Recent Research on WaterManagement Problem in Proton Exchange Membrane Fuel Cells: A Brief Review

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ABSTRACT

Proton exchange membrane fuels cell (PEMFC) is fuel cell that useshydrogen and oxygen as its fuel and the most interesting thing about this cell is that it only produces liquid water as its main by-product. This makes PEMFCsas one of the promising and interesting sources of power for the future because they are fully in compliance with the environmental policies and goal of this generation. However, commercialization and full harnessing of this novel cell has yet to commence despite showing some strong prospectsand potentials. This may be largely due to the technical issues surrounding the operation of PEMFC. The two main issues that pose serious concern are water and thermal managements. Concerning the water management, two important critical issues that are inter-related involve cell dehydration and water flooding, both of which have adverse effects on the performances of these cells.Subsequently, these concerns draw the attention of the research community, where a large number of research has been carried out employing different methods and approaches to solve this problem. In this review, some of the recent advances in the research on water flooding and removal problems in PEMFC are reviewed and their research findings reported, especially with regard to the factors that affect the water flooding and removal, influence and effects of some of the scientific approaches to solving these problems. These factors include those emanating from the gas flow channel design, use of acoustic vibration and gas diffusion layer modification, all of which are reported in this study.

Keywords: *Proton exchange membrane fuels cell (PEMFC), gas diffusion layer, water flooding,reactants,water removal*

1.0 INTRODUCTION

Polymer electrolyte membrane fuel cell (PEMFC) is a source of energy that operates by supplying hydrogen and oxygen as reactants, in which they undergo electrochemical reactions that result in the formation of water as a by-product at cell cathode catalyst layer. [1]. It is regarded as one of the alternative sources of energy, particularly to automotive applications, because of their low emission which makes them environmentally friendly, and also due to their high volumetric power density at low operating temperatures [2].

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Research on PEMFC attracts the attention of research community worldwide, due to its promising potentials in producing a much cleaner source of energy than many of the renewable energy counterparts but some important issues that delayed its development and commercialization are the thermal and water managements. Thus, many research works are on-going on these issues and some significant levels of improvements are recorded so far, but still, there is much to be done concerning managing of water in PEMFC, especially when operating at a high current density.

One of the ways to have this cell operating at its best is through designing a flow field that ensures uniform and proper distribution of the reactants within the cell because uneven distributions of the reactant flow causes uneven water production heat and current, which later resulted in cell flooding [3]. Different approaches of removing the water have been proposed and developed by researchers to address and solve this pressing issue. It was stated that improving the membrane electrode assembly (MEA) durability and performance is paramount because it isone of the important components of the cells where the chemical energy conversion process takes place. This is where the chemical energy is directly converted to electrical form and hence, many research works are currently focusing on this area [4]. Figure 1 shows a schematic of the PEMFC while Figure 2 shows an exploded view of the PEMFC, detailing out the essential components.

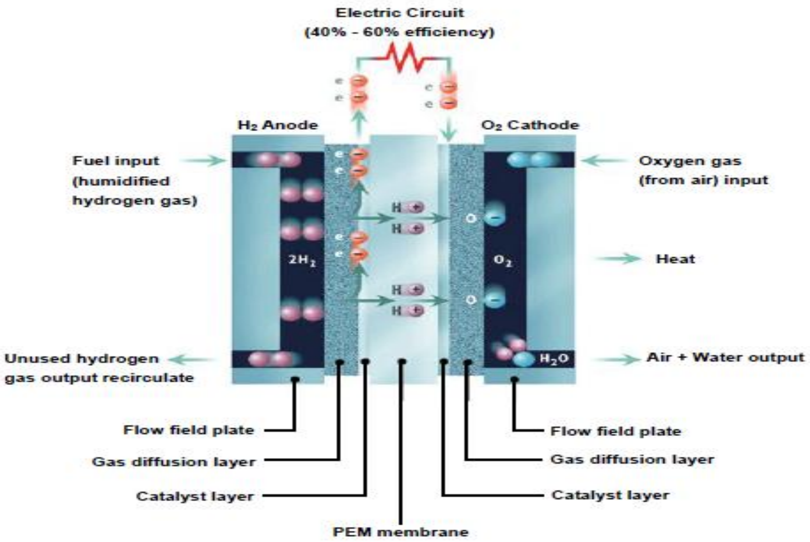

Figure 1. Schematic diagram of the PEMFC [5]

