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TRANSPARENT PEM FUEL CELLS FOR DIRECT VISUALISATION EXPERIMENTS

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ABSTRACT

This paper reviews some of the previous research works on direct visualisation inside PEM fuel cells via a transparent single cell for the water behaviour investigation. Several papers which have employed the method have been selected and summarised and a comparison between the design of the cell, materials, methods and visual results are presented. The important aspects, advantages of the method and a summary on the previous work are discussed. Some initial work on transparent PEM fuel cell design using a single serpentine flow-field pattern is described. The results show that the direct visualisation via transparent PEM fuel cells could be one potential technique for investigating the water behavior inside the channels and a very promising way forward to provide useful data for validation in PEM fuel cell modelling and simulation.

INTRODUCTION

The proton exchange membrane (PEM) fuel cell is an electrochemical energy conversion device that converts the chemical energy of hydrogen and oxygen into electricity and heat by electrochemical redox reactions at the anode and the cathode of the cell, respectively. This procedure produces water as the only by-product [1]. There are several types of fuel cells and of which PEM fuel cells are the most popular ones. There have been several commercial opportunities for fuel cells that favour low temperature electrolytes, PEMs and direct methanol fuel cells (DMFCs) with over 98% of the manufacturing being low temperature units [2]. In addition to its low emissions and quietness, the great advantage of PEM fuel cells are generally that they are more efficient than the combustion engine [3]. It operates at a very low temperature of about 80°C and this allows for a quick start-up. A survey reported that the end-use of PEM fuel cells can be classified into three main groups: transportation (including niche applications, light duty markets and buses), stationary (large and small applications) and portable [4]. Buses, recreational vehicles, and lightweight vehicles are the most promising applications for PEM fuel cells [5].

For this type of fuel cell, the hydrogen is supplied through the flow-fields to the gas diffusion layers and the catalyst layers at the anode. The oxidation reaction occurs and the atoms split into H+ ions and electrons. The H+ ions will diffuse across the electrolyte to the cathode and the electrons are pushed around through the external circuit and this produces the electrical current. In other ways, the oxygen flows through the flow-fields to the gas diffusion layers and catalyst layers at the cathode. The oxygen reacts with the electrons and H+ to produce water.
The challenge of water management is the focus of researchers from all over the world in order to improve the performance, and durability of PEM fuel cells. This is a major part of the remaining challenges for the commercialization of PEM fuel cells [5]. In order to achieve an effective operation, the electrolyte must be saturated with water in order to allow the transport of the H+ ions from the anode to the cathode side. Therefore the water management criteria, such as the streams humidification, pressure drop, temperature, stream-flow regulations, gas diffusion layer (GDL) characteristics and the design of the gas distributor becomes an important consideration. An effective management of the water produced in the PEM fuel cell is required to alleviate flooding and/or the drying out of the membrane over the full operating range of the PEM fuel cell. Research and development is required to improve the design of the gas diffusion layers, gas flow-fields in the bipolar plates, catalyst layers and membranes to enable the effective water management and operation at subfreezing conditions [6]. Currently, PEM fuel cells are relatively

expensive and there are a number of issues still outstanding in terms of research, development and demonstration (RD&D), codes and standards and the fuel infrastructure/distribution [2]. Therefore, there are numerous opportunities for research, development and innovations in PEM fuel cells and the technologies are still rapidly developing [1]. This paper investigates the opportunities of having a direct visualisation experiment in order to obtain a better understanding of the processes that occurs inside PEM fuel cells. The data and visual form of the experiments have the possibility to validate the PEM fuel cell models, especially in water management problems. At present, although a number of advanced PEM fuel cell model approaches have been developed by various research groups, as well as some CFD vendors, they are often based on substantial simplifications in the processes that exist in PEM fuel cells [7]. A comprehensive PEM fuel cell modelling capability, which accounts for the detailed processes of the chemistry, electrochemistry, electrical transport, heat generation, and material stresses in the PEM fuel cell, as well as the validated PEM fuel cell modelling methodology, has not yet been fully established [7]. Improved and validated mechanistic models are required to enable a better design of PEM fuel cells and PEM fuel cell components [8]. There are several techniques that could be used in order to visually look inside PEM fuel cells.

