Study of Water Droplet Dynamics and its Removal in Polymer Electrolyte Fuel Cells: A Review

Dr. Kamal Kishore Pathak
1Department of Mechanical Engineering
1Government Polytechnic Sheikhpura, Bihar
pathakkamalkishore@gmail.com

Abstract—The depleting nature of fossil fuels has encouraged the exploration of alternate source of energy. Fuel cells have emerged as a clean energy technology with the advantages of formation of harmless by products. PEMFC (Proton exchange membrane fuel cells) have gained attention over the last few years as a promising power source. Water is the main by product of PEM fuel cell. Despite of the fact that some quantity of produced water can intensify the performance of the cell by hydrating its membrane, a plenty amount of liquid water can decrease the performance of the cell by filling the open pores of the gas diffusion layer (GDL). Therefore water management to protect the membrane from drying and electrode from excess water is the main concern during the operation of fuel cells. This study mainly concerns with the measurement and disconnection of liquid droplets in channel attached with cathode for PEM fuel cells. Many fuel cell researchers have actively conducted studies with the help of visualization techniques. Besides this various numerical approach have also been investigated to understand the droplet dynamic behavior. However the lack of a comprehensive understanding of the underlying liquid water transport mechanism through the GDL causes certain limitations in modeling studies. In this review various experimental results will be presented and discussed. The effects of GDL parameters, such as micro-porous layer and GDL thickness, on droplet removal are generally studied by analysing the contact angle hysteresis with inlet air flow. The discovery of this study is that for enhancement of water droplet removal the proper tailoring of the GDL parameters (wettability, thickness etc) is essential.

Keywords— Fuel cell, Proton exchange membrane (PEM), Gas diffusion layer (GDL).

1. INTRODUCTION

Fuel Cell, as the name indicates, is an electrochemical device that generates electricity by converting chemical energy in a fuel directly into electrical energy. The electricity produced from the fuel cells can differ from trivial devices of only a few watts, extend up to large powerplants generating megawatts. A fuel cell can run for an unspecified time period, as long as it is supplied with a source of hydrogen and a source of oxygen (usually air). Oxidation and reduction electrochemical reactions occurring inside the fuel cell, produce heat and low-voltage current. The former is wasted while the latter is used to do useful work [1]. Based on the choice of fuel and electrolyte, fuel cells are classified into different types. The fuel cells are mainly classified as follows:
1) Polymer Electrolyte Fuel Cell (PEFC)
2) Alkaline Fuel Cell (AFC)
3) Phosphoric Acid Fuel Cell (PAFC)
4) Molten Carbonate Fuel Cell (MCFC)
5) Solid Oxide Fuel Cell (SOFC).

The main difference in these types of fuel cells are discussed in table 1. In general, the choice of electrolyte determines the electrode reactions, the type of ions that carry the current across the electrolyte and it also dictates the operating temperature scale of the fuel cells. The operating temperature of fuel cell further recite some of the properties of the materials used in cell components, such as physicochemical and thermomechanical. The current analysis focus on the Polymer electrolyte Membrane fuel cells (PEMFC).

<table>
<thead>
<tr>
<th>Type of fuel cell</th>
<th>Fuel required</th>
<th>Operating temperature</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer Electrolyte fuel cell</td>
<td>Hydrogen supply</td>
<td>80 °C</td>
<td>Low temperature operation, high efficiency, high H2 power density, Quick</td>
<td>Expensive catalyst, poor-quality waste heat, thermal and water management</td>
</tr>
</tbody>
</table>

Table 1 Types of fuel cells and their advantages and disadvantages
<table>
<thead>
<tr>
<th>Type</th>
<th>Hydrogen supply</th>
<th>Operating Temp</th>
<th>Efficiency</th>
<th>Oxygen reaction</th>
<th>C1. Must run on pure oxygen without CO₂ contamination</th>
<th>C2. Low CO₂ tolerance, good quality waste heat, durability</th>
<th>C3. Low power density, slow startup, expensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline Fuel cell</td>
<td>Hydrogen</td>
<td>70 °C</td>
<td>High</td>
<td>Low oxygen reduction reaction losses</td>
<td>Must run on pure oxygen without CO₂ contamination</td>
<td>High efficiency, low oxygen reduction reaction losses</td>
<td>C1. Must run on pure oxygen without CO₂ contamination</td>
</tr>
<tr>
<td>Phosphoric Acid</td>
<td>Hydrogen</td>
<td>200 °C</td>
<td>Low CO₂</td>
<td>good quality waste heat, durability</td>
<td>Low power density, slow startup, expensive</td>
<td>C3. Low power density, slow startup, expensive</td>
<td>C2. Low CO₂ tolerance, good quality waste heat, durability</td>
</tr>
<tr>
<td>Molten Carbonate</td>
<td>Hydrogen and carbon monoxide supply</td>
<td>650 °C</td>
<td>CO₂ tolerant, use with many fuels, high-quality waste heat, low-cost catalyst</td>
<td>Long start-up time, electrolyte maintenance, CO₂ injection to cathode</td>
<td>C1. Must run on pure oxygen without CO₂ contamination</td>
<td>C2. Low CO₂ tolerance, good quality waste heat, durability</td>
<td>C3. Low power density, slow startup, expensive</td>
</tr>
</tbody>
</table>

