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WATER MANAGEMENT CONCEPTS IN PEMFC WITH BIOMIMETIC AND TRIZ DESIGN METHODS

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ABSTRACT

Excessive water accumulation at the cathode can cause cathode flooding in a fuel cell. Two design methodologies, TRIZ (Theory of Inventive Problem Solving) and biomimetic design, were applied to address the problem. A concept generated from TRIZ involves reversing the direction of cathode flow periodically to introduce dryer gas to the previous outlet, where it is previously saturated, with the humidified gas exiting the previous inlet. The concept is intended to reduce the potential for a channel to flood. A prototype apparatus was created to evaluate the concept. It consisted of a cell with a bare Nafion™ membrane pressurized by water on one side and with air flowing on the other side. The prototype apparatus demonstrated a potential loss of overall water removal efficiency in air. Therefore, the flow direction reversal concept may not benefit an actual fuel cell. A second concept generated from the biomimetic design method involves gathering liquid water with cavities and directing the liquid water out of the flow channels. Cavities for water collection in the flow channels of a bipolar plate are created in two configurations. In the first configuration the cavity is created by extending a straight channel from the u-bend in the channel. In the second configuration, the cavity is created by a hole perpendicular to the channel into the bipolar plate. Once the liquid water is collected at cavities, the water is directed out of the cell with wicking materials. A prototype with injected liquid water demonstrated the potential benefits for a fuel cell.

INTRODUCTION

The proton exchange membrane (PEM) fuel cell is a promising energy conversion device. When the hydrogen used to fuel it is generated from renewable energy sources, the PEM fuel cell can generate pollution free electricity. This low temperature fuel cell can be started faster than other fuel cell types that require pre-heating. Quicker start up and lower operating temperature are beneficial in many areas, such as portable devices. However, PEM fuel cell operation at temperatures below 100 $^{\circ}$C is not without difficulties. Liquid water can form within the fuel cell and block transport of reactants to the active sites. Minimizing and/or removing liquid water can prevent fuel cell performance deterioration. Many researchers have tackled this challenge of water management by modifying operating conditions or through fuel cell system design, such as adding additional structures to improve water removal, and membrane electrode assembly (MEA) modifications to achieve optimal performance [1]. This paper describes the application of two formal design methodologies – the Theory of Inventive Problem Solving (TRIZ) and Biomimetic Design - to overcome the challenge of cathode water removal. These methodologies can bring a different perspective to the water management problem.

BACKGROUND

Design is a creative process that depends on insight and the ability of the designer to synthesize concepts into reality. A successful design is often attributed to a “Eureka moment”, but the task of synthesizing new concepts can sometimes be difficult. Researchers have developed design methodologies to inspire our creative thinking. Two such methodologies, the Theory of Inventive Problem Solving and Biomimetic Design, are used to trigger ideas to overcome the water management problem. The two methodologies, described in the following paragraphs, introduce stimuli from two different regimes to generate possible concepts: TRIZ provides stimuli from existing technologies, while biomimetic design provides stimuli from our understanding of natural phenomena.

Theory of Inventive Problem Solving (TRIZ) – Altshuller [2] first began to develop TRIZ in the 1940’s from studying more than a million patents. The origin of the acronym, TRIZ, is "Theory of Inventive Problem Solving" in Russian. The acronym TIPS from the English translation is also commonly used. Altshuller and his colleagues derived a list of 39 engineering parameters and 40 engineering principles from the generalization of methods used to solve the engineering problems in the patents. One method for using TRIZ is the classical contradiction table. The descriptions for the engineering parameters and engineering principles used for this paper are from the textbook, *Product Design Techniques in Reverse Engineering and New Product Development* by Otto and Wood [3]. The contradiction table method first requires the identification of contradictions from a given engineering problem. Two parameters are identified from each contradiction regarding what is to be improved and what is being degraded in the process. Each parameter is translated into one of the 39 engineering parameters. The engineering parameters are then used in the contradiction table, where the table provides suggestions on which engineering principles can improve the current problem. Each suggested principle is then examined to generate concepts.

Biomimetic Design – Biomimetic design is the use of biological knowledge and phenomena to solve engineering problems. Some classic examples include the invention of the airplane from observing the movement of a vulture in flight, and the invention of Velcro from imitating the hook structures of burrs, that allow them to cling onto animal fur and people's clothing. The link between engineering problems and biological knowledge may be limited by the designers' knowledge and experience. Vakili and Shu [4] developed a systematic method to link engineering problems with biological knowledge, which leads to generation of design solutions from biology. The methodology involves a plain language search on written biology knowledge to find relevant biological phenomena to be used as analogies. Keywords that describe the functionalities of the engineering requirements are first created. Then a keyword search is performed on the text, *Life, the Science of Biology* [5]. The search returns biological phenomena containing the keyword and the phenomena are then used as inspirations for design solutions. Success in applying the biomimetic design method was demonstrated in design for remanufacture [6], assembly of micro-parts [7], and mechanical locking joints [8].

CONCEPT GENERATION

The two design methodologies described above have been applied to the problem of water management in PEM fuel cells.