Some previous works have been performed experimentally to visualise the water distribution and/or gas flow inside the PEM fuel cell by using X-ray radiography [9], neutron radiography [10-18], magnetic resonance imaging [19-22], gas chromatography (GC) measurements [23, 24] and optical visualisation using transparent PEM fuel cells [18, 25-34]. Figure 1 shows an example of a transparent PEM fuel cell, see [27].

Neutron beams can penetrate through the metal of the PEM fuel cell plates in order to observe the real-time liquid water profile along a flow-field that is integrated through the cell thickness. However the technique is currently limited in both the spatial and temporal resolution and this makes it difficult to capture the two-phase flow phenomena in a PEM fuel cell and the imaging has yet to distinguish the liquid water distribution on the anode and cathode, respectively [30]. Water distribution measurements using GC provide unique information on the species distributions on the anode and cathode, as well as the water transport across the membrane. However this diagnostic tool is applicable to the situation where liquid water is abundant [30]. Although direct flow visualisation requires a special cell design, it is a very attractive experimental technique since optical access to the channels provides high spatial and/or temporal resolution, depending on the combination of the optics and recording equipment [32]. The recent research work by Spernjak et al. [18] investigated the water dynamics in PEM fuel cells by the simultaneous neutron imaging and visualisation. By combining these techniques, two sets of images were obtained in an operational PEM fuel cell: Liquid water dynamics in the flow-field were visualised optically, while the complete water content was measured by processing the neutron images [18].

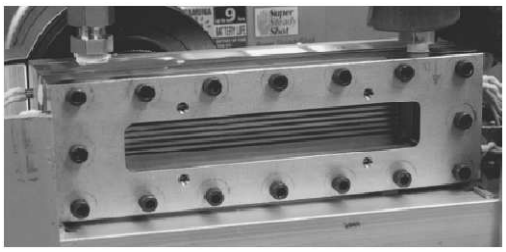


Figure 1. A transparent PEM fuel cell [27].

LITERATURE REVIEW

Several researchers have investigated the water behaviour inside PEM fuel cells using direct visualisation techniques. Selected works have been reviewed and their focus area, design, size and dimension of the electrode and channel, type of materials and recording devices that have been used for transparent PEM fuel cells have been investigated. The first reported paper that uses a transparent PEM fuel cell is the visualisation of the liquid water on a GDL at the cathode flow-field of a transparent PEM fuel cell operating at low current densities and at room temperature [25]. These conditions are used in order to prevent water condensation on the inner surface of the transparent window. They investigated the influence of the hydrophobic and hydrophilic GDLs compared to using standard carbon papers on the cell performance and flooding. The images of the water formed inside the cathode gas channels for water flooding phenomena are shown and the effects of air stiochiometry, temperature, air humidity and different characteristics of the diffusion layers are discussed. Figure 2 shows a photograph taken inside the transparent PEM fuel cell used by [25]. It clearly shows the water formation and flooding phenomena inside the channel of the cell. To overcome the limitation in the range of operating conditions, some researchers [27, 30] use an antifogging coating on the inner surface of the transparent plate in order to prevent fogging and water condensation. Spernjak et al. [32] overcame the fogging problems by heating the cell, and this is an alternative way of using coated end plates.

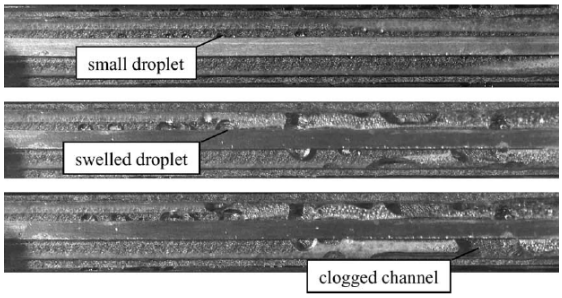


Figure 2. Photograph taken inside of the transparent PEM fuel cell [25].