1.1. **PEM fuel cells**

The proton exchange membrane fuel cells (PEMFC) take a proton exchange membrane (PEM) as electrolyte and represents the most common type of fuel cells. Its operating temperature range is about 80°C and efficiency is in the range 40 to 50 percent. Operating principle of the PEMFC is explained as: hydrogen fuel is oxidized at the anode, releasing electrons & producing protons. The protons and electrons flow through an external circuit and passes through proton exchange membrane, to cathode, then they combine with the dissolved oxygen to produce water and heat[1]. PEMCs are being followed for a wide variety of practical applications, especially for main power of fuel cell vehicles (FCVs)

1.2. **Components of PEM fuel cells**

PEM fuel cell consists bipolar plates and MEA (membrane electrode assembly). As shown in figure 1, the Bipolar separator connect the cell electrically in series in a stack, additionally, it also separate the gases in adjacent cell. Bipolar plate is generally made of two different material which are graphite composite and metallic. A typical MEA is made up of a Polymer Electrolyte Membrane (PEM), two Gas Diffusion Layers (GDL) and two catalyst layers.

- Gas diffusion layer (GDL): It is a porous material made by pressing carbon fibres in conjunction into a carbon paper (Toray, Sigracet). It is used to transport and distribute heat and fluids between bipolar plate gas channels and the catalyst layer. GDL also transport electrons from and to bipolar plates. Now a days, a micro porous layer (MPL) and hydrophobic treatment (PTFE) is made to the GDL to distribute the fluids furthermore in the catalyst layer.

- The Catalyst layer is where the electrochemical reaction occurs. It is where the protons, electrons, and oxygen react electrochemically and produce water and heat. The most commonly used catalyst for the PEM fuel cell electrochemical reaction is Platinum (Pt). The availability and the size of the active area of the catalyst is important factor rather than the amount of the catalyst. Hence, researchers have been able to reduce the amount of platinum from 5 mg/cm² to 0.5 mg/cm² to reduce the cost.
- The membrane is used to separate anode side from the cathode side. Simultaneously, it transports the proton from anode to cathode. The membrane is typically made of perfluorosulfonic acid ionomer (PSA). The best known membrane is a Teflon-like material known as Nafion. It provides mechanical strength, proton conductivity & dimensional stability. In the membrane assembly, three mechanisms govern water transportation, these are the electro-osmic drag, diffusion, and permeation. The mechanism is induced individually by moving protons, the difference in water concentration, and the difference in pressure between the two sides of fuel cell, respectively. The electro-osmic drag transports water from anode to cathode, because of the proton transfer mechanism; whereas, the diffusion and permeation can move water from any of the sides to the other, depending on the difference in concentration.

![Figure 1 Components of Fuel Cells](image-url)
1.3. Working of PEM fuel cell

The basic diagram of the various components a PEM fuel cell is represented in figure 1. Hydrogen gas is supplied to the fuel cell anode, which then travels through gas diffusion layer (GDL) to anodic catalytic layer where it get oxidized, leading to transfer of proton via the exchange membrane (PEM) & electron transfer through the external electrical circuit. Oxygen, at the same time is fed to the cathode and diffuses into cathodic catalytic layer, after that it combines with the protons and produces water. The anodic and cathodic reactions as well as the overall cell reaction are shown below:

Anode: \[2 \text{H}_2 \rightarrow 4 \text{H}^+ + 4e^- \quad (1)\]
Cathode: \[\text{O}_2 + 4 \text{H}^+ + 4e^- \rightarrow 2 \text{H}_2 \text{O} \quad (2)\]
Overall Reaction: \[\text{O}_2 + 2 \text{H}_2 \rightarrow 2 \text{H}_2 \text{O} + \text{heat} + \text{electrical energy}\]

The different transport process occurring inside the electrode are as:

1. The product and reactant gases the gas channels and between the catalyst layer respectively.
2. Electrons between the catalyst layer and the current collector via gas diffusion layer.
3. Protons to/from the membrane and the catalyst layer.
4. Protons via membrane from the anode to the cathode.