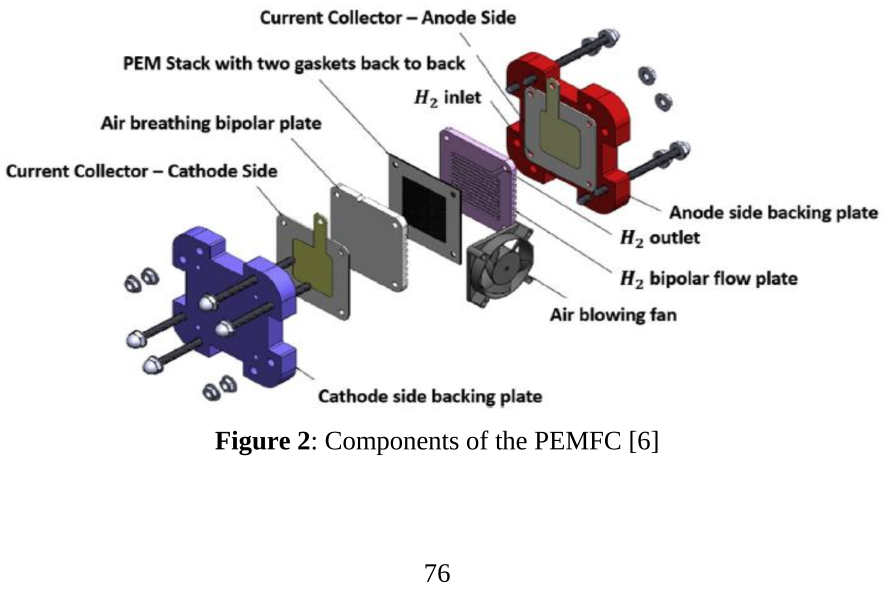

Figure 2: Components of the PEMFC [6]

2.0 WATER FLOODING

Water management proves to be one of the critical issues hindering the commercialization of PEMFC due to its tremendous impacts on the performances and durability of the cell [7]. Water in PEMFC usually comes from two sources; vapor in humidified reaction gas which significantly enhances the hydration of the proton conductive membrane which in turn strengthens proton conductivity. The other source is water that is produced as a result of electrochemical reaction at the cathode [8]. An excess amount of water can occupy open pores of the gas diffusion layer (GDL); these pores are mean to serve many purposes like providing uniform transport of reactants to the catalyst layer (CL) of the cell, protecting the fragile membrane, providing access for removing the excess water from the cell membrane, and also proving electrical conductivity between electrodes and current collectors [9].

Due to some working conditions of these cells, it is normal that during the high-density working condition, PEMFC produces large quantity of water at the cathode catalyst layer as one of its by-products. Therefore, the risk of water accumulations or flooding on GDL is becoming unavoidable [10] because transporting this excess water to GDL obstruct reactants flow to the cells catalyst layer and causes GDL flooding, which has a serious effect on the PEMFC performance and durability [11]. Uneven reactant species concentration in the cell also causes distribution of the cell local current density, temperature, and water which results in flooding or drying of cell membranes as such stress is formed at various cell region [12].

As it was reported that water flooding results in concentration drop due to hindering the transportation of reactants from the gas channels (GC) or flow channels to the catalyst layer, (CL), as such it affects the PEMFC performances [7]. Among the consequences of water, flooding is a non-uniform or uneven distribution of current, poor, or decrease in cell performance, unstable operation, and rapid cell degradation rates [13]. Other important factors also affect cell performance, apart from the water flooding, e.g.,cell thermal management is another issue of its own, which requires serious attention.