Flow reversal concept from TRIZ – Operating a fuel cell at a higher power density will increase the water production rate. Water can be produced at a rate higher than the reactant gas can carry away. The increase in liquid water prevents reactants from reaching the reactive sites, thus decreasing the power output. A conflict arises where high power output is desired, but accumulation of water increases as a result. The conflict was translated into TRIZ's engineering parameters, where the quality to be improved is the power output, Parameter 21, and the undesired side effect is quantity of substance created, Parameter 26. With the parameters and the contradiction table, the resulting engineering principles were Principles 4 - Asymmetry, 34 – Discarding and regenerating parts and 19 - Periodic action. Principles 4 and 34 did not lead to new ideas. When applying the principle of asymmetry, focus was fixed on a concept previously generated with the biomimetic design method relating to plant's solute excretion [9], where a flow field design incorporated channels branching like plants. Principle 34 led to ideas focused on recycling of water. The concepts were related to commonly existing solutions for recycling water in wet exhaust gas to humidify the incoming dry gas.

Principle 19, the principle of periodic action stated: "use periodic or pulsed actions, change periodicity" [3]. This led to the idea of periodically reversing the flow of air through the cathode side of the fuel cell. Pulsing of the current load was also considered as a possible solution, but a smooth current output is normally desired, so this type of pulsing is not useful. Instead, periodically reversing the direction of air flow was considered. In normal operation, air gains moisture as it passes along a cathode channel. The closer to the exhaust port along the cathode channels, the more the water vapor builds up. As saturation is approached, the air's ability to carry additional evaporated water away is reduced. The ability of a gas stream to carry away evaporated water in a convective flow is an exponential decaying function with distance. That is, a higher rate of water can evaporate into the oxidant flow near the entrance, where relative humidity is low, than near the exhaust, where the gas is more saturated. By reversing the direction of air flow, a dryer gas is introduced through the outlet to allow better moisture carrying ability of the oxidant flow through a region where water may have previously accumulated. Therefore, periodically reversing the cathode air flow in the fuel cell can potentially reduce the amount of accumulated liquid water.

A literature review reveals another fuel cell design that can be said to operate using the principle of periodic action. Nguyen et al. [10] demonstrated a fuel cell that operated on a periodic change of state. Their design did not involve changing the flow direction, but instead sequentially gated the exhaust ports in a 3-cell PEM fuel cell stack. Only one gate at time is open in a sequential order along the stack, to ensure adequate reactants to each cell and to flush liquid water out of each cell with the sudden high flow with opening of the gate. While our design and Ngyuen et al.'s design both operate using the principle of periodic action, our generated concept relies on a different mechanism.

Liquid water collection concept from biomimetic design – When a fuel cell begins to flood during high current operation, water is not evaporating at a fast enough rate to be removed by the cathode gas flow. Thus, water droplets start to form in the flow field channels. A two phase flow, air-water vapor mixture and liquid water, is developed. As more water accumulates along the channels, severe liquid water build up can develop which causes channel blockage.

A biomimetic design keyword search was performed using the keyword "direct". "Direct" was generated as a keyword based on how a fuel cell is required to "direct" the reactants, electrical current, and gaseous and liquid water in and out of the cell. The keyword search returned a potential match with auditory systems, as follow:

> "Auditory systems include **special structures** to **gather** sound waves, **direct** them to the sensory organ…" (p803). [5]

Auditory systems in organisms do not appear in the entire body of the organism. Instead, only a specific location is dedicated for hearing. By mapping the objects in the biological phenomenon with objects describing the engineering problem to the auditory system in the returned passage, a new fuel cell design concept was developed. The passage was mapped as:

> A fuel cell can include **special structures** in its flow fields to **gather** water droplets and **direct** the droplets to an area in the cell where they can be removed more readily.

The usage of wicks was the primary thought for directing the liquid water out of the cell. However, the concept for special structures only appeared after the realization that liquid tends to remain at the corners of the flow channel in a two phase flow. This realization was based on observations of experiments with the apparatus built for examining the flow reversal idea. A small amount of liquid water seemed to collect at the corner more often, and we theorize that it might be harder for liquid water to turn the corner than air due to the liquid's higher inertia. A cavity could be created by extending the straight flow channel past a u-bend, as illustrated in Figure 1.

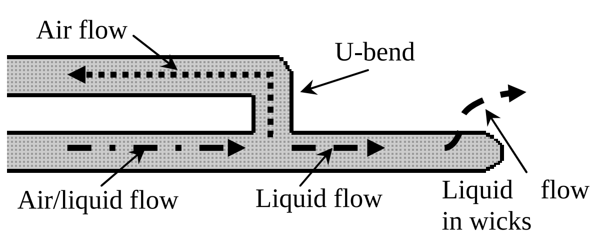

Figure 1. Liquid water collection concept – channel extension idea.