1.4. Advantages of PEM FC

Among various advantages, one of the most important advantage of PEMFC is that as Hydrogen is used as fuel, its emission is free of pollutants. It has a low operating temperature that allows rapid start-up. It does not have any corrosive cell constituents so the use of the exotic materials for preventing corrosion is not required. The PEMFC fuel cell has a solid electrolyte which allows excellent resistance from gas crossover. Other advantages of fuel cell includes High power density, high efficiencies.

1.5. Disadvantages of PEM FC

Water management is critical challenge in PEFC design, because balancing enough hydration of electrolyte against submerging the electrolyte is must. The low operating temperature range makes thermal management difficult, mostly at very high current densities, and makes it difficult to use the waste heat for cogeneration. Additionally, PEM fuel cells are very sensitive to poisoning by trace levels of contaminants including sulfur, CO, and ammonia.

1.6. Water management in PEMFC

In a PEM fuel cell, condensation of the water generated in the electrochemical reaction in PEMFC is inevitable as the cell operates under a low temperature. Condensed liquid water appears mainly at the cathode side of the PEMFC where water is generated from the reduction reaction. As there is water concentration difference on the anode side so some liquid water may transfer to that side across the MEA, but the amount of the liquid water in the anode side would be very small compared to that in the cathode side [3]. At the interface of the membrane and the cathode side catalyst layer in the PEMFC the reduction reaction occurs. The condensed water will move through the gas flow channel and the porous layers, while the amount of water increases by continuous reaction. The liquid water behavior in these areas has a large influence on the fuel cell performance. On one hand, a certain amount of water in the PEMFC is necessary to help enhance the ion conductivity of the membrane. Else ways, excessive liquid water can corrupt the fuel cell performance causing low efficiency and instability. The reason for saying liquid water will corrupt the fuel cell performance is that the porous layers and channel where liquid water will move through are also the essential path ways for the reactant gas to reach the membrane and join the reaction. The liquid water in these areas will influence or even block the gas flow, thus reducing the electrochemical reaction rate and reduce the fuel cell performance. In actual fact, a detailed investigation of the liquid water removal process is unavoidable to improve the PEMFC performance.

1.6.1. Static droplet

Figure 3 shows an illustration of static droplet of water on a hydrophobic porous material surface. A liquid droplet seating on the solid surface has mainly spherical shape & its patch contact area is dependent only on material properties. The most frequently geometric parameter used to characterize the material with liquid interaction is the static contact angle \(\theta_s\), that is the angle between the solid material surface and tangent
to the surface of liquid at point of contact. It is basically the angle within the liquid and is larger or smaller than 90° depending upon the material nature, i.e., hydrophobic or hydrophilic respectively.

2.1.2. Deformed droplet

When the droplet illustrated in the preceding section is subjected to the gas crossing-flow, it disfigures in the direction of the flow, forming a pinning with the upstream part as represented in figure 3. The static contact angle changes, precisely, the downstream one increases while the upstream one decreases. For this reason, they are named receding $\theta_R$ and advancing $\theta_A$ contact angle respectively.

![Figure 3: Schematic of the drop in the flow channel](image)

2.2. Forces acting on droplet

Surface tension and surface energy is important part for calculating both the adhesion forces together with droplet deformation. Surface energy is basically the energy linked with intermolecular forces at the interface between the two surfaces. The surface energy per unit area is equals to the surface tension also known as free surface energy. Other terms that needs to be defines is the work of adhesion. The reversible work that is done to separate two unit areas of the different material from contact to the infinity in the vacuum is known as work of cohesion.

![Figure 4: (a) Droplet image in existing air flow and (b) Force acting on droplet](image)

In order to forecast the behavior of water droplet in a flow channel, macroscopic force balance is illustrated in Figure 4.