Table 1 shows the focal areas that have been chosen from the previous investigations on transparent PEM fuel cells for visualising the water behaviour inside the cells and some of them [25, 27, 30, 32] have investigated the effect of the GDL in removing water from the PEM fuel cell. It is already known that GDLs play a crucial role in the water management and this maintains the delicate balance between the membrane hydration and water removal from the catalyst layers to the flow-field channels [35]. For investigating the possibility of water flooding at the anode side, the visualisation could be made from both sides of the anode and cathode. This can be achieved by designing the PEM fuel cell to have a transparent window both at the anode and the cathode sides [31] or by performing two series of experiments [32]. The advantage of having both sides of the PEM fuel cell having a transparent window is that we could observe both sides in the experimental investigation. Thus, the investigation through the visualisation of the liquid water formation could be made at the both sides simultaneously. As we know, the water travels from the cathode to the anode side or vice versa and this phenomena could give a significant effect to the water formation inside each of the channels.

Various flow-field patterns have been used from previous research works, such as the serpentine and parallel channels which are popular patterns. Liu et al. [29] compared three different flow-field patterns which are the parallel, interdigitated and cascade using a visualisation technique which reveals and proves the advantages of the interdigitated patterns in terms of having a better removal of the water capability as claimed by previous researchers [36]. By having a PEM fuel cell transparent design which is close to the normal PEM fuel cell design, thus having a comparable performance, some researchers [26, 28, 33] have investigated the water behavior by using typical shapes of the flow-field and typical sizes of the active area. A summary of the designs and dimensions which have been employed by other researchers is given in Table 2.

Several types of materials have been used in the fabrication of the gas distributor plate in PEM fuel cells. For normal PEM fuel cells, a variety of materials, such as non-porous graphite, non-coated or coated metal, composite materials, etc. have been suggested for use in the gas distributor plate [37, 38]. However for transparent PEM fuel cells, which need a clear contrast between the plates and the GDL for imaging purposes, the use of a metal, such as stainless steel, would be more practical. This type of material offers a lower thickness and good mechanical stability [38] which are suitable for transparent PEM fuel cell applications for matching the required shapes of the flow-fields and the depth and width of the channels. For more chemical stability, the coated metal, such as gold plated stainless steel as in [27, 30], would be a good choice, especially when performing long term performance testing of transparent PEM fuel cells. For the end plates, a material which is transparent and has good mechanical strength, such as polycarbonate and plexiglass would be suitable. Some designs [27, 30] add a coated material on the inner surface of these plates to prevent the formation of fog or water droplets instead of using a heating method. Table 3 summarises the materials used in the PEM fuel cell transparent design as used by previous investigators. Table 4 shows the recording and image capturing devices that have been used in their investigations.

For preventing fluid leakage across the channels, between the rib of the gas distributor plates and the transparent plates, the seal or gaskets have to be sandwiched between the transparent plate and the flow field rib. This is a very important issue since it is difficult to perform any tests to make sure that there is no leakage and moreover the need to be completely sealed for representing the transparent PEM fuel cell as a normal PEM fuel cell. If not completely sealed, the fluid leakage will form a short circuit flow between the channels and this will lead to a dissimilar and non-comparable performance with normal PEM fuel cells. Some previous research work in [29, 31] have used Teflon® coated glass fiber cloths as the sealing strip. The silicon rubber material could be a possible option for sealing. The design of the flow-field dimensions for the gas distributor plate of the transparent PEM fuel cell should be investigated to reduce the leakage. Increasing the channel ribs is an option to reduce the risk of leakage, since the seals or gaskets are easier to be shaped or put in position if the ribs are wider. However, increasing the width of the ribs will decrease the gas consumption [39], unless the channel width is also optimised. Therefore, the dimension of the channels and ribs should be chosen to be a realistic value to make it comparable to a normal PEM fuel cell. Figure 3 shows a schematic diagram of the location of the seal or gasket in the transparent PEM fuel cell.