3.0 WATER REMOVAL

3.1 Use of Acoustic Vibration

The increase in current density causes a corresponding increase in the water productions and flooding in PEMFC. This is due to the rapid growth of water droplets, evacuation of this water droplet is only easier with when there is less pressure build-up from hydrogen flow channel [14].Several approaches attempted to solve this problem, among which is the use of acoustic vibration; the aim here is to device a way of easing water removal from the cell. Palan *et al*. (2006) theoretically examined the PEMFC cell water removal by using vibro-acoustic methods [15], the effect of applying flexural waves, acoustics waves and surface waves to a PEM stack and then compared with the minimum vibration energy required to remove each droplet. They found that water droplet of about 2mm radius can be removed from the gas channels using parasitic power equipmentas a 21mW of energy. They concludedthat with regard to the energy utilization of acoustic waves is the most convenient among all the tested methods. Mortazavi*et al*. (2019a) studied the excess water removal from PEMFC by superimposing acoustic pressure waves on the reactant channel airflow [2]. The experiments were conducted at a frequency range between 20 to 120Hz, at an interval of 20Hz, with the CCD camera mounted over an ex-situ PEMFC which is transparent. The results show that superimposing the acoustic pressure waves shows the tendency of greatly reducing the water build-up, which will, in turn, reduce the tendency of two-phase flow pressure drops. Figure 3 depicts the process of water transport in a PEMFC.

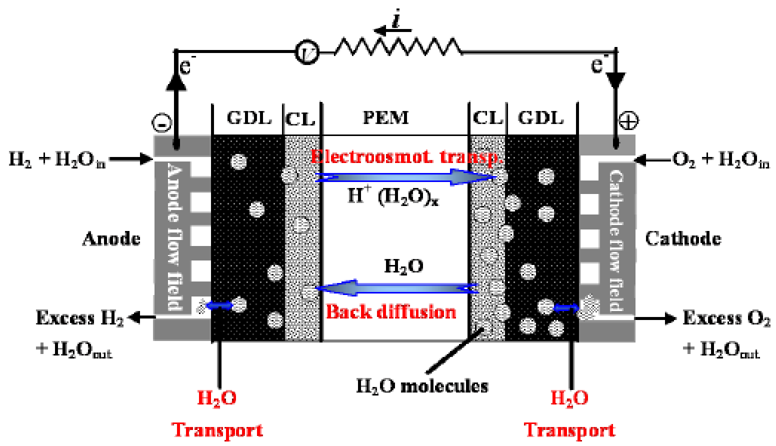

Figure 3: Water transport in PEMFC [5]

3.2 Effect of Hydrophobicity

The influence of air velocity and wettability during the penetration of liquid water on the whole process during liquid water was investigated by Han and Chen (2018)) using a generalized two-dimensional model and volume of liquid (VOF) method [16]. The results show that wettability of the medium has greater effects than the flow rate for the penetrations of liquid water in GDL, it also shows that with favorable hydrophobicity and high air velocity in GC is very helpful in removing liquid droplets on the GDL surface. It was also noticed that stable water droplets spacing on the surface of GDL is highly dense and the percentage area covered by the liquid is more extensive at low velocity and hydrophilic case[17], using a one-step ultrasonic atomizing spray technique to spay surface hydrophilic reagent (aerosol ® ot-75 surfactant: polyacrylic acid: deionized water ¼ 1:1:8). The energy dispersive spectrometer (EDS) is used to confirm the presence of both hydrophilic and hydrophobic synergistic surfaces throughout the gas diffusion layer, it was reported that cell performance greatly improves as compared to the cell with normal gas diffusion layer. Guo *et al*. (2016a)was able to develop a novel water transport medium in which a liquid water equilibrium within the cell is achieved through both humidification and evacuation [18]. This hydrophilic porous carbon plate (HPCP), shows an increase in cell performance was at a current density of about 1000mAcm-2 cell voltage with HPCP was about 270mV Higher than a cell with solid Plate (SP) so also the cell run time was improved to almost twelve-time higher than those with a solid plate under dead-ended cathode operation.Because of the need to have an appropriate water balance in the cell. They further developed a novel hydrophilic porous carbon plate (HPCP), with continuous hydrophilic pores to serve as water transport plate (WTP), because of its good humidification and water transports functions [18].

