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DESIGN IMPROVEMENTS ON A BIPOLAR PLATE WITH PASSIVE WATER MANAGEMENT USING THE BIOMIMETIC DESIGN METHOD

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ABSTRACT

Liquid water build up in the cathode flow channels of a polymer electrolyte membrane fuel cell (PEMFC) can limit performance. A mechanism that removes accumulating liquid water continuously from the flow channels is required. While a number of water management strategies have been demonstrated, the search for improvements continues. This paper describes a novel technique of using biomimetic design to systematically generate a passive water management system concept for PEMFCs. Studies have shown that biology is a good source of analogies for engineering design. We believe that biomimetic design is an effective design methodology for PEMFC designs due to several common characteristics of biological systems, such as efficient use of material and energy, a self-regulating characteristic, and high tolerance to a wide range of operating conditions.

A passive water management solution was generated based on two biological phenomena identified using the biomimetic design method. The biological phenomena inspired use of design elements such as random abrasions and polyethersulfone strands to remove water from the flow channels. The design was demonstrated on a simple test apparatus with low air flow rates and low inlet pressure. Preliminary experiments with the test apparatus have shown total recovery from flow channel catastrophic flooding within seconds. The present paper discusses the biomimetic design process, implementation, and prototype results.

1. INTRODUCTION

Biomimetic design is the emulation of biological phenomena in engineering design. Biomimetic design takes inspiration from nature to aid in design by humans, including various forms and levels of modeling, system design, process design, elements and assembly design. This paper describes application of the biomimetic design process to a polymer electrolyte membrane fuel cell (PEMFC) design problem, namely water management. First, a summary of the biomimetic design process will be presented. Next, difficulties which arise in the PEMFC water management system will be described and a summary of related and previous work will be provided. The process of identifying the related biological phenomena that will help to solve these difficulties will be summarized next. Finally, the physical implementation and experimental validation of the strategy will conclude this paper.

2. NOMENCLATURE

Corpus (plural: Corpora): A large structured set of text. The corpus on which the biomimetic search tool performs is *Life, the Science of Biology* (Purves et al., 2001).

Match Excerpt: One or two sentences surrounding the search keyword in a section.

Part-of-speech: Linguistic category of words, such as verbs, nouns or adjectives.

Phrase Group: A group of words functioning as a single entity in a sentence.

Section: A logically divided group of words from the corpus.

WordNet: A lexical database that organizes words according to their relationships to each other (WordNet, 2010)

3. BIOMIMETIC DESIGN

Biomimetic design methodology examines nature and emulates from our surroundings to solve design problems. The transfer of knowledge between the biology domain to the engineering domain is desirable due to analogies from conceptually different domains have been observed to result in more creative design solutions (Benami & Jin, 2002). Gordon (1961) also noted that the specific domain of biology provides the richest source of direct analogies.

Biomimetic design has generated innovations in diverse fields such as mechanical design, computer algorithms and manufacturing processes. Obvious biomimicry designs such as the use of fish to inspire underwater robots and birds to inspire planes are common. Higher level biomimetic designs, such as the use of leaf abscission to inspire the remanufacturing process (Hacco & Shu, 2002) and biomimetic design for the lunar environment (Davidson et al., 2009) require a systematic search of biological systems.

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Some of the characteristics of biological systems that might be relevant to fuel cell design include:

• Efficient use of materials and energy: biological organisms usually use the minimum amount of energy and materials needed to survive, excessive material and energy use decrease chance of survival (Paturi 1976).

• High tolerance: Living systems can operate in a wide range of conditions. They are able to adapt to variations in their environment. (Affholter and Arnold 1999).

• Environmentally sustainable: Biological systems survive by recycling materials and energy (Benyus 1997).

• Independent, self-regulating: Organisms and cells have brains and are self-controlled. Organisms maintain internal functions through homeostasis—the maintenance of steady levels of metabolism, chemicals and temperature (Galbraith et al. 1989).

• Precise: Biological synthesis is very precise (Paturi 1976) even though they require minimal energy, machinery and control relative to most man-made synthesizing methods (Bond et al. 1995).

• Diverse: The biological world offers a huge scope of solutions and adaptations, from microorganisms to ecological systems.

• Suitable: Biological systems are always well suited to the given environment (Paturi 1976).

• Self-assembling: through mechanisms like synthesis, reproduction, and succession, biological systems automatically create and re-create tissues (Bond et al. 1995), organisms and ecosystems, respectively.

Despite the demonstrated usefulness of biological analogies in design, designers are likely limited by their personal knowledge of biology. Researchers such as Linsey et al. (2007) support the idea that designers require tools and systematic methods to access cross-domain knowledge.