A drawback of extending the flow channels is that the extensions require extra planar area to accommodate the feature. This in turn can lead to an increase of membrane material use or a reduction of the channel area exposed to the active membrane area. In order to reduce the planar area usage, an alternative is to create the cavities as wells. Holes can be created perpendicular to the planar surface of the channel into the bipolar plate as shown in Figure 2. The wells do not rely on the inertia of liquid as in the extension concept above. They simply act as connections between the wicks and the channels' surface.

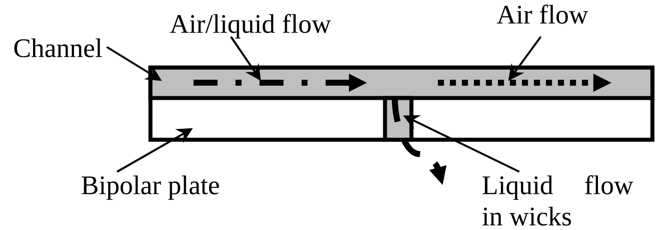

Figure 2. Liquid water collection concept – channel well idea.

Various researchers have proposed wicking materials for water removal and management. Litster et al. [11] demonstrated an active system with a porous bipolar plate and an electro-osmotic pump to draw out liquid water. Strickland and Santiago [12] created a flow field with polymer wicks molded in. In order for the flow channel's dimension to remain, the polymer wicks displaced some exposed land area for electrical contact with gas diffusion layer. The layer of polymer can potentially becomes an insulation limiting the heat transfer from the reaction to the coolant. Ge et al. [13] inserted two strips of wicking material between the gas diffusion layer and the channel to redistribute liquid water within the channel to humidify incoming gas. Ke et al. [14] proposed a land and bipolar plate detached design. Strands of polyethersulfone (PES) hollow fiber, a low cost wicking material commonly used in medical applications, were sandwiched between the sectional surface roughened land and bipolar plate. Liquid water is drawn through the roughened surface by capillary effect into the PES strands and then directed out of the cell.

These researchers attempted to cover the entire cell with water removing materials, but the current concepts attempts to only to remove liquid water at specific locations where required. That is to minimize the disturbances to the internal electrical contacts and the use of wicking material.

EXPERIMENTAL SETUPS

Simple experiments were conducted to evaluate the two concepts generated by TRIZ and by biomimetic design.

Flow reversal concept (TRIZ) – There are many modes of water uptake at the cathode: these include water production from chemical reaction, electro-osmotic drag when protons travel across a Nafion™-based membrane, back diffusion from cathode to anode due to partial pressure, and inlet humidity of the gases. In order to quickly verify the effect of cathode air flow direction reversal, a simplified apparatus was set up involving an apparatus that releases water at the membrane surface as in a fuel cell but without chemical reactions or electron flow. The schematic of the apparatus is shown in Figure 3. Water on one side of a Nafion™ membrane is pressurized to create a large partial pressure gradient across the membrane. The amount of water released on the air side is determined by the temperature, the water side pressure and the thickness of the membrane.

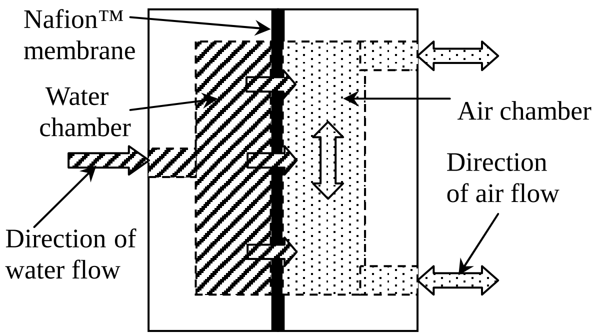

Figure 3. Flow direction reversal apparatus schematic.

The apparatus consisted of a two chamber cell, in which liquid water is transported through a gas-water separating media, a Nafion™ membrane. One chamber, the water chamber, contained pressurized liquid water in a dead-end mode. Another chamber, the air chamber, had air flow across the surface of the water-transport media. The air chamber has a dedicated inlet and a dedicated outlet for each of the forward and backward flow of the reversal.

The main function of the apparatus was to allow water to appear on the surface of the membrane, in order to simulate the water production in the cathode of an actual fuel cell. A serpentine flow field with dedicated inlets and outlets was milled directly on an acrylic back plate of the air chamber, shown in Figure 4 with matching inlets and outlets labeled. The channel had a dimension of 1 mm wide by 1mm deep and a land width of 1 mm.

A Toray coated carbon paper was placed on the air chamber side of the Nafion™ membrane. The carbon paper is in direct contact with the air flow field, simulating an approximately 5x5 cm^2 active area in an actual fuel cell. The membrane was supported on the water chamber side with a wire mesh. The apparatus was sealed from leaks with either silicone or EPDM (Ethylene Propylene Diene Monomer) rubber. The experiment was performed with the apparatus placed in an insulated space convectively heated to 55 $^{\circ}$C. A compressed air tank supplied dry air to the air chamber with atmospheric back pressure. In a non-flow reversing situation using dry air could lead to membrane drying at the inlet. However, in a reversing flow, all parts of the membrane are alternately exposed to air with high moisture content so membrane drying is lessened. The use of dry air maximizes water removal potential.