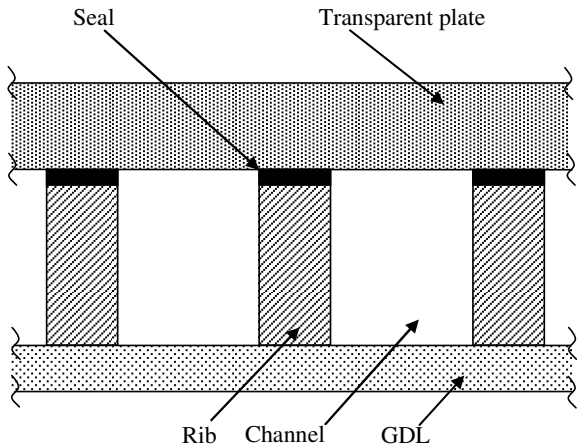


Figure 3. Schematic diagram of the cross section of the transparent PEM fuel cell.

Table 1. Focal areas for the direct visualisation technique of PEM fuel cells from different researchers.

References	Focal areas
Tuber et al. [25]	Visualisation and investigation of the liquid water behaviour on the GDL at cathode sides at room temperature.
Hakenjos et al. [26]	Visualisation of the liquid water content and an

	investigation of the temperature influence inside the cathode channel.
Yang et al. [27]	Visualisation and investigation of the liquid water transport on the cathode GDL and channel under a high current density and temperature.
Sugiura et al. [28]	Visualisation of the flow-field flooding on the cathode gas distributor plates with a water absorption layer and waste channels.
Liu et al. [29]	Visualisation of the liquid water in three transparent PEM fuel cells with different types of cathode flow beds.
Zhang et al. [30]	Visualisation and investigation of the liquid water distribution on the cathode GDL surface and inside the channels.
Weng et al. [33]	Visualisation and investigation of the water flooding at the cathode side.
Liu et al. [31]	Visualisation of the liquid water and an investigation of the pressure drop influence in the anode and cathode channels.
Spernjak et al. [32]	Visualisation of the liquid water formation and transport at anode and cathode sides and an investigation of the effectiveness of various GDL.
Weng et al. [34]	Visualisation of the flow under different operating conditions at the anode and cathode sides by using different flow-field patterns.
Spernjak et al. [18]	Visualisation and investigation of the liquid water dynamics on the cathode sides by the simultaneous neutron imaging and direct visualisation techniques.
Current investigation	Visualisation of the water distribution on the anode and cathode sides simultaneously.

Table 2. Designs and dimensions for transparent PEM fuel cells from different researchers.

References	Active area (cm^2)	Flow-field patterns	Channel dimension (mm), channel width × depth × rib width
Tuber et al. [25]	4.03	Two straight channels	1.5 × 1.0 × -
Hakenjos et al. [26]	20.25	Single channel	1.0 × 2.0 × 1.0
Yang et al. [27]	14	Seven straight channels	1.0 × 0.5 × 1.0
Sugiura et al. [28]	25	Single serpentine and parallel channels	1.6 × 0.8 × -
Liu et al. [29]	5	Parallel, interdigitated and cascade	0.8 × 1.0 × -
Zhang et al. [30]	14	Seven straight channels	1.0 × 0.5 × 1.0
Weng et al. [33]	100	Two serpentine channels	2.0 × 2.0 × -
Liu et al. [31]	5	Parallel	0.8 × 1.0 × -
Spernjak et al. [32]	10	Single serpentine	- × 1.0 × -
Weng et al. [34]	100	Ramification and serpentine	2.0 × 2.0 × -
Spernjak et al. [18]	25	Parallel, single serpentine, and interdigitated	0.8 × 0.8 × 1.0
Current investigation	50	Single serpentine	2.0 × 1.0 × 2.0

Table 3. Materials used for transparent PEM fuel cells from different researchers.