One approach to support biomimetic design involves searching for instances of functional keywords in biology knowledge sources in natural-language format, e.g., books, papers, etc. Matched text excerpts containing keywords are examined for relevant biological phenomena that can be applied to the engineering problem of interest. This method takes advantage of the extensive biological information already existing in natural-language format. A method was developed to use word collocation and frequency analyses to identify biologically meaningful keywords that bridge the different lexicons of the fields of biology and engineering (Chiu & Shu, 2007). Cheong et al. (2008) translated terms of the Functional Basis into biologically meaningful keywords, not obviously related to the functional keywords, to use as search keywords.

We have implemented a part-of-speech and phrase group identification system into a biomimetic search tool. This biomimetic search tool was previously developed to locate biological knowledge in natural-language format by finding occurrences of keywords describing the engineering problem. While difficulties common to natural-language processing occur, this approach does not require the tremendous and somewhat subjective task of categorizing all biological phenomena by engineering function. Thus, this approach can readily take advantage of the enormous amount of biological knowledge already in natural-language format. Figure 1 shows the biomimetic design process.

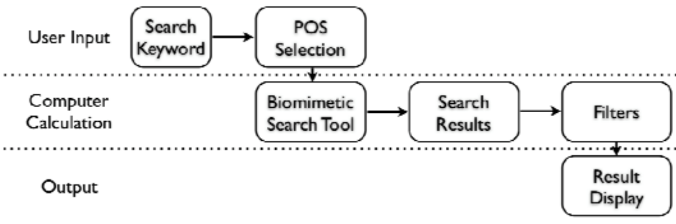

Figure 1. Biomimetic design process workflow.

Our approach of searching for biological phenomena in natural-language format has aided in several design exercises, including design for remanufacturing (Hacco & Shu 2002), the micro-assembly gripper (Shu, et al. 2006), and more recently, dust protection in the lunar environment for the Canadian space agency (Davidson, et al. 2009).

The aforementioned characteristics of biological systems suggest that biology can be a rich source of design ideas applicable to fuel cells. Specifically, solutions inspired by biomimetic designs have the characteristics that are desirable in fuel cell designs, such as passive solutions, self-regulating mechanism, and efficient use of energy.

4. APPLICATION OF BIOMIMETIC DESIGN TO FUEL CELL WATER MANAGEMENT

Proton exchange membrane fuel cells (PEMFCs) are used in low-temperature power generation applications. The polymer membrane inside the PEMFC must be properly hydrated and kept at a controlled temperature of ~70 ^{o}C to efficiently conduct protons. The proton conductivity of the polymer electrolyte membrane is directly proportional to its water content. Fuel cell operating conditions and membrane characteristics determine the membrane water content (Fuel Cell Handbook, 2000).

Water, a product of the fuel-cell reaction, must also be removed from the cathode side to prevent congestion, or flooding, in the oxidizer flow channels. At high current densities, the rate of water production can tax the ability of the cathode flow field to remove it. Liquid water can build up and stagnate in the flow channels. This reduces the flow of oxidizer to the cathode and reduces the overall efficiency of the fuel cell. A mechanism that removes accumulating liquid water continuously from the flow channels is required. Desirably, the mechanism will use minimum or no energy and will not have a drying effect on the membrane. A common strategy to minimize flooding in a serpentine flow field is to supply a high oxidant flow rate to force liquid water out of the system. However, the small flow channel cross-section (~1mm x 1mm) and the long flow channel length (meters) require a relatively high inlet oxidant pressure. Use of parallel flow channels can reduce the pressure differential across the flow field by orders of magnitude compared to serpentine channels (Litster et al., 2007). However, parallel channels are susceptible to uneven air flow through the channels with potentially complete blockage of one by flooding, which degrades performance.

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Typically, the PEMFC's bipolar plate contains the water removal mechanism. The focus of this paper is to generate concepts for liquid water removal that can be incorporated into a bipolar plate. The biomimetic design approach for concept generation is demonstrated and used to identify possible liquid water removal solutions.

4.1 Existing water removal strategies

A number of researchers have achieved recent advances in PEMFC water removal:

Litster et al. (2007) incorporated an electro-osmotic pump for water removal. This active water management system prevent flooding and provides rapid recovery from severe flooding. A power density improvement of up to 60% at low air stoichiometry was observed.

Metz et al. (2008) described a capillary droplet actuation system for passive water removal. Excess liquid water is transported away from the oxidant flow channel by geometry induced capillary force.

Strickland et al. (2009) demonstrated a passive water management system using in-situ polymerization to mold and deposit wicks on the channel walls. The integrated wicks increase performance for very low air stoichiometry.

These advances notwithstanding, there is still room for additional concepts for water management. Accordingly, biomimetic design methodology was applied to the problem.