In general, the liquid droplet shape on the surface is controlled by surface tension, the normal stress on the free surface as a result of gravity, and fluid flow within the drops [16]. A simple drop shape is spherical with negligible gravity effects on the small droplets. Figure 4 illustrates a macroscopic force balance model of the droplet in the existence of air flow. The control volume is defined with planes A and B, and the depth is equal to the diameter of the droplet. The pressure difference between A and B is the total pressure force. Pressure force ($F_p$) is created by the difference of pressure between the front and back of droplet in the flow field and can be written as

$$F_p = (P_A - P_B) \times \text{Area} = (P_A - P_B)2B \times 2R$$

where $P_A$ and $P_B$ represent the pressure at A and B planes, and $2B \times 2R$ denotes the cross-section area of the control volume. The drag force ($F_{drag}$) is generated by the fluid shear alongside the surface of the droplet, and the difference of pressure is the total exerted force on the droplet. Therefore, force balance is given by

$$F_{drag} = F_p + F_{shear}$$

where $F_{shear}$ is the shear force exerting on the top of droplet due to the no-slip condition. In static condition, the drag force is balanced by the surface tension force, which is the force that relates to the attractive force by molecules of a liquid and the surface contact angles of the droplet emerging on the plate as represented in Eq. 5 for stable condition. If the surface tension force is equal or more than the drag force, the droplet will not move from the channel. The crucial condition is a point when the droplet tends to move. In the force balance model, the critical state is the situation when the surface tension is counterbalanced by drag force. If the drag force is increased above the critical point, the droplet will become unstable and start to move from the channel.

$$F_{ST} > F_{drag}$$

In the balance equation the force caused by surface tension is a key factor because it is connected to traction and contact angle of water droplets evolving in the channel surface.

2.3. Contact Angle

![Figure 5: Schematic of contact angle of droplet wetted to surface](image)
The wetting of the solid due to liquid is measure by contact angle \( \theta \). It is geometrically defined as the angle formed by the liquid droplet at free phase boundary that is intersection point of the gas, liquid and solid as shown in Fig. 1. The low values of contact angle show that the liquid advances, or wets the surface, and high values indicates poor wetting. As clear, zero contact angle represents complete wetting and formation of liquid film on the surface. If the three-phase (liquid–solid–air) boundary is in true movement the angles developed are termed as dynamic contact angles and are referred as ‘advancing’ and ‘receding’ angles. The difference between ‘advanced’ and ‘advancing’ as well as ‘receded’ and ‘receding’ contact angles is that these angles are realised at condition of static droplet rather than in true liquid movement but as a deformed shape deviating from being spherical.

Macroscopically, adhesion forces can be found as a result of the variance of surface tension forces at solid–liquid–air boundary. Let \( \sigma_{sl} \) denotes the interfacial tension developed due to the liquid–gas surface, \( \sigma_{lg} \) to denotes the interfacial tension developed due to the solid–liquid surface and \( \sigma_{sg} \) to refers to interfacial tension of solid–gas surface. In thermodynamic equilibrium the static contact angle \( \theta \) is described by Young’s law:

\[
\sigma_{sg} = \sigma_{sl} + \sigma_{lg} \cos \theta
\]

(7)

3. EXPERIMENTAL AND NUMERICAL WORKS ON DROPLET REMOVAL FROM PEM FUEL CELLS

The main factors influencing fuel cell performance is the fluid flow inside the fuel cell. The gas and liquid water transportation behavior inside the PEMFC has become the center of the research concentration in the current scenario. To investigate physical phenomena, experimentation is always firstly considered, however in a PEMFC system, electrochemical reaction and multi-component mass transport are involved together, so the detailed investigation cannot be achieved by experiments. Therefore, numerical modeling & simulation are mostly applied to investigate the PEMFC in detail. In recent years, along with the continuous improvement of numerical models, different experimental setups are also constructed to observe some of the phenomena in the PEMFC and validate the numerical models.

Theodorakakos et al [24] in 2006 investigated experimentally and computationally the disengagement of liquid droplets from a porous material surface along with proton exchange membrane (PEM) fuel cells within the control of the crossflowing air. The water produced under the PEM formed droplets on the surface of gas-diffusion layer was been disclosed by CCD images on the transparent fuel cell. These droplets were wiped away when the velocity of the streamlined air is more than the critical value for known droplet size. The single-stuck transparent model with bipolar plates and MEA was constructed for visualizing the water flow within air channels of the fuel cell. The width & depth of the air channel were 1.46 × 0.29 mm, respectively. The droplets tested were detached from the surface at air speeds in the range 6 to 15 m/s, and corresponding Reynolds no. was between 1500–4500. The dynamic advancing & receding contact angle datas were estimated with the last image recorded just before droplet disengagement. Those values were also used by the computational model for predict predicting the separation curve. The effect of the incoming air velocity profile and the droplet location within the air channel was investigated experimentally. The results established that uniform air speed disengages liquid droplets at the lower mean air speeds. In addition to that, the influence of water flow linking the liquid droplet with the porous material, the effect of water temperature & the effect of gravity were investigated numerically.