3.3 Effect of Contact Angle

The effect of the contact angle at gas GDL/channel interface has its influence and prospects improving water removal process from the PEMFC. Zhang *et al*. (2017) found out that increasing the contact angle at GDL/ channels facilitate water removal process in channels, thereby improving cell performance [19]. Their finding also stated that addition of baffles in the cathode channelsincrease oxygen concentration in the porous electrodes and improve the water removal process.

Gas-liquid two-phase flow of the PEM fuel cell that is operating at a low temperature was simulated to study the water removalin anode channel by Hou *et al*. (2017) using VOF (volume of fluid) method, it was found out that removing of liquid water from anode channel is more challenging than it was in the cathode channel under similar cell operating condition, it was also noted that increasing the contact angle and humidification rate is important in improving water removal process in the cell[20].

3.4 Effect of Channel Design

Cell flow field design has a very significant influence on removing water from the cell.Shimpalee and Vanzee (2007) explained that altering of water flowflown orientation and designs like, changing path length of the channels or heights to have an even distribution system of the reactant, will help in reducing the stress developed within the cells which are the courses of the effects such as cell flooding [12]. Kahraman*et al*. (2017) stated that flow channels or fields have a significant influence on the supply of the reactant gases to the catalyst layers and also on liquid water evacuation from the cell, a good and efficient flow channel or field design should provide a uniform mass distribution, minimize energy lost, and pressure drops [21]. Yin *et al*. (2019) studied the water droplet movement in a single serpentine flow channel of PEMFC using different U-turn designs [22]. It was found that water droplets can pass through the U-turn with large fillet radius, while they get stuck at corners with small fillet radius, it was also noted that water droplets are move as a whole or complete droplet without breakup at low airflow speed while they split at U-turn into smaller water droplets at higher airflow speed.

Yan *et al*. (2006) comparedthe cells performance between a cell with interdigitated flow field and conventional flow field [23]. The results show that cell with interdicted flow field gives higher cell performance with less fuel consumption than a cell with a conventional flow field. Wang *et al*. (2019a) developed an M-like gas flow channel and compare it with the conventional wave-like channels [24]. The results show that the novel M-like channels have higher heat and mass transfer then the convectional gas flow channels and this is due to it has lower entropy generation under the same pumping power.