References	MEA and GDL	Gas distributor plate/current collector	End plate
Tuber et al. [25]	Gore PRIMEA®	Copper wire	Plexiglass
Hakenjos et al. [26]	In-house MEA with TORAY® carbon paper	Graphite	Zinc selenide
Yang et al. [27]	In-house MEA with TORAY® carbon paper	Gold plated stainless steel	Polycarbonate with a hydrophilic and antifogging coating
Sugiura et al. [28]	-	-	Polycarbonate
Liu et al. [29]	Fuyuan Century Fuel Cell Power Co. Ltd.	Stainless steel	Plexiglass
Zhang et al. [30]	In-house MEA with TORAY® carbon paper	Gold plated stainless steel	Polycarbonate with an antifogging coating
Weng et al. [33]	-	Brass plate	Acrylic
Liu et al. [31]	Fuyuan Century Fuel Cell Power Co. Ltd.	Gold plated stainless steel	Plexiglass
Spernjak et al. [32]	In-house MEA with TORAY® and Sigracet® carbon paper and AvCarbTM carbon cloth	Stainless steel 316	Polycarbonate
Weng et al. [34]	-	Brass	Acrylic
Spernjak et al. [18]	In-house MEA with catalyst-coated membrane by Ion Power Inc.	Stainless steel 316	Quartz (fused silica)
Current investigation	Commercial and standard MEA from Electrochem Inc.	Stainless steel 316	Polycarbonate

Table 4. Visual and recording device for transparent PEM fuel cells from different researchers.

References	Device
Tuber et al. [25]	Digital camera
Hakenjos et al. [26]	Charged couple device, CCD camera
Yang et al. [27]	Digital camcorder with microscopy lens
Sugiura et al. [28]	12-bit CCD camera
Liu et al. [29]	High speed video (PHOTRON, FASTCAM 10K) and digital camera (Sony, DSC-F505V)
Zhang et al. [30]	High-resolution 3-CCD video camera
Weng et al. [33]	CCD camera
Liu et al. [31]	Digital camera (Sony, DSC-F505V)
Spernjak et al. [32]	Digital camcorder (image) and high speed camera (velocity of water droplet)
Weng et al. [34]	CCD camera
Spernjak et al. [18]	12-bit LaVision Imager Intense
Current project	Digital camera (Nikon D40)

As there are some significant differences in the design of the gas distributor plates of the transparent PEM fuel cell, which is one of the major components of the PEM fuel cell, the issue of non-comparable performance compared to the normal PEM fuel cell would be an interesting topic for further discussion. This issue should be considered carefully in order to improve the reliability of the experimental data of the transparent PEM fuel cell to represent the PEM fuel cell in general. Therefore, in order to make the data more comparable to the data which is produced by the normal PEM fuel cell, some of the important issues or ideas are as follows:

i. The size, shape and dimensions of the MEA active area and flow-field patterns have to be similar or as close as possible, to those used in the normal PEM fuel cells. Varying the flow-field patterns to the more complex geometries for the representation of the realistic features of the commercial PEM fuel cells which have more complex patterns and geometries.
ii. Validate the transparent PEM fuel cells with normal PEM fuel cells which have the same designs, except for the cut through channels. This will ensure that the different designs in the transparent PEM fuel cells do not make a significant effect in terms of the produced electricity or power output.
iii. Improve the design of the transparent PEM fuel cell, especially in the heating system in order to make sure that the transparent PEM fuel cell is uniformly heated and the design of the end plates in order to make sure that the transparent PEM fuel cell could be operated at a higher pressure.
iv. Increase the size of the MEA active area to make it comparable with normal PEM fuel cells and produce more realistic experimental data.
v. Visualise both sides of the anode and cathode simultaneously in order to obtain a set of data on the running of the transparent PEM fuel cell in the same materials and operating conditions. The data could be used in order to investigate the behaviour of the water travelling across the GDL and membrane.