5. BIOLOGICAL ANALOGIES

In this section, we describe two biological phenomena relevant to developing a novel passive water management system. The biological phenomena were found using methodology previously developed for finding suitable search keywords (Cheong et al., 2008). The keywords were then systematically processed to locate relevant search results in a natural-language corpus (Ke et al., 2009).

5.1 Initial search keyword

The design objective is to transport water efficiently. The corresponding quality that can accurately describe this design objective was initially unclear to the authors. Therefore, WordNet was used to explore and identify potential search keywords. The initial starting keyword is "wet", chosen for two reasons: first, "wet" is a common adjective with several related adjectives within the WordNet hierarchy, thereby increasing our chances of finding more relevant search keywords. Second, "wet" loosely describes the design objective, increasing the resulting excerpts' chance of containing biological phenomena that can lead to design concepts.

Our past work found that WordNet relationships are excellent sources for alternative keywords (Chiu & Shu, 2008, Vakili & Shu, 2001). Antonyms and synonyms are key organizational relationships for adjectives. Figure 2 shows the partial exploratory path taken to find additional search keywords within WordNet.

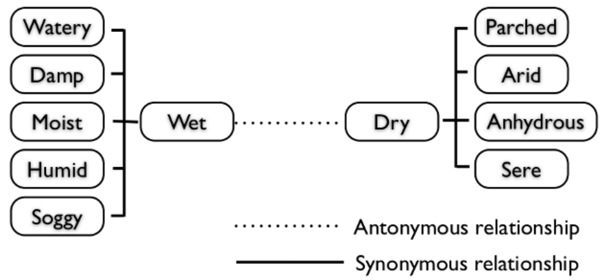

Figure 2. Related words of "wet" based on WordNet v3.0 relationships.

5.2 Water transport in plants due to cohesion-tension theory

This phenomenon was found using the keyword "evaporative", and is described in the following partial excerpt:

> *Transpiration, the **evaporative** loss of water from the leaves, generates a pulling force (tension) on the water in the apoplast of the leaves* (Purves et al., 2001).

We chose to investigate this particular phenomenon due to the similar water transport difficulty faced by both leaves and fuel cell bipolar plates. Specifically, both leaves and fuel cell bipolar plates require a mechanism to move water through small channels with relatively high flux.

In cohesion-tension theory, which was first proposed by H.H. Dixon (1914), water is drawn up in plants by transpiration. Due to the cohesive and adhesive properties of water, as water molecules evaporate from the stoma, they will pull additional water molecules from the lower part of the plant through xylem, a type of transport tissue.

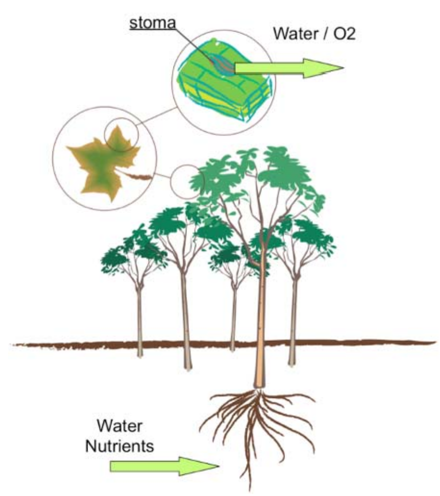

Figure 3. Water transport in plants

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5.2.1 Application to PEMFC water management

The strategy extracted from the cohesion-tension theory is to use a series of passive water transport phenomena to overcome gravity and drag within plants. With the cohesion-tension phenomenon, water can be pulled to a height of more than 100 meters through xylem (Figure 3 and Figure 4).

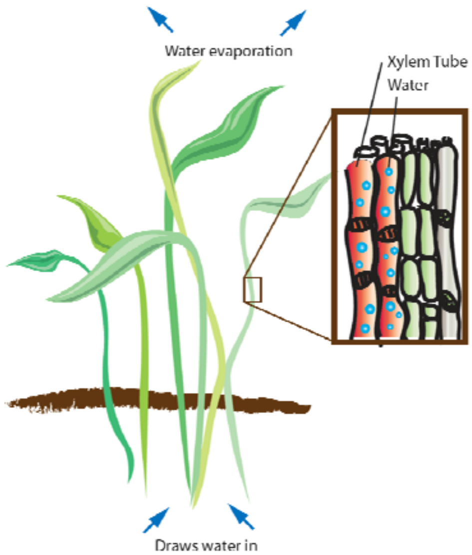

Figure 4. Xylem in plants

5.2.2 Proposed design

A possible physical realization of the above strategy is a xylem like structure which "pulls" excess water away from the flow channels, where one end of the xylem-like structure evaporates water to the atmosphere and the other end of the xylem draws water into the xylem.

