channel 25 cm^2 aluminum flow field. The wick is created and integrated using a novel photopolymerization and molding process which we detail in Section 2.2. The wick spatially defines regions for water (wick) and air (open channel) transport. The channel wick is contiguous with a thin "wick header" molded into the top surface of the outlet manifold. This wick header is 150 μm thick and also connects hydraulically to the outside of the fuel cell via a separate porous wick "bridge" which, when saturated, allows water transport while maintaining a gas seal. The wick bridge is 47 mm wide, and made from glass filter cloth (Whatman GF/D, UK). The integrated, *in situ*-polymerized wicks are hydrophilic. We measured a contact angle of ∼55° on a non-porous polymer sample (made using the same chemistry and procedure but without adding porogen chemical) using a contact angle analyzer (FTA200, First Ten Angstroms, Portsmouth, VA). The wick structure in the channels therefore initially absorbs liquid product water once it emerges from the GDL. Wick capillary pressure, defined as the surface tension induced difference between gas and liquid pressures, decreases from a maximum value at low water saturations (where only the smallest pores are filled) to zero when the wick is fully saturated. Therefore, capillary forces initially redistribute water by inducing liquid pressure gradients which transport water from high to low saturation regions.

Once the wick is fully saturated, capillary pressure becomes negligible and liquid and gas pressure gradients likely become equal. This is because even a small amount of liquid water on the wick surface is enough to prevent menisci on the wick surface from supporting a wick-to-channel pressure difference (see Litster et al. [28] for further discussion of wick capillary pressures and wick-to-channel pressure differences). As a result, and as per Darcy's law [30], axial in-channel air pressure gradients induce water flow downstream within channel wicks and to the wick header in the outlet manifold. Excess product water then either travels out through the gas outlet or through the wick bridge via a slight pressure difference between the outlet manifold and ambient. Consistent with discussion by Litster et al. [28], we assume full wick saturation during steady-state operation. Therefore, in effect, wicks provide a liquid water transport pathway from reaction sites to outside of the fuel cell by leveraging air pressure gradients.

Fig. 1 shows the passive cathode water management flow field (WMFF) design. Our control (no wick) flow field is shown in the inset. We fabricated both flow fields to have approximately identical open flow areas in both channels and manifold. This resulted in nearly identical inlet-to-outlet pressure drops for both the wick and no wick cases. Carefully controlling geometry is important, as pressure drop and air velocities relate directly to water removal rate and air compressor parasitic power. We note that the wick material is a dielectric polymer. As a result, the WMFF has a reduced conducting area in contact with the GDL. Conductive rib thicknesses are 370 and 670 μm for the WMFF and control, respectively. Current interrupt measurements revealed a slight increase in area specific resistance, from 100.5 to 101.0 mΩ cm^2 (a difference smaller than the uncertainty of our impedance measurements). For all cases, we used a triple serpentine anode flow field to prevent anode-side flooding.

2.2. Fabrication procedure

2.2.1. Injection molding

In this section, we describe the molding process used to fabricate wicks on the surface of the cathode water management flow field. We first precision end-milled aluminum (McMaster-Carr, Chicago, IL) flow fields for both the water management (wick) and control (no wick) cases. We machined the water management flow field to have channel and manifold dimensions 150 μm larger to allow room for subsequent polymerization of surface mounted wicks. We then used a solvent resistant, polyester resin (TAP Plastics, Mountain View, CA) to cast the top "negative image" mold for injection molding. The control flow field plate itself served as the casting