Numerical study of PEMFC with matrix flow field carried out in[25] by using tree–dimensional two-phase full cell model and volume of liquid method (VOF). The result showed matrix flow field can facilitate high cell performance output, by enhancing the oxygen supply to gas diffusion layer (GDL), liquid water hardly gets blocked by the array blocks and so can leave GDL quickly, thereby he concludes that matrix flow field can perfectly fit the PEMFC high current density demand. Hou *et al*. (2017)further stated that in semicircle U-channel, liquid water removal is more efficient than rectangular–U channel, because water gets stuck at the corner, but this can be prevented by changing the contact angle to hydrophilic or hydrophobic [20]. Bao *et al*. (2019) found that in a 3D baffle, air guidance has a significant contribution into a more proper reactants transport, though it was observed that, there is a separated liquid–gas transport, which minimizes the area covered liquid on GDL surface [26].Thus, it paved way for mass transfer due to large passage area. Thitakamol *et al*. (2011) designed an interdigitated or mid-baffle flow field for PEM for fuel cells and test its effect on fuel cell performance at different gas (oxidant) flow rates and operating pressure [27]. The results showed that when the air was used as cathode oxidant, a cell with interdigitated or mid – the baffle flow field performs better than the cell with convectional flow field, where a power output of about 1.2 to 1.3 times higher was recorded. Kahraman *et al*. (2017)introduced a new innovative design to the flow channels, which is inspired by leaves veins of trees, where they added cylindrical obstacles at the bottom of the daughter channel with the view of increasing diffusion to gas diffusion layer and reducing concentration loss meanly at high current density [21]. It was observed that the cell performance was better with new invention than with the serpentine design. Vijayakrishnan *et al*. (2019)tried to address the issue of water lodging at cell cathode using a novel sinuous flow field, in which he scaled up 25cm^2 PEMFC to 100cm^2[28]. Theresults showed an improvement in water removal on the normal serpentine flow field; he explained that the improvement is as the results of inter-channel diffusion and convection at under the rib. Xu *et al*. (2019) explained that wave-like gas flow channels (GC) of PEMFCs, with air feed, show more significance than the straight GC; this is due to the lack of collision of the secondary flow and also diffusion in the gas diffusion layer in the layer [29]. Therefore, it is more prone to water flooding than the wave-like gas flow channels which results in higher pressure drop and reactant flow blockage. Guo *et al*. (2016) investigated the effect of low gravity on liquid water removal from PEMFC [30]. The cell was tested at both horizontal and vertical flow orientations. Using a 3.6s short microgravity circumstance equipment, the cell performance at horizontal orientation deteriorated while that at vertical orientation was slightly improved. Molaeimanesh and Akbari (2016) investigated the effects of the two most important ant parameters pertaining to water management in the fuels cells, that's gas diffusion layer wettability and water droplet size, using many 3D LB [31]. Simulations results confirm that removal may face some certain difficulties at initial stage when GDL is not hydrophobic enough, or if the water droplet sizes are a bit large. Karthikeyan *et al*. (2020) in an effort to address this formidable task, PEMFC liquid water management, inserted a porous insert in-line and staggered orientation at point of serpentine flow landing[32]. The inserts used were: porous carbon insert (PCI) and porous sponge insert (PSI). Results showed a better power density with PSI then with the carbon porous insert.Qi *et al*. (2018) used a PEMFC with modified gas diffusion layer which has a hydrophilic needle, and investigated the effects of the needle orientation, and gas velocity on water transport and its evacuation process [33].Their findings show that, at large needle angle of inclinations and gas velocity, the water removal process is more effective, while water flows within the flow channel experience small pressure drop when the needle inclination angle is small. They also noted that these modified channels with a needle are more effective in terms of water removal from the PEMFC than the convectional flow channels at low gas velocity. Wan *et al*. (2020) stated that channel flow geometry in bipolar plates (BPs) also affects the performances of the cell, and in his research, he tried to optimize straight channels by targeting minimum entropy generation[34].

3.5 Effect of Micro Porous Layer (MPL)

Properties of gas diffusion layer GDL, is very crucial in PEMFC performances. A thin layer that is coated on GDL with a much smaller pore then fibrous substrate, forms an improved mass transport barrier for the gases that are coming from gas flow channels and its effective diffusion improve the cell performance in general [35]. It was found that higher liquid microporous layerporosity results in a decrease of liquid water saturation which as such increase the PEMFC performances, while thick MPL shows negative results in which the cell performance reduced [36].It was also noted that having MPL not only help in water management but also improve the cell thermal management which is an issue that poses a serious concern too, just like water management. Experimental results confirm that the addition of MPL, is significant in improving the performance because it helps in humidifying the cell electrolyte membrane, thereby resulting in better cell performance [37]. They also explained that adjusting the MPL contact anglehigher had effects on improving the cell performances.Lin *et al*. (2019)explained that MPL has a significant influence on PEMFC performance [38]. They also investigated some factors that affect the MPL performance in the cell such as hydrophobic agent, the ratio of carbon powder to hydrophobic agent, carbon powder and microporous layer loading. They noticed that amongst the factors investigated, the ratio of carbon powder to hydrophobic agent has the least effect on the cell performances, because the other three factors affect the cell mass transfer and its ohmic resistance.Pourrahmani *et al*. (2019) stressed the fact that researches confirmed the influence of MPL on cell performance both in water and thermal management of the cells [39].They also investigated the effect of MPL thickness on the cell performance in which the results showed that thick MPL gave higher heat transfer rates.Salim *et al*. (2020) studied the effects of added MPL to both the cathode and anodes of the PEMFC, using 3D numerical single phase model [40].Results showed that the MPL improved the cell performance in regard to heat and mass transfer. Tseng and Lo (2010) found that the presence of MPL helped in decreasing the saturation water at gas diffusion layer, and facilitate the oxygen gas transport to the catalyst layer of the cell [41]. Pasaogullari and Wang (2004) stated that putting microporous layer(MPL) between the gas diffusion layer and PEM improves liquid water removal and also decrease catalyst layer saturation, especially catalyst layer saturation is reduced when thin and highly hydrophobic MPL was used [42]. Investigation on the role of MPL in water transport in PEMFC by [43] revealed that the function of the microporous layer is based on the humidity level and temperature at which the cell is operating, MPL enhances cell performances at both low and moderate temperature conditions under either low or high cell humidity, at high humidity MPL prevent the water formation at its tiny pores than in GDL, there reduce the risk of flooding, while at low humidity, its prevent loss of water to the gas channels which improve back diffusion, and minimize membrane dehydrations. An experimental study by [44] showed that the cell performance, especially at low current density, is improved when MPL was added. This development was as a result of good hydration condition of the cell membrane.Kang and Ju (2009)developed a model using Mixture model to investigate the functions of MPL in PEMFC operation [45]. They found that MPL that is free from liquid improves water backflow across the cell membrane to cell anode, and this enhances cell performance because its help avoids membrane dehydrations GDL flooding. Carcadea *et al*. (2020)investigated the effect of GDL thickness, where it explains that a cell performs much well when GDL thickness was reduced so also when the GD porosity increase[37].