5.3 Water transport in nontracheophytes due to capillary action

This phenomenon was found by searching for the keyword “damp”, and was described in the context of the below match:

> *They (nontracheophytes) often are found on* ***damp****, cool ground, where they form thick mats* (Purves et al., 2001).

We chose to investigate this particular excerpt due to the similar operating environment and water transport objective between nontracheophytes and fuel cell bipolar plates. Specifically, both nontracheophytes and fuel cell bipolar plates operate in damp environments and require a mechanism to transport the moisture through a barrier.

The text section corresponding to the above match explains that nontracheophytes (i.e. liverworts, hornworts) usually inhabit moist environments but lack vascular tissue to circulate liquid (Purves et al., 2001). Nontracheophytes contain several physical features that assist external water conduction. For example, overlapping leaves, rhizoids (shown in Figure 5), ridged leaves, and tiny warts help water conduction by maximizing the effectiveness of capillary action.

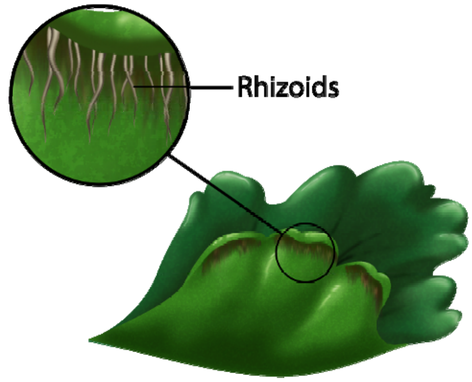

Figure 5. Rhizoids on liverworts

5.3.1 Application to PEMFC water management

There are several strategies that can be extracted from nontracheophytes’ method of water transport. The main identified phenomenon is capillary action due to geometrical features. The capillary action describes the sufficient surface tension acting on the liquid to overcome gravitational and intermolecular forces. In nontracehophytes, capillary action helps in conducting external water, such as collecting morning dew. Similarly, in PEMFC, implementing capillary action can help with overcoming removing liquid water from flow channels.

5.3.2 Proposed design

Geometrical features induce capillary action and are relatively easy to replicate physically. There are multiple capillary action-inducing geometries recognized from the identified phenomenon. Several strategies, such as incorporating micron-sized posts and ridges have already been investigated by Ou et al. (2004) with positive results. However, Ou's method of making the channels hydrophobic cannot remove water in situ. An in situ water removal method can be implemented by using capillary action to promote water movement to a dedicated water removal channel, de-coupling the flow channel's function. The proposed design feature to implement capillary action arose from a laboratory observation that a component damaged by abrasion very effectively removed water. Closer examination of the surface roughness created by the abrasion inspired the micro-channel idea.

6. PHYSICAL IMPLEMENTATION OF IDENTIFIED BIOLOGICAL PHENOMENA

In this section we present a passive water management system that was designed using the biomimetic search tool, and suggest how it can be integrated into the design of a fuel cell. The present design is for a true parallel flow channel PEMFC with a modified cathode flow channel as shown in figure 6. The added features, micro channels and polyethersulfone (PES) hollow tubes, enable passive water management to the PEMFC.

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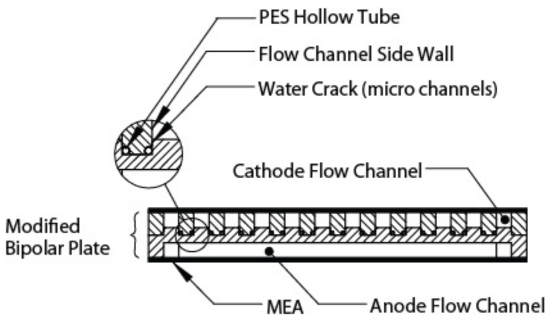

Figure 6. Proposed PEMFC bipolar plate configuration (not to scale)

6.1 Water Gap/Micro channel

Similar to ridged leaves, micro-channels maximize capillary action and direct excess water away from the flow channels. In the physical prototype, arbitrary abrasions on the prototype surface induce capillary action. The arbitrary abrasions are similar to the water transport features on nontracheophytes.

Experiments are also planned with micro-channels in place of random abrasions. Future prototypes will incorporate capillary action inducing features with consistent geometrical patterns. Micro-channels are situated perpendicular to the oxidant flow, with one end connecting the flow channel while the other end connecting to a water removal channel. Figure 7 shows a possible implementation of the micro-channels.