A water supply line, pressurized to 5 psig by a compressed gas tank, supplied water to the water chamber. The water level was recorded by reading a scale through the transparent water line. The air flow rate of 0.6 slpm was adjusted with a needle valve and a rotameter. The outlet humidity was monitored with a Vaisala handheld humidity probe, HMP75B.

Liquid water collection concept (Biomimetic design) – A prototype test cell was created to demonstrate both the channel extension and well concepts. A short

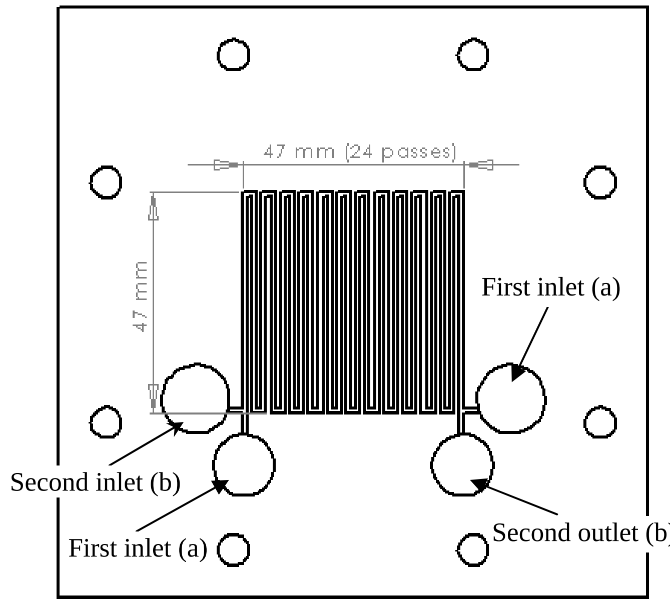

Figure 4. A 1.1m serpentine flow field for the flow direction reversal apparatus.

serpentine channel having dimensions 1mm width x 1mm depth x 94.5mm long with a 1 mm land was milled on an acrylic plate with an extension cavity and a well cavity embedded along the channel as illustrated in Figure 5.

The extension was milled at the end of the second long section in the channel from the inlet. A well of the same diameter as the channel width was drilled on the third u-bend. Absorbent paper wicks were inserted at both locations to collect liquid water. The extension and well's wicks were

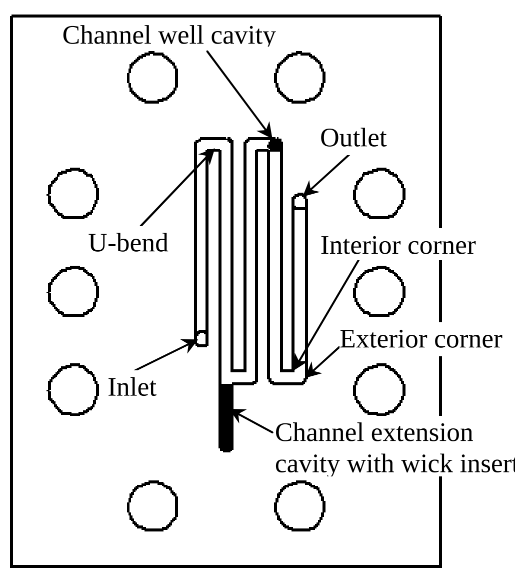

Figure 5. Liquid water collection apparatus.

placed flush or slightly protruding into the channel. The top face of the channels was sealed with packing tape (used as a gasket material) and then topped with a 1/16" thick acrylic sheet to provide a rigid support for the top channel wall. New wicks were inserted prior to each assembly for an experiment. Fresh dyed water droplets were placed into the flow channels with a syringe. The experiments were run with the cell placed vertically as shown in Figure 5. A needle valve and a rotameter were used to set an air flow rate of 0.6 slpm for an assembled cell without any water injected. The flow of air was then subsequently controlled with a solenoid on/off valve. Photographs of the channels were taken before and after for evaluation.

RESULTS AND DISCUSSION

Flow reversal concept (TRIZ) – Experiments were carried out for a non-reversed flow (control) and for flow reversals every 10 seconds and every 30 seconds. The average water uptake for the control experiments (non-switched cathode air) ranged from a mean of 7.6×10^{-7} kg/s to 9.3×10^{-7} kg/s. The average water uptake for the 10 and 30 seconds cases was approximately 1×10^{-7} kg/s (~12%) less compared to the control cases with the membrane NR-211 and NR-212, as shown in **Error! Reference source not found.**. Conversely, there was a slight increase of about 0.17×10^{-7} kg/s (~2%) in average water uptake for the 10 and 30 seconds cases for N-117 compared to the control case was observed.

A linear behavior with respect to the thickness of the membranes was demonstrated with the control cases in **Error! Reference source not found.**. The flow reversal experiments with a 30 second switching interval also exhibited a linear relation with respect to thickness. The slope compared to the control was nearly an order of magnitude lower. Membrane thickness had a lesser effect on the flow reversal cases. On the other hand, the 10 second interval flow reversal case did not show such linearity. The standard deviation of the average water uptake for the 10 second interval experiment, 6.7×10^{-8} kg/s, with a NR-212 membrane was two to three times greater than the NR-211, 2.1×10^{-8} kg/s, and the N-117, 2.9×10^{-8} kg/s, with the same flow reversal interval.