4.0 MAINTENANCE OF WATER CONTENT

Effects of Low Water Content and the Importance of Maintaining Water Balance in PEMFC

As the removal of excess water from the cell is important so is the maintenance of the water content within the cell, because low water content also affectsthe cell performances.Maintaining good conductivity of proton is one of the keys to having a better cell performance, so that the water content in the cell has to be maintained at a level that ensures the cell membrane remains hydrated [46]. MPL has shown good sign and of significant impact to the issues of water removal and management of the PEMFC. It was observed that at both low and medium current density condition of the cell operation, the addition of MPL greatly improves the cell performance, because it lowers theohmic (resistance) losses. Due to good hydration state of the cell membrane, it also forms a pressure barrier that forces the water produced at the cathode to anode which helps in attaining a water balance but at the expense of increasing the liquid water flooding at high current density condition, as the water floods the anode gas flow channel [44].

Using numerical modeling of the analysis of micros porous effect on PEMFC performance, it was found that when the MPL is free from liquid water, the water flow across the cell membrane to anode (back flow) is greatly enhanced, thereafter reducing the fear of dehydration of the cell membrane since a water balance is attained and also it alleviates the GDL flooding. Thus, the study also confirms the improvement of the performance with the introduction of the MPL [45].The operating temperature is another parameter that affects the cell performance; increasing the temperature is very undesirable as it tempers the cell water balance by dehydration of the membrane. Also, another issue related with the cell water content is the voltage undershoot issue, which is noted to normally arise when there is a dynamic change between the membrane water and that of the humidifier [47].The effect of the operating pressure was also investigated in depth by many researchers. Misran *et al*. (2013) studied the effects of the operating pressure and temperature on liquid water transport in the PEMFC [48]. The results showed that the reduction inthe relative humidity at the anode of the cell was due to the high temperature and pressure, which cause the liquid water content along the channels to decrease, therebyaffectingthe cell ionic conductivity. Favorable operating conditions or parameters not only improve the cell output but also its life cycle, though research on the impact of these parameters is very limited. It isalso evident that uneven distribution of gas is yet another reason behind the fuels cells life degradation and this is directly related to the cell operating conditions [8].

5.0 CONCLUSION

From the review work, it was shown that great efforts have been placed toward developing a sustainable and most efficient away of attaining the water balance in PEMFC for more efficient and long-lasting operation. A great deal of progress is achieved concerning the issue, but yet it is not enough to make these fuels commercially viable. Moreresearch is needed on this issue, particularly when these cells are to operate at a high current density as this is one of the conditions where the severity of the water flooding is felt the most. As more water is being produced from the cathode, it makes the condition more difficult to handle and causes degradation and reduction of the PEMFC performance.

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