TRANSPARENT PEM FUEL CELL

In order to visualise and investigate the liquid water and flooding inside a PEM fuel cell, a special design of a single cell has to be made in which we replace the end plates with a transparent material. Basically the transparent PEM fuel cell has the same components as a typical PEM fuel cell but it uses a transparent material, such as polycarbonate, acrylic or plexiglass, as a window to visually observe inside the PEM fuel cell. Figure 4 shows an exploded view of the transparent PEM fuel cell which consists of two end plates, two gas distributor plates and a membrane electrode assembly (MEA) with gaskets. The gas distributor plates, or the flow-field plates, have been made from a high electrically conducting and low corrosion rate material, such as stainless-steel. In the design, the polycarbonate plates have been used as the end plates with a 12 mm thickness in order to make sure it could sandwich the MEA without any bending problems, otherwise it could lead to problems with leakage. The 2 mm thickness of the stainless-steel plates have been used as the gas distributor plates and also it serves as a current collector. The single serpentine flow-field pattern has been used for the gas channel. Other flow-field patterns, such as interdigitated and parallel, could be used for transparent PEM fuel cell's flow-field patterns. However the possibility of the fabrication and machining of the channels need to be considered as the slots are required to be grooved through on the plates to allow a straight view of the GDL. As an example, for the parallel flow-field pattern, the ribs of the flow-field will be disconnected from the main gas distributor plate if the channels are grooved through. For sure this would not produce a working PEM fuel cell unless some modifications have been made in the channel's manifolds of the gas distributor plates.

In the design, the channels have been cut to a depth 2 mm, width 2 mm and with a rib width 1 mm. The grooved through channels form the flow-field when the plates are installed between the MEA and the end plates. The flow-field design has been made as close as possible to the normal design of a PEM fuel cell in order to obtain a realistic view for the operating PEM fuel cell. For preventing the formation of fog on the inner surface of the end plates, the end plates are required to be heated, otherwise the formation of fog on the surface will cover the channels. In the design, silicon rubber heaters have been used and attached to the extension regions on both sides of the gas distributor plates for directly and uniformly heating the gas distributor plates and also the end plates. The temperature sensor is placed at the centre of the gas distributor plates in order to give an average cell temperature reading which represents the temperature on the plate. The MEA is a standard commercial 5 layer MEA from Electrochem Inc. and the active area of the MEA is 50 cm^2 with 1.0 mg Pt/cm^2 on both sides of the anode and cathode catalyst layers. Silicone rubber sheets, with a thickness of 0.25 mm, have been used on both sides of the MEA to prevent any fluid leakages from the MEA and for the electrical insulation between both the anode and the cathode gas distributor plates. Figure 5 shows a photograph of the transparent single PEM fuel cell that has been designed and fabricated for the PEM fuel cell performance and visualisation experimental work. Capturing and recording devices have been used to obtain the visual data of the water and the flooding phenomena inside the PEM fuel cell. The direct visualisation investigation could be made inside the channels of the transparent single PEM fuel cell at both the anode and cathode sides.

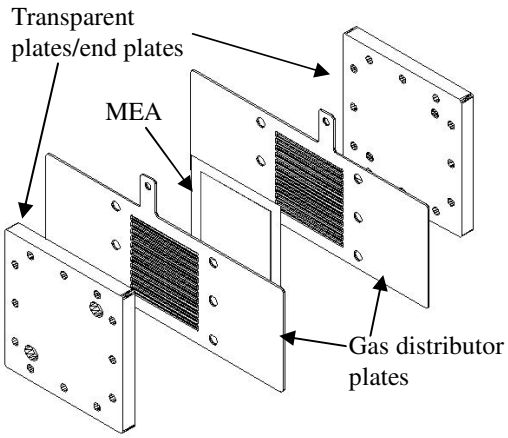


Figure 4. A schematic diagram of an exploded view of the investigation transparent PEM fuel cell.

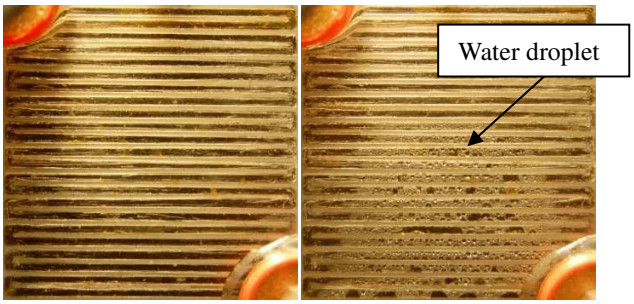
Figure 5. A photograph of the investigation transparent single PEM fuel cell.