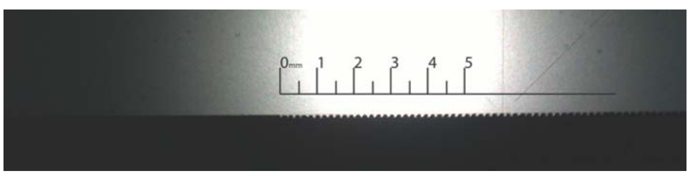

Figure 7. Back-lit photograph of the micro-channel features that induces capillary action

6.2 PES hollow tube

PES hollow tubes function similarly to xylem in plants, efficiently transporting water from the flow channels. Like xylem, PES hollow tubes must be continuous and under tension to maximize water flux.

6.3 Water removal from PEMFC

Figure 8 shows a sample apparatus to achieve water removal from the fuel cell. Two valves control the air inlet path: air can either be humidified by the wet PES hollow tubes by forced convection or air can be let into the fuel cell unmodified. Figure 8 shows a possible water removal method by forced convection and transpiration; other water removal methods, such as conduction (e.g. a sponge), are also applicable.

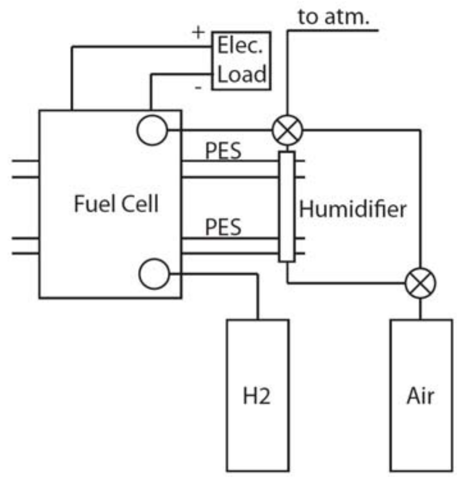

Figure 8. Sample water removal diagram

6.4 Domain mapping

Figure 9 shows how the biological phenomena are translated into the engineering domain.

Biological Domain		Engineering Domain
Xylem and water transport in plants	>	PES hollow tube for water removal
Ridged leaves	>	Machined micro-channels induce capillary action
Transpiration	>	Convection

Figure 9. Mapping from biological phenomena to redesign of PEMFC bipolar plate

7. EXPERIMENTAL SETUP

A simple prototype representing the flow field structure was created to expediently validate the proposed concept prior to application in a fuel cell. The prototype, shown in figures 10 and 11, was demonstrated on a test apparatus with low air flow rates and low inlet pressure. Preliminary results show total recovery from flow channel catastrophic flooding within seconds.

The prototype consists of a top cover, made of acrylic to aid visual inspection, side walls, made of machined aluminum 6061-T6 plates for providing clamping pressure for the silicon seals (not shown), and a prototype piece with integrated micro channels and PES hollow tube slots. The PES hollow tubes (0.26mm OD) are manufactured by Membrana, and used in a hemodialysis unit (Baxter Diapes PES-150). Figure 12 shows a cross section view of the PES hollow tubes that were cut by freezing with liquid nitrogen and cutting with a knife.

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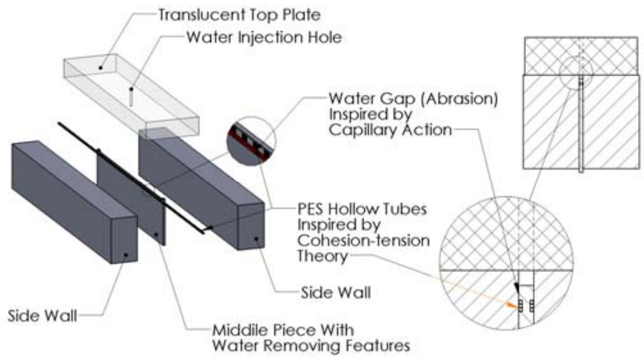