Fang et al [14] proposed a numerical volume of fluid (VOF) theory which takes into account surface adhesion forces by focusing the influence of contact angle hysteresis. Two experiments were conducted including droplet disengagement on a rotating ring and liquid slug flow in a micro channel for verification of the model, and a methodical comparison between experiments & simulations was performed. Droplet disengagement on four materials, along with coated silicon wafer, GDL with 0%, 5%, & 10% teflon was tested. The silicon wafer was rendered hydrophobic by Molecular Vapor Deposition (MVD). With increase in the concentration of the added Teflon, the hydrophobicity of the GDL increases. In liquid slug flow experiment in microchannels with sidewall water injection, the channel is etched to 45 μm depth and 500 μm in width. Air passes through the microchannel & the water is supplied into a microchannel through a 20 μm wide slot situated 2/3 of the way downstream from microchannel air inlet. To provide the microchannels hydrophobic, Molecular Vapor Deposition (MVD) of the Self-Assembled Monolayers (SAMs) is done. In both the cases, quantitative matching is received for a wide range of fluid conditions & the importance of contact angle hysteresis effect has been clearly described.

Karthikeyan et al., [33] studied an experimental examination on serpentine flow channel along with various operating variables for PEMFC execution. Water concentrations in the flow channel were measured and the image of the disassembled fuel cell has been captured to study the impact of water on PEMFC performance. This study is very important to convey further experimental examination on PEMFC along with various porous flow channel outlines. Also, this study enriches the current database of the experimental results on the PEMFC performance.

Liu et al. [23] in 2012 carried out an ex situ simulation of the cathode side of a PEMFC for GDL samples with four different morphologies. Water emergence through the GDL was visualized and coupled with capillary pressure measurement to analyze the dynamics of water transport through the GDL samples. A 20 mm 5mm rectangle was cut into the bottom polycarbonate plate to supply water through the GDL and the upper plate featured a 24 mm 11 mm visualization rectangle that was open to atmosphere [23]. A
syringe pump supplied water to the GDL sample which was sandwiched in between two polycarbonate plates. A differential pressure sensor measures the difference between atmospheric & water pressure. The GDLs tested were 30 mm 15 mm carbon fiber, carbon cloth, carbon cloth with a MPL applied on one side, and carbon cloth with MPLs applied on both sides. The simulated water production rates were 10, 20, and 50 µL min-1 and the water was injected up through the MPL, if the specimen featured one, and then through the fibrous part of the GDL. The carbon paper GDL exhibited a linear increase in water pressure until the CBP value was reached. Subsequently, a sharp decrease in pressure occurred and a steady residual water pressure was established.

Wan et al in 2013 [17] investigated the working characteristic of the dead-ended proton exchange membrane fuel cell (PEMFC) placed in vertical orientation. The relationship between the channel geometry & wettability of the gas diffusion layer (GDL) surface was theoretically analysed. The straight flow channels with 2.0 mm width and 1.0 mm depth are considered for experimental analysis & moisture is condensed in the stack end to improve water removal. It was found that the designed fuel cell can work for about 1 h at 750 mA cm⁻² & the performance of fuel cell decreases with the increase in the working temperature.

Yoon et al [10] in 2014 carried out ex situ measurement study of water droplet expansion & its removal on GDL surfaces in a simulated non-reacting cathode channel for PEM fuel cells. The experiments were carried out using three types of SGL carbon GDLs (SBL10BA,SBL10BC, and SGL24BA, with SGL 10BA as base GDL material). Water was allowed to penetrate the GDL using syringe pump and capillary tube to mimic the water transport through GDL. A charged-coupled device (CCD) was used to observe the growth and detachment of liquid water droplets. The images of the deformed water droplet were recorded and analyzed to measure droplet height, and the dynamic contact angle. The effects of GDL parameters (wettability, GDL thickness, and MPL inclusion) were mainly investigated on the water droplet removal by analysing contact angle hysteresis with inlet air flow rate (Reynolds number). It was observed that the water droplet on GDL with a MPL (SGL 10BC) tends to removed at a high critical Reynolds no. under the same droplet height.