DIRECT VISUALISATION EXPERIMENT

A transparent PEM fuel cell, as shown in Figure 5, has been used for observing the water formation inside the channels by operating at different relative humidity conditions. For the preliminary work, two cases have been run using the transparent PEM fuel cell; a humidified inlet at the cathode with a dry inlet at the anode and a humidified inlet at the anode with a dry inlet at the cathode. The photographs of the water formation in the channels and the power produced by the transparent PEM fuel cell have been investigated for evaluating the effect of the inlet's humidification. The experiment was operated at 75°C for the cell temperature with a 1.2 stoichiometry ratio for the anode inlet and a 2.5 stoichiometry ratio for the cathode inlet. During the experiment, the inlet gas temperature was maintained at 75°C when in the humidified condition in order to prevent condensation of the water in the tubes and 28°C when in the dry condition. A low operating pressure, 0.5 barg was employed at both the anode and cathode inlets in order to prevent any overboard fluid leakage as the end plates were sandwiched at low torque in order to prevent the bending at the polycarbonate plates. For safety issues, the transparent PEM fuel cell has been pressure tested at the designed pressure in order to prevent any leakage. In each experiment, the transparent PEM fuel cell has been run approximately 15 to 30 minutes until the performance reached its steady state.

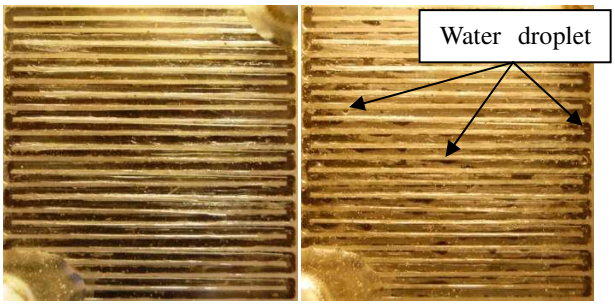
Figures 6 and 7 show photographs of both sides of the channels obtained from the operating transparent PEM fuel cell. The photographs show the liquid water distribution at the anode and cathode flow-field channel. They were taken at 0.9V and 0.6V operating conditions. The reactants have been set to approximately 50% relative humidity at the cathode inlet and dry condition at the anode inlet. In the 0.6V operation, the water was condensed after approximately half of the anode flow-field. As there was no humidification at the anode inlet, the water was diffused through the membrane from the cathode side where the water was produced from the reaction or the water which was supplied from the humidification. At the cathode channels, the condensed water forms water droplets and these have been forced to move from one channel to the next channel then to the cathode outlet. The water droplets appear to be easily removed from the cathode flow-field and this gives good agreement with [40], namely that the serpentine flow-field pattern which has been used in this investigation is efficient in removing excess water as no clogged water has been detected and no flooding phenomena was observed in the channels.

In contrast, when the anode inlet was humidified with approximately 50% relative humidity and let the cathode inlet be at the dry condition, then the photographs have been taken for the operating voltages at 0.8V and 0.6V, as shown in Figure 8 and 9. The small water droplets have been observed in the first channel on the anode side for the 0.8V operating voltage and these were bigger than for the 0.6V operating voltage. Dry conditions have been observed for the cathode side for both operating voltages. There was no condensed water and water droplets formation observed on the cathode side. As the inlet cathode gas was dry, the humidification for the PEM fuel cell operating condition was inadequate. Therefore the membrane became dehydrated and thus there was a decrease in the electrochemical reaction rate and the production of water. As a result, the power performance was found to be lower compared to the case in which the inlet cathode gas was humidified. It shows that, in these cases, the humidification is more significant to the water balance in the PEM fuel cell at the cathode side compared to the anode side. The higher flow-rate, which usually is in the cathode inlet stream, will carry more water when it passes through a humidifier. This gives a higher mass flow-rate of the water in the cathode inlet stream. At an appropriate level of water content, the carried water in the cathode stream can help in maintaining a good level of hydration in the membrane which is essential for the ionic transport through the membrane. However, at an extremely low water content, the high flow rate of the cathode stream could dry out the membrane leading to a deterioration in the performance of the PEM fuel cell.