The outlet relative humidity readings, shown in **Error! Reference source not found.**, generally had a similar linear relationship with membrane thickness for the control and the 30 seconds interval cases. A non-linear relationship was found for the 10 seconds interval. For this case, there were disagreements between the water uptake and the outlet relative humidity for the different thicknesses. NR-212 water uptake was higher than that of NR-211, while its relative humidity was lower than NR-211.

The relative humidity might not be directly comparable between different reversal intervals, because of the saw-tooth like humidity readings. The global peaks were taken as the relative humidity readings. Moreover, the sharp saw-tooth like readings for the 10 seconds interval indicated non-stabilized outputs, given the rated response time of the humidity probe is 17 seconds. The saw-tooth like readings was due to the shared channel path between first inlet and second outlet, and second inlet and first outlet. At a switching of the flow direction, some dry inlet gas left in the connecting tubing (between an apparatus inlet port and a valve) would flow directly into the outlet without passing the flow channel. The wasted dry gas would also affect water uptake results, but it was probably relatively negligible. Overall, no water droplets visible to the naked eye were observed in the channels for all the experiments.

A non-parametric Kruskal-Wallis test was employed to compare the water uptake between the different membrane thicknesses and flow reversal intervals. All analyses were performed using SAS v9.1 for Windows and all reported p-values were 2-sided. A p-value < 0.05 was considered significant.

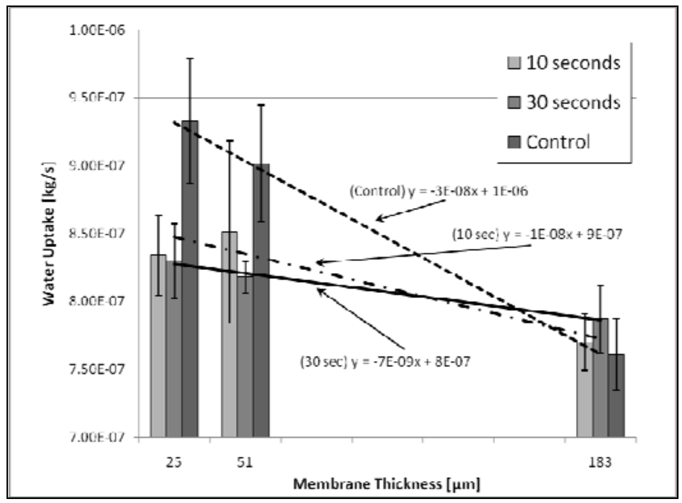

Figure 6. Water uptake for flow reversal (10 & 30 sec) and membrane thickness (Control – NR-211, NR-212, N-117).

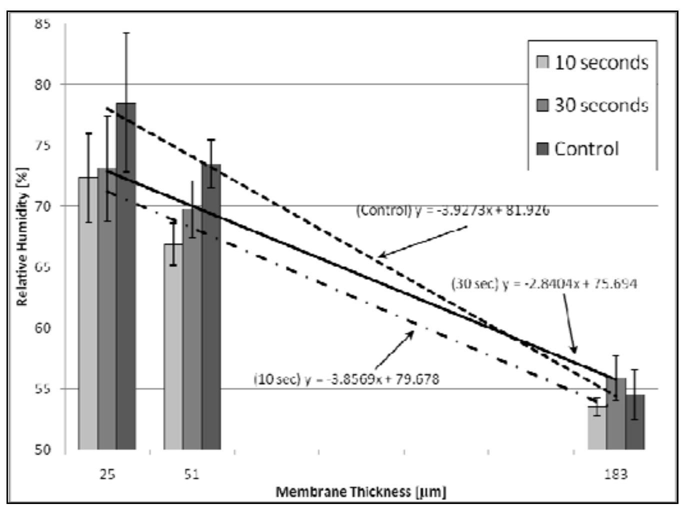

Figure 7. Outlet relative humidity for flow reversal (10 & 30 sec) and membrane thickness (Control – NR-211, NR-212, N-117).

The results presented in Table 1 suggest that there is a significant interaction between the average water uptake and the membrane thickness. Therefore, individual cases were analyzed.

The water uptake for the control cases is dependent on the membrane thicknesses, while the water uptake for 10 and 30 seconds intervals were not statistically different among the various membrane thicknesses.

The water uptake with respect to the flow reversal experiments was significantly different for NR-211 cases only; the water uptake for the 10 and 30 seconds intervals was less than the control case for the NR-211 membrane. The NR-212's water uptake at 10 seconds flow reversal case seemed to be less than the control case, but the water uptake differences were not statistically significant. The N-117's water uptake for the control and flow reversal cases seemed to be relatively similar. Thicker membranes seem to have a smaller effect on water uptake for both the non-flow reversal (control) and the flow reversal cases.