Figure 10. Prototype Detail

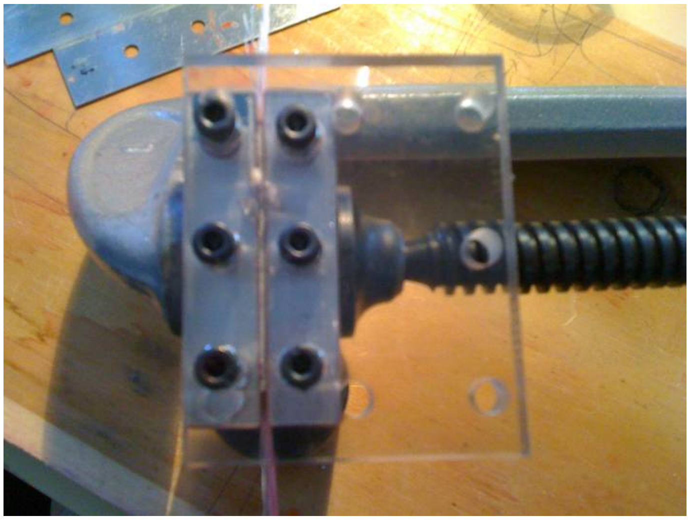

Figure 11. Physical Prototype

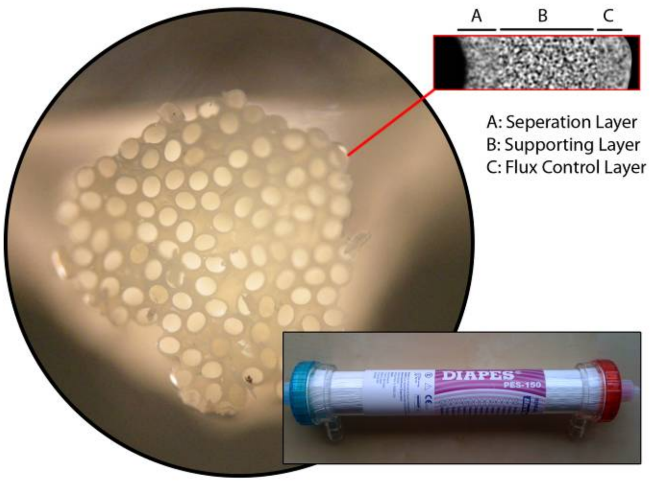

Figure 12. PES hollow tubes from Diapes PES-150

7.1 Test apparatus and experimental setup

Figure 13 illustrates the experimental setup. The test apparatus consists of the following components:

- Chromatography microsyringe – for water injection
- Side wall/top cover - cathode flow channel
- PES hollow tubes - water removal
- Prototype - flow channel with micro channels
- C-clamp - assists sealing
- Fan - simulates water removal by forced convection

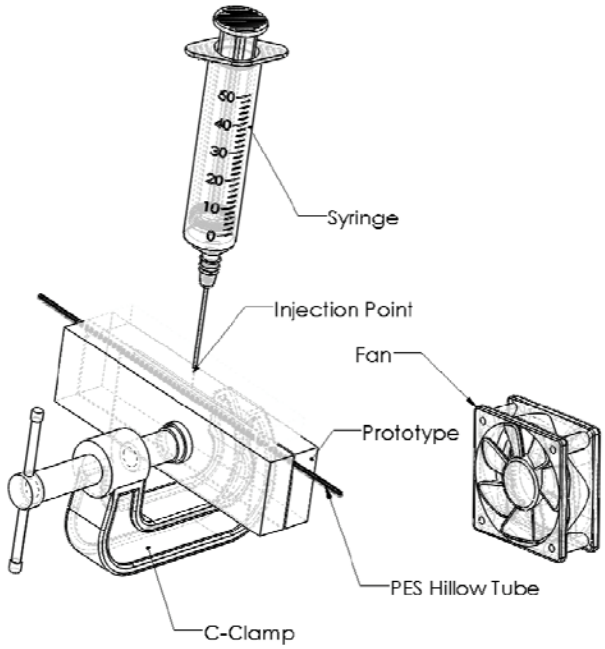

Figure 13. Experimental Setup

7.2 Procedure

The flow channel has the dimension of 1mm x 1mm x 40mm and a volume of 40μl. All machined parts are polished to ensure even sealing contact. Six PES hollow tubes, three on each side as shown in figure 10, are used in the prototype.

The prototype was tested nine times under each of the three fan settings: high speed, low speed, and off. The fan is located 40mm away from the water removal end of the PES hollow tubes. A chromatography syringe was used for water delivery of 10μl of water into the flow channel. Two time intervals were recorded for each experiment. The first time interval recorded was the water injection duration. This is important because if the water was injected too slowly, the injection rate might be slower than the water removal rate. If the water was injected too rapidly, the injection pressure might undesirably aid in the water removal process. We waited 60 seconds between each test to let residual water from the previous test settle.

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A total of 27 additional tests (nine for each fan setting) were performed to evaluate the water removal effect when the PES hollow tubes are nearing their maximum carrying capacity. Under this test, a much larger amount of water - 35µl - was injected into the flow channel continuously.

8. EXPERIMENTAL RESULTS

8.1 Correlation between injection rate and water removal rate

T-tests were performed to verify there was no correlation between the injection rate and water removal rate for each test. The t-test results are 1.46, 8.47 and 21.13 with a degree-of-freedom of 16 for the three different fan settings. All tests indicate with a high confidence level that there was no correlation between water injection rate and water removal rate.