Shimpalee et al [16] in 2016 analyzed the liquid water droplet motion by taking into consideration the change of contact angle with variable flow rates, they used surface roughness properties to report the contact angle & droplet removal force on the stainless steel flow channel. The experiment was performed in a channel with channel width =4mm, channel depth = 2mm, and channel length =120mm. The channel length was long enough for flow rates up to 2500cm³/min to be fully developed as laminar flow. Samples of electrochemically etched stainless steel plates with various average roughness (Ra) values were placed into the inserted channel floor space to determine the distortion and the motion of liquid droplet under different surface properties. The average roughness (Ra) and roughness factor (r) were measured by AFM. The surface roughness of the sample plate was changed by changing the etching parameters, specifically increasing or decreasing the forward (anodic) peak voltage of the etching waveform or removing the reverse (cathodic) peak voltage from the waveform. It was found that the contact angle rises with the increasing values of surface tension. it was found that the surface roughness which has the best water removal properties at the lowest pressure drop was the smoothest surface.

Hussaini and Wang [6] in 2009 presented an in-situ visualisation study of the cathode flooding in an working fuel cell. Four flow patterns were identified in the two-phase flow; single phase flow, droplet flow, film flow, and slug flow. A flow pattern was drawn identifying the four flow patterns according to air and water velocities. Channel flooding was found to increase the pressure drop dramatically and cause a voltage drop under low stoichiometry conditions.

Lu et al. [9] examined water management in fuel cells in a series of studies, however in their recent study [10] they examined the influence of channel surface wettability, cross-sectional geometry & orientation on the two phase flow in parallel gas channels. Three wall wettabilities were examined; hydrophilically coated, uncoated, & hydrophobically coated. The hydrophilically coated walls were found to be beneficial over the other types for providing uniform water and gas flow distribution and favouring film flow; the most desirable flow pattern in a PEM fuel cell gas channel. Three cross-sectional geometries were examined; rectangular, sinusoidal, and trapezoidal. Sinusoidal geometry was in favour for providing a film flow and low pressure drop when compared with the other geometries.

Wu and Djilali [19] in 2012 investigated the water droplet dynamics emerging from a pore in airflow channel, representing a fuel cell gas channel. Three flow patterns were identified: slug, droplet, and film flow, under various air and water velocities. An increase in air velocity changes the flow pattern from slug to droplet and film flow which is due to a decrease in the dynamic contact angle. This angle represents droplet stability, which is its ability to resist the drag force on a given surface.

In 2013, San and Isik-gulsac [32] changed the wettability of polymer composite bipolar plates using organic based hydrophobic and inorganic based hydrophilic additives, and then analysed fuel cell performance. Performance was reportedly unaffected by the additives at low current densities; however, the cell with a bipolar plate with no additives showed better performance than the cells with organic or inorganic additives at medium and high current densities. According to their results, the highest performance data obtained was with a polymer composite wall, with a contact angle of 80°. The contact angle of the GDL was not specified and the wettability combination of wall and GDL possibly affected the liquid droplet behaviour.

Gopalan and Kindlikar [13][18] (2013; 2014) studied the effect of channel material on the behaviour of liquid water in a trapezoid gas channel. Air velocity and contact angle influenced water behaviour in the channel. Contact angle also
affect liquid water filling in the corners, which influenced channel blockage. Low air velocities allowed liquid water to fill the channel corners and form a slug flow, while at high air velocities water did not fill the corners and to form a film flow.

**4. Effect of Parameters**

**4.1. Effect of wettability**

The contact angle is an effective measure of the wetting characteristic of a solid surface by liquid droplets [34][35]. Figure 6 represents the static contact angle and dynamic contact angle of a liquid water droplet seated on GDL surface. Various studies have been done which shows that the contact angle is used as a main parameter in water management of fuel cells. It can be identified by surface adhesion force, drag force and capillary pressure. In addition to that, the contact angle measurement can be used to obtain information on the surface material and surface roughness [35].

In a study done by Yeogun et al [13], the static contact angle is adopted as the main parameter for estimating the surface energy of the adopted GDL samples. When the droplet is subject to an air shear flow, they are deformed in the longitudinal flow direction by the force exerted by the gas flow. In that case, the left (receding) and right (advancing) side dynamic contact angles are observed. The difference between these angles is represented as the contact angle hysteresis. They performed the experiment with GDL material SGL 10BA and SGL 10BC, with different hydrophobicity and found that there are no larger differences in the static contact angles between the samples. The contact angle hysteresis is also known to be a key factor in estimating the surface adhesion energy and droplet mobility. Theodorakakos et al [24] have performed experiment for measurement of static and dynamic contact angles using the sessile drop method. They measured static contact angles for the three materials as function of droplet size. It can be seen that each material has a different static contact angle. It was found that the material which shows the larger value of static contact angle indicates smaller droplet deformation. It is thus expected that for this material smaller air velocity will be needed to remove the droplet from its surface.