Table 1. A non-parametric Kruskal-Wallis statistical method performed on water uptake at different reversal intervals and thicknesses.

(N = 27)	Mean water uptake [kg/s]			
	10 sec reversal	**30 sec reversal**	**Control (non-reversal)**	**Kruskal-Wallis Pr>Chi-Square**
NR-211	8.34E-007	8.30E-007	9.33E-007	0.0069
NR-212	8.51E-007	8.18E-007	9.02E-007	0.1277
N-117	7.70E-007	7.87E-007	7.61E-007	0.2048
Kruskal-Wallis Pr>Chi-Square	0.0899	0.1469	0.0005	**Interaction** 0.0027

The water uptakes for air flow reversal cases were less than that of non-reversal cases for NR-211 and NR-212 membranes, which suggested that flow reversal could potentially reduce the "evaporating power" of the available air stream. Between the different air flow reversal intervals, there were lesser differences between the water uptakes. Thus, different intervals did not affect the "evaporating power" of the air stream greatly. The overall performance effect on an actual fuel cell would need to be tested to verify. This preliminary investigation suggests a potential reduction of performance in removing water from a fuel cell with the flow reversal concept.

Liquid water collection concept (Biomimetic design) – The test cell was assembled with dyed liquid water placed in the channel as shown in Figure 8a. In this demonstration, liquid water was absorbed into the extension (i) and the well's (ii) wicks indicated by the blue area at the two wicked locations shown in Figure 8b. The wicks did not absorb all the liquid placed in the apparatus, instead some

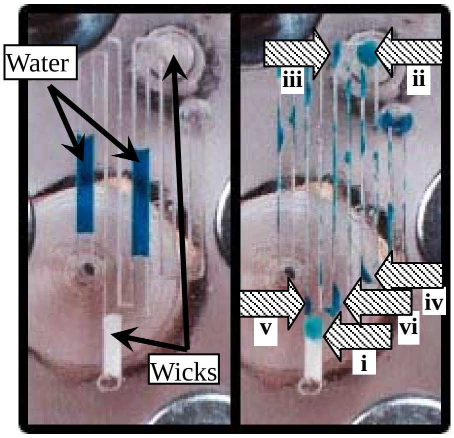

Figure 8. Liquid water collection test; left (a): before, right (b): after. Arrows indicate areas with liquid mentioned in the report.

liquid adhered to the side walls and the rest flowed through the exhaust port. The adhesion of liquid water (iii) at the exterior corners of the u-bends was not as pronounced in this prototype as initially suspected. Naturally, the exterior of a corner minimizes the overall surface area of the liquid exposed to the gas, thus minimizing the surface energy to maintain this state as compared to the interior of a corner or a straight surface. The exterior corners of the u-bend closest to the exhaust port showed some retained liquid (iv).

Two slugs of water were found near the extension cavity: one located before the extension cavity on the exterior of the u-bend (v), and another located after the extension cavity on the interior of the u-bend (vi). Further experiments on the water adhesion of the two liquid slugs were performed without inserted wicks.

The first experiment examined the water adhesion to exterior corners, shown in Figure 9. Water droplets were placed upstream of the exterior corner on the exterior corner side of the channel. The after photograph shows that the liquid halted right before reaching the extension cavity (vii). This might be due to the lack of inertia force flow pass the corner or into the cavity. The droplet possibly stopped at an air recirculation zone, caused by the extension cavity. On the other hand, a droplet approached a u-bend but did not seem to adhere to the corner (viii). In additional, a droplet remained at the same location before and after the experiment (ix). A high flow velocity of 10 m/s (0.6 slpm) was not able to move the stationary droplet. The acrylic and the sticky sealing tape might create a high adhesion force on the droplet to prevent it from moving.

The interior corner droplet adhesion was tested with water droplets placed in the channel toward the side of the interior corner upstream of the corner, as shown in Figure 10a. The after photo is shown in Figure 10b. A droplet adhered to the interior of the u-bend (x). The droplet might not have enough kinetic energy to flow past two interior corners, where an

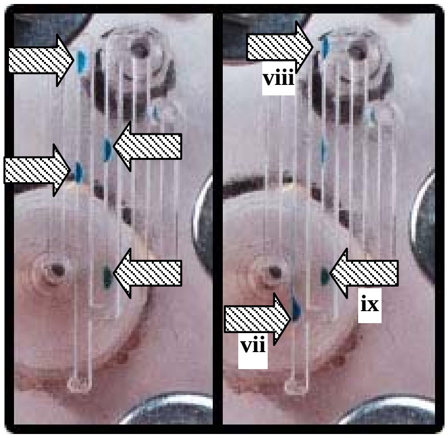

Figure 9. Liquid water collection exterior corner test; left (a): before, right (b): after. Arrows indicate areas with liquid mentioned in the report.