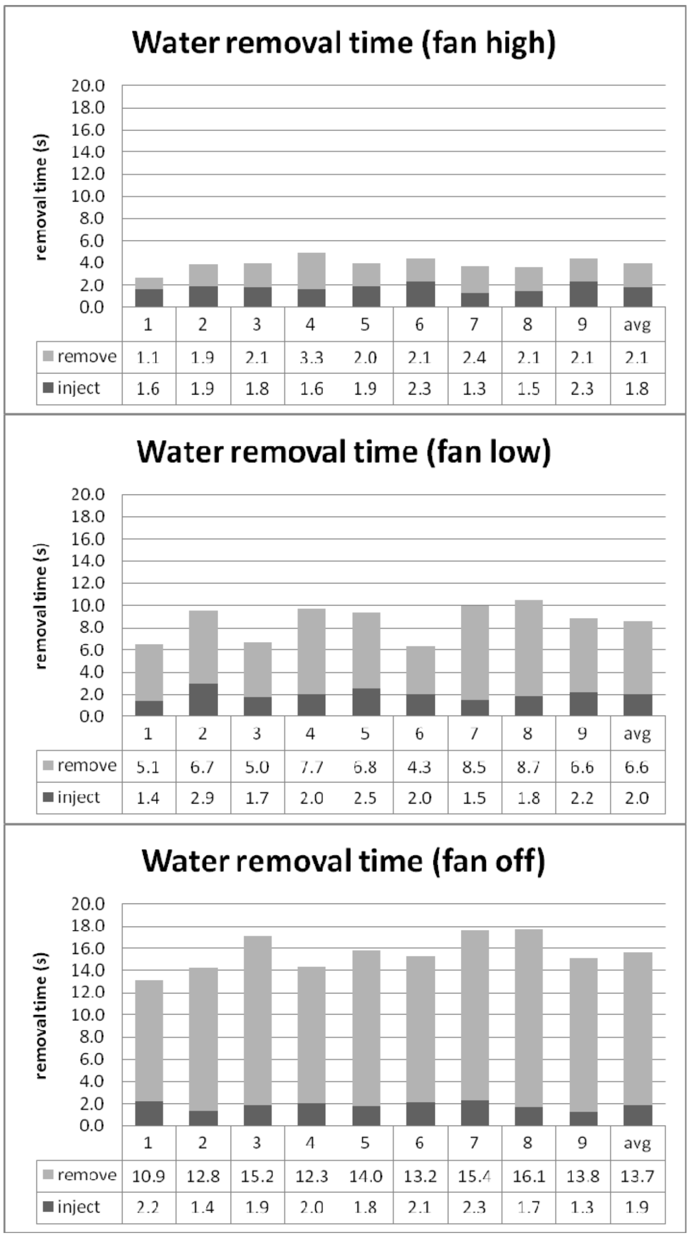

Figure 13. Time required to remove water

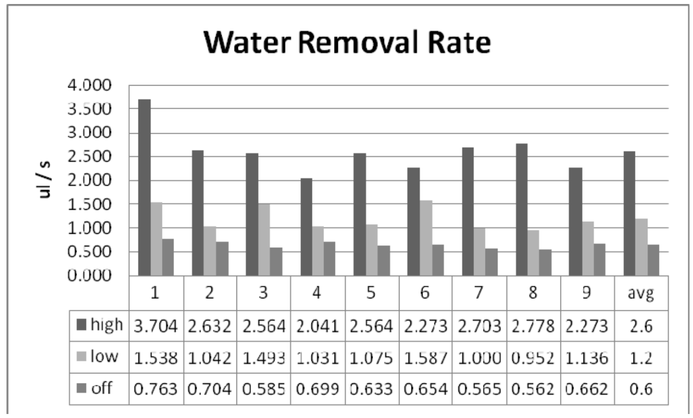

Figure 14. Water removal flow rate

8.2 Time required to completely remove water from the flow channel

Figure 13 shows the time required (in seconds) for the test apparatus to completely remove 10µl of the injected water from the flow channel. Complete water removal is defined as no visible water in the flow channel. The average water removal time for the three fan settings are: high: 3.9s, low: 8.6s, off: 15.6s.

8.3 Water removal flow rate

Figure 14 shows the water removal rate. As expected, the water removal rate is positively correlated with fan speed. For high fan speed, the water removal rate is 2.6µl/s, while the water removal rate is 0.6µl/s when the fan is off. Although there is a noticeably slower water removal flow rate when the fan is off, we believe that under normal fuel cell operations, the implementation of micro-channels and PES hollow tubes will help with water management in PEMFC with or without forced convection acting on the PES hollow tubes. No visible water droplets were observed during these tests.