**4.2. Droplet dynamics at gas flow channel/GDL interface**

Liquid water forms droplet on the GDL as it offers the least transport resistance. The emerged droplet grows in size until it becomes large enough to detach from the GDL surface. Moreover, it is not possible to detach the droplet with a low superficial gas velocity. The drag force come into existence due to the gas velocity and it increases with the air flow rate as shown in figure. The imbalance of the drag force and surface adhesion force determined the change of shape change of the liquid water droplet in the gas flow channel. The surface adhesion force holds the water droplet on the surface, although the drag force supplied from the flowing gas tries to disengage the droplet from surface. Droplet detachment carried out when drag force overcomes the surface adhesion force.

![Figure 7 Force acting on a droplet in air flow](image)

The contact angle hysteresis depends on the air flow rate (Reynolds number), surface characteristics of the GDL (PTFE content), surface roughness, and droplet size (height and chord length)[10][31]. The detachment of the droplet also depends on the GDLs treated with different PTFE contents, which is related to spreading factor. The spreading factor, can be described as the ratio of the droplet diameter to droplet detachment diameter. The GDLs with a large amount of PTFE droplets requires less time to extend to the size at which they disengage [34].

**4.3. Impact of GDL type on water droplet removal**

The GDL plays a important role in water droplet removal. Some of the tasks performed by GDL in the fuel cell are (a) it removes heat & excess water from the electrode to stop local hotspots & catalyst flooding, (b) it distributes reactant gases uniformly from the flow field for electrochemical reaction. Therefore GDL should have good electrical & thermal conductivity also high thermal & chemical resistance and enhanced water & gas permeability. In addition to that, the GDL thickness influences all these mentioned characteristics, hydrophobicity & alignment of carbon fibers. Generally, there are three basic types of carbon fiber substrates which can be employed as a GDL: carbon cloth, carbon paper & carbon non-woven.

In the GDL, the deformation of the liquid water droplet in the gas flow channel is determined by the imbalance of two main
forces (the drag force and surface adhesion force). The drag force exerted by the air flow increases with the air flow rate, and causes an increase in the contact angle hysteresis. In addition, with increased velocity, the surface adhesion force between the water droplet and GDL cannot resist the increased drag force. At that instant, the droplet detachment from the GDL surface starts. The contact angle hysteresis is dependent on the surface characteristics of the GDL (PTFE content), air flow rate (Reynolds no.), droplet size (height and chord length), and the surface roughness [20][22][23].

Yeogun et al [13] investigated the effects of GDL parameters on the water droplets removal by analysing the contact angle hysteresis with the inlet air flow. It was found that the water droplets on a thinner GDL is about to be removed under higher critical Reynolds number. It was shown that the chord length of a water droplet varies with the tested GDL sample. An increase in the droplet chord length by the spreading of the droplet on the GDL surface causes an increase in the surface adhesion force, which can lead to droplet stabilization. This implies that a liquid water droplet is not easily removed from the GDL surface. Therefore, it should be noted that the increase in droplet chord length resulting from the variation in the GDL parameters can have a meaningful effect on the water droplet removal from GDL surface.

It can be seen that the critical contact angle hysteresis difference is relatively small in spite of the meaningful differences between the critical Reynolds numbers. The increase in the surface adhesion force due to the spreading of a droplet serves to stabilize the water droplet. Moreover, under an increased surface adhesion force, the GDL surface acts like a more hydrophilic surface. It is known that hydrophilic surfaces are less affected by the contact angle hysteresis than hydrophobic surfaces. Hence, this trend can also be understood by the effect of the water droplet spreading on a thinner GDL (SGL 24BC).

The GDL plays a vital role in water management that balances membrane hydration & water flooding. Gas diffusion media are commonly treated with a hydrophobic agent (for example PTFE) to restrict flooding the porous spaces with the accumulated water. It changes the wetting characteristics so that the water is better discharged. Hence most of the product water (at the cathode) can be accurately removed from the GDL to the flow field channels. These kinds of experiments lead to a combination of hydrophobic and hydrophilic pores in the GDL and hence, restrict water condensation in the GDL pores completely and assure a low water saturation level [24]. Hence, the hydrophobic pores allow a pathway for gas transport whereas the hydrophilic pores facilitate liquid water transport.