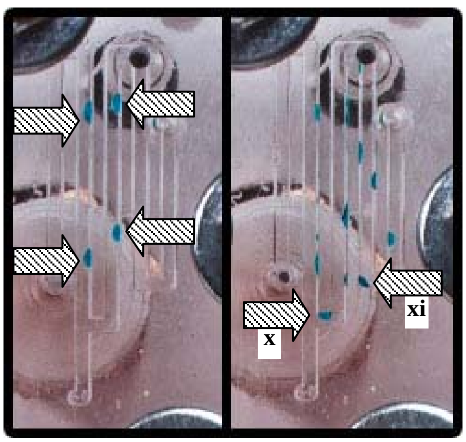

Figure 10. Liquid water collection interior land test; left (a): before, right (b): after. Arrows indicate areas with liquid mentioned in the report.

interior corner creates a high liquid surface area exposed to the gas. A droplet at an exterior corner could also be found (xi).

Both extension and well cavities were demonstrated to collect liquid. Better wicking material might provide a more effective transport of absorbed liquid from the cell. The effectiveness of collecting liquid depended on where the liquid attached on the side walls for the extension concept. Unlike the extension concept, the well concept could absorb attached liquid on both sides of the wall. The well concept seemed to outperform the extension concept with this experimental set up. However, small water droplets can form in a fuel cell and move along the surface of the gas diffusion layer and do not have contact with the bottom of the channel where it is suggested that the wells be located.

It is possible to combine the well and extension concepts. Instead of placing the well along the channel at any locations, the well can be placed next to and directly connecting to the extension wicks. This way, the wicks for the well concept do not require to bore through the uni-polar plate, in order to collect and remove the liquid on the side of the plate.

Further study of the biological phenomenon – Upon further study of the mammalian auditory system, an enhancement of the well and channel extension concepts was conceptualized. The enhancements can potentially minimize the limitation found in the experimental results shown in Figure 8, in which excess liquid flowed passed the wicks.

The outer ear, including the pinna (visible portion of the ear), ear canal and surface of the ear drum, is responsible for collecting sound. The middle ear, including the back of the ear drums and ossicles (the three ear bones), is responsible for transferring and amplifying the sound pressure to the inner ear for converting the sound to electrical signals. The structure of a human ear is shown in **Error! Reference source not found.**. The amplifying function of the middle ear stimulated the thought of "amplifying" water accumulation where the water collection occurs, near the area with wicks.

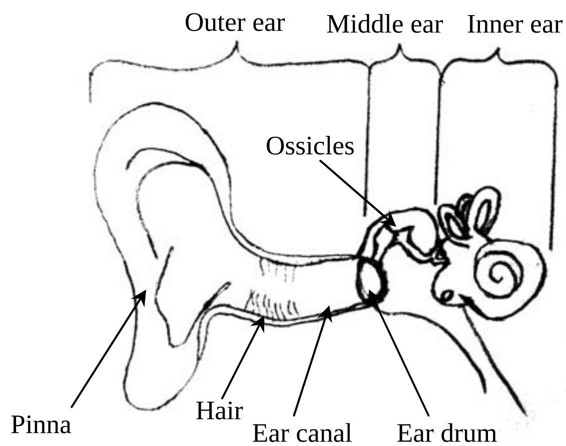

Figure 11. Structure of a human ear.

Two possible methods are proposed: First, by coating the local area of the channel with a hydrophilic finish, and second, by increasing the local channel cross sectional area, as illustrated in **Error! Reference source not found.**. The localized hydrophilic finishes can trap more liquid water in the area where water is collected by the wick. The localized larger cross sectional area of the channel will slow down the flow to allow slightly more time for water collection.

The pinna and ear canal have a further function in addition to collecting sound waves and that is preventing foreign objects from entering the inner part of the ear. Hair and ear wax produced in the ear canal are the main structures that prevent object intrusion, clean the ear and prevent infections. Instead of viewing the liquid water as a sound wave, liquid water can be treated as a foreign object. The liquid water can then be retained with "hair", where the mobility of liquid water is limited. Hair-like features can be added to the channel slightly downstream of the wick to capture more liquid water from the

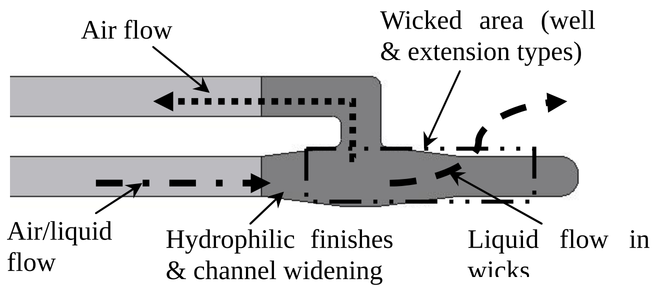

Figure 12. Enhanced liquid water collection concept.