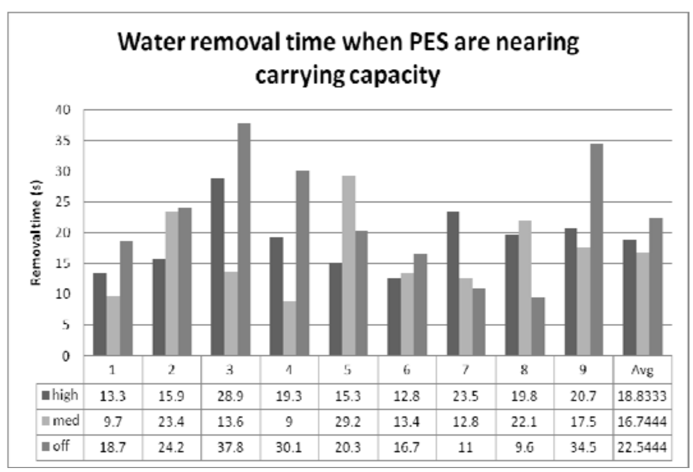

Figure 15. Water removal flow rate when PES are nearing maximum carrying capacity

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8.4 Water removal rate when PES are near maximum carrying capacity

When the PES hollow tubes reach their maximum carrying capacity, water will not be able to move effectively from the flow channel to the PES hollow tube and water droplets are formed at the end of the PES hollow tubes. Water droplets fell from the PES hollow tubes when the droplets' size reached a critical dimension where gravity and air resistance overcame the droplets' surface tension acting on the PES hollow tubes.

This observation can partially explain the variability displayed in figure 15 between each test's water removal times. When plotted in a graph, all three fan settings water removal times result in a repetitive pattern as shown in figure 15, where the water removal time steadily increases and then decreases. The increase in water removal time corresponds to the water buildup (e.g. droplet forming) in the PES hollow tubes, and the decrease in water removal time corresponds to the water removal (e.g. droplet dropped due to gravity) from the PES hollow tubes.

When we analyze the standard deviation of the water removal time, we found that when the fan is on, the standard deviation is 6.02, compared to 9.94 when the fan is off. We believe the difference in the standard deviation is due to the forced convection method of water removal being a relatively continuous process when compared to the water removal process when the fan is off, which mainly relies on gravity. The difference in water removal mechanics is directly observed in the experiments, where water droplets detach from PES hollow tubes more frequently. The droplets are also observed to be physically smaller when the fan is on.

9. DISCUSSION AND FUTURE WORK

We have designed and tested a single channel PEMFC bipolar plate with passive water removal mechanisms. Water removal rates from the test rig show that the new bipolar plate design can passively prevent flooding and recover from catastrophic flooding. This could result in lower air stoichiometry by eliminating the need for using excess air flow to remove water. Despite the advantages of this design, we must note the following drawbacks:

a. Manufacturability of the current design is under investigation. Strict tolerances and miniaturized components of the new bipolar plate add to the manufacturing and assembly cost of a PEMFC.

b. Durability of the PES hollow tubes limits viable applications of the current design (i.e. automotive applications are not currently feasible due to potential damages due to vibration).

c. Added complexity to the PEMFC might not justify the increase in performance using the new bipolar plate design.

Due to the dynamic nature of fuel cell water transport phenomenon, performance in an actual fuel cell might differ from the anticipated performance increase described in this paper. Future work includes implementing the current design into a fuel cell to comprehensively evaluate the performance impact. Work is also underway to solve the manufacturability and durability problems of the current design.

10. CONCLUSION

Proper water balance is a consistent challenge in PEMFC development. The unique technical requirements serve as excellent motivation to use biomimetic design methodology to aid in the design of a PEMFC water management system. We believe that biology is a good source of design analogies for the PEMFC water management system; biological systems have many characteristics that might benefit fuel cell designs including efficient use of materials and energy, environmental sustainability, and the ability to self-regulate.

Using biomimetic design methodology, we identified two biological phenomena as good stimuli for design concepts. After several design sessions, we have created a prototype that can passively remove water from parallel flow channels. The design combines micro-channels and PES hollow tubes for water removal, similar to the capillary action inducing physical features of nontracehophytes and the cohesion-tension phenomenon in xylems.

A prototype based on the identified biological phenomena demonstrated promising results. The prototype was able to passively remove water at 0.6μl/s from a single channel plate with a 1mm x 1mm cross section. The prototype was able to recover from a simulated catastrophic flooding in seconds with stagnant inlet flow and no inlet pressure.

Ongoing research is focused on creating a comprehensive prototype to better integrate our concept into an actual fuel cell. Future designs will also focus on the cost reduction and manufacturability of our concept. In addition, we are applying the biomimetic design methods to solve other fuel cell issues including membrane design, fuel storage and cell durability.

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