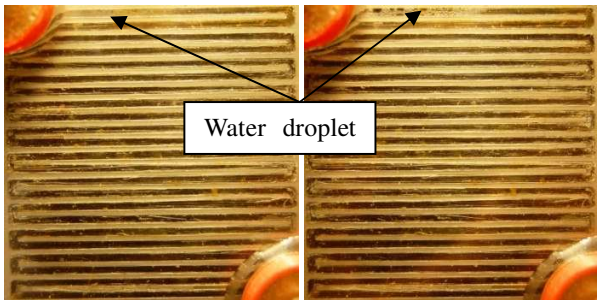
(a) (b)

Figure 6. Photographs of the water distribution at the anode channels with 50% relative humidity at the cathode and dry condition at the anode when operating at: (a) 0.9 V and (b) 0.6V.



(a) (b)

Figure 7: Photographs of the water distribution at the cathode channels with 50% relative humidity at the cathode and dry condition at the anode when operating at: (a) 0.9V and (b) 0.6V.



(a) (b)

Figure 8: Photographs of the water distribution at the anode channels with 50% relative humidity at the anode and dry condition at the cathode when operating at: (a) 0.8V and (b) 0.6V.

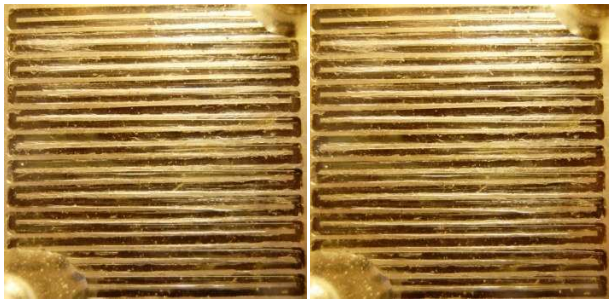


Figure 9: Photographs of the water distribution at the cathode channels with 50% relative humidity at the anode and dry condition at the cathode when operating at: (a) 0.8V and (b) 0.6V.

In the future, we will produce the performance curve for the transparent PEM fuel cell and compare it with the performance curve obtained from a normal PEM fuel cell. This will be a very important continuation of this work in order to investigate if the transparent PEM fuel cell, that has been used in this work, will produced a reliable and comparable performance. This investigation is underway and the results obtained will be reported in a future publication. Furthermore, in the future we will focus on improving the design of the transparent PEM fuel cell and investigate the effects of the relative humidity, temperature, and pressure on the performance of the PEM fuel cell by evaluating the water distribution inside the channels. Also the efficiency of the different flow-field designs, especially in terms of its capability of removing the excess water may be of interest to investigate when using the direct visualisation method as employed in this paper.

CONCLUSIONS

As a conclusion, the method described in this paper using a transparent PEM fuel cell for the visualisation of the water behaviour is a very attractive and easy manner to gain access to the inside of the PEM fuel cell channels. In our investigation, the technique has given a clear and rapid image of the flow inside the transparent PEM fuel cell and it could be used as useful data for the performance investigation and model validation. From this review, it is shown that there have been several works that have used the direct visualisation method, either to investigate the effect of different designs in term of the water behavior inside the PEM fuel cell or to produce clear images of the flow inside the channels for the water management investigation. However there are still some issues that need to be considered which have been described in this paper in order to improve the design and produce more reliable and useful data for the development of the PEM fuel cell. From the experimental results, it has been shown that the single serpentine flow-field pattern removes the excess water effectively. Furthermore, the humidification at the cathode side is more significant compared to the anode side in order to humidify and supply sufficient water to the cell and the higher

flow rate at the cathode side could assist in the water balance by removing the excess water from the cell.

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