Gopalan et al [11] performed experiments to evaluate the effect of a GDL material on the growth of water droplet and its removal. For the experiment, TGP-H-060 & SGL-25BC with 6% PTFE as GDL materials was used. It was found that Hydrophobicity of the GDL material reduces with a longer work time, & tends to increase the accumulation of liquid water in channel when compared to that of fresh GDL samples. Which resulted in reduction of the available surface for the gas transport on the GDL surface & increase in gas transport resistance with more run times.

Generally, different GDL materials used in PEM fuel cell possess different surface characteristics, & hence vary in their droplets accumulation properties within the gas channels. A few detailed studies have further attempted to evaluate different channel properties, mainly focusing on the liquid water stagnation. It was found that the hydrophilicity of channel surface eases the removal of water by wicking it into channel corners. These results were in agreement with the conclusions derived from the more recent studies performed by Lu et al., [10] who found that the hydrophilic channels support in homogeneous water distribution along GDL surface. They stated that the hydrophilic channels aid in creating a film flow in the channel, & reduce the pressure drop in system compared to the hydrophobic channels.

4.4. Impact of Micro porous layer on water droplet removal

The micro-porous layer (MPL) that covers the surface of the GDL has a significant impact on water transport phenomena in GDL-MPL assembly. MPL is mainly a carbon powder-bound along with a hydrophobic material such as PTFE & has different microstructural characteristics as compared to GDL.

The role of MPL on the water transport within the cell has been described by different hypotheses. Some studies claim that coating a GDL with MPL helps water transport from catalyst layer to GDL due to the pore size gradient [9][10]. Some studies address that cathode MPL result in increment of the back diffusion of water from cathode to anode & others report that the MPL has no influence on the back diffusion of the water. According to the literature, an MPL plays a significant role in stabilizing the preferential pathway of water through the GDL. It has also been reported that the MPL facilitates water paths with less water entry points into GDL [25]. It was seen by yoon et al [13] that the contact angle hysteresis at the droplet detachment for the GDL with the MPL is larger than that for the GDL without an MPL.

Blanco et al. [35] studied the effect of MPL in the cathode GDL on the pressure drop measured in the anode and cathode of an operating PEM fuel cell. They measured the two phase flow pressure drop for the anode and cathode when the cell was operating at 25% and 100% relative humidity. Separate experiments were run for the cathode GDL with and without MPL. They found that MPL impacts water crossover from the cathode to the anode. It was found that cathode pressure drop of GDL without the MPL is more than that of the cathode pressure drop for a GDL with MPL, which further attributed to a lower amount of accumulated water in cathode flow channels when MPL was used.

5. Conclusion

This report reviewed the major issue impacting the performance and durability of PEM fuel cells, which is mainly the water Management. By optimizing the water management, it is possible of not only lowering the cost, but also increasing the durability and optimizing the cell performance. To achieve
optimum water management a subtle equilibrium between membrane dehydration and liquid water flooding is the key. The water management depends on several variables, such as the structural and wetting properties of the GDL and MPL, the reactant stream humidification, and the flow field layout. Extensive research works have been carried out over the past few decade on water management. These works includes visualization of liquid water distribution, experimental measurements, prediction through numerical modeling, and optimum strategies of water management including optimum operational condition, convenient cell system design and MEA material and structure design. Water management strategies needs to be addressed with due consideration to the overall system design, to maintain the overall system simplicity and minimize the system parasitic power loss, thereby decreasing the costs and increasing reliability. Structures and materials of the MEA must be given more attention than all strategies against water flooding because the first drop of water is produced in that, and there is almost no any important power loss and on assistant equipment is required by adjusting MEA materials and structure. Some of the important observation of this review is as follow:

(a) Enhancing the hydrophobicity of the GDL/GFC interface (that is the static contact angle) tends to decrease droplet height at departure. This reduces channel interactions which can result in flooding.

(b) Increasing the gas channel mean velocity will result in a decrease in droplet height at departure

(c) GDL roughness can be neglected when considering droplets.

6. REFERENCES


**AUTHORS PROFILE**

**Dr. Kamal Kishore Pathak** is currently working as a Lecturer (Selection Grade) at Government Polytechnic Sheikhpura (Bihar). He did his B.Sc. Engineering in Mechanical Engineering from Bihar College of Engineering, Patna in 1987. Since then he has been engaged in teaching and research. He obtained his M.Tech and Ph.D. from B.R.A. Bihar University, Muzaffarpur. He has wide exposure in the Mechanical Engineering field and has 30 years of experience in teaching engineering students. He is the life time member of Indian Society for Technical Education (ISTE) and also the author of the book "Strength of Materials (Mechanics of Solids)" ISBN : 978-8193003756, First Edition, Nexus Publication, Patna, 2017.