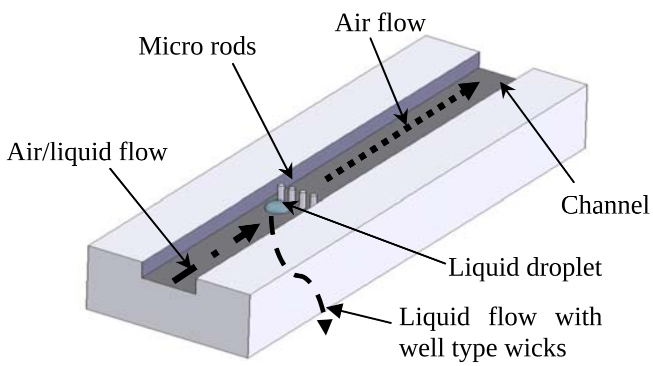

Figure 13. Trapping liquid with hair-like features.

two-phase flow. The hair-like feature can be a series of finely spaced protruding micro hydrophobic rods with gaps small enough to limit water passing (by surface tension), but without reducing the air flow rate significantly. An illustration is shown in Figure 13.

Possible implementation – A uni-polar plate design is proposed with a thin layer of wicking material. A design with four parallel serpentine channels is displayed in **Error! Reference source not found.**. The design incorporates extension and well concepts with a single piece of shaped wick connecting to the exhaust port. The thin layer of wick can be molded in the channel with polymer (without blocking the flow field) like the method demonstrated by Strickland and Santiago [12].

The inlet and exhaust ports are placed at opposite diagonals of the flow field and the wick is molded on the exhaust-side at the edge and beyond of the active area. The wicks are molded on the bottom and the wall of the channels. Hydrophilic finishes can be applied on the channels near the molded wicks. Liquid water is bought to the channel area with exposed wick where it is absorbed into the wick. Collected water in the wick is then driven directly to the exhaust by capillary force and by the gas pressure gradient between inlet and exhaust. With carefully control of the gas penetration rate of the wetted wick, gas flow through the wick can be minimized or prevented.

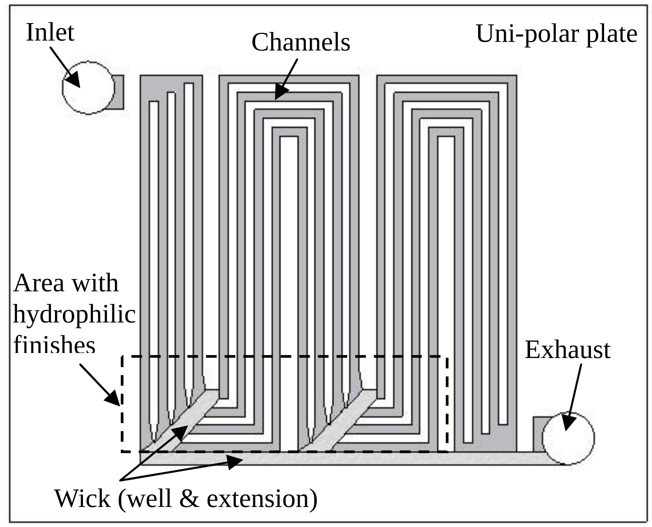

Figure 14. A possible implementation for the liquid water removal concept.

TRIZ and biomimetic design – Both TRIZ and biomimetic design can provide idea stimulation to generate possible solutions to the water management problem. These stimulations were provided from two different areas of studies. TRIZ was created from studying existing patents, which provide stimuli based on existing technologies. On the other hand, biomimetic design provides stimuli from existing biological phenomena which are similar to the engineering problem at hand. Different areas of studies can provide a wider perspective to the problem.

The design methodologies provided initial stimuli and direction for potentially overcoming the engineering problem of water management. Together with stimuli, experience, and technical knowledge, concepts were generated. For example, the TRIZ flow reversal case was based on our judgment as to what may be possible to periodically change or pulsate. Also for biomimetic design, the concept of liquid water collection was based on the experience of the possible behavior of air-water flow. The stimuli provided by the methodologies allow linking to relevant knowledge and experience in our thoughts. However, searches through external sources to satisfy the ideas/suggestions recommended by the methods are also possible.

Further concept developments are possible with better understanding of the biological phenomena. The biomimetic design provided a potential biological phenomenon that is not only useful as an initial stimulus, but also for further transfer of strategies presented in the biological system. The auditory system is not a simple system, but rather a complex system that is made out of many sub-parts with different functions. The initial function of *gathering sound waves with a special structure* was used to generate the well and extension concepts. Further concept development was from *amplifying sound wave with ossicles* and *trapping foreign objects with hair*, where "amplifying" (trapping) the liquid water problem at locations of liquid water collection. Thus, more concepts can be potentially generated from deeper understanding of potential biological phenomena. On the other hand, further studying of existing technologies that applied the suggested TRIZ principle can potentially provide further concept inspiration. However this was not pursued in the current work. A short list of existing technologies for each principle is provided in the textbook, *Product Design Techniques in Reverse Engineering and New Product Development* [3].

CONCLUSION

TRIZ and biomimetic design methodologies were applied to overcome difficulties in water management for a PEM fuel cell. Two concepts were generated, air flow reversal and liquid water collection. The air flow reversal concept was shown to potentially reduce the ability of air carrying water vapor. On the other hand, the liquid water collection concept demonstrated potential for liquid water removal. Actual performance effects with the concepts will need to be tested on a fuel cell to verify their potential. Applying design methodologies provided different perspectives to meeting challenges, which is beneficial for fuel cell design.

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