Effect of PTFE Content in Gas Diffusion Layer on Water Transport in Polymer Electrolyte Fuel Cells (PEFCs)

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Abstract

Water management in polymer electrolyte fuel cell is still one of the most challenging issues needed to be solved before this type of energy system can be widely commercialized. In this study, liquid water transport on the surface of the gas diffusion layer (GDL) is studied for different polytetrafluoroethylene (PTFE) content and superficial gas velocities within the gas channel. Taking an ex-situ approach, liquid water was injected on the back side of the GDL and droplet emergence and detachment on the other side of the GDL within a gas channel were visually recorded. Air and hydrogen were supplied separately to simulate droplet behavior in a gas channel in cathode and anode side of an operating fuel cell, respectively. Although it was observed that liquid water droplets showed similar contact angles on GDLs with different amount of PTFE, smaller droplet detachment diameters from GDLs with higher PTFE content were measured. Applying PTFE to the

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GDL decreases the surface roughness and since droplets tend to detach more easily from less rough surfaces, smaller diameter would be required for detachment. It was also observed that superficial gas velocity significantly affects the detachment diameter. Finally it was observed that droplets detach at higher superficial hydrogen velocity compared to air. Hydrogen’s lower density compared to air can be named as the main reason causing higher superficial hydrogen velocity required for detachment.

**Keywords:** Water management in PEFC, Gas diffusion layer, Droplet detachment diameter, Contact angle, Surface adhesion force, Drag force

1. **Introduction**

Polymer electrolyte fuel cells (PEFCs) are considered as promising power sources in automotive, residential and stationary applications [1]. They benefit from high efficiency as well as high volumetric power density without emitting greenhouse gas as they operate. However, there are some issues that need to be solved before this type of energy system can be commercially released. One of the most challenging issues not yet solved for researchers is the water management in PEFCs. As the electrochemical reactions occur in PEFC, hydrogen fuel is converted into useful power with water and heat as byproducts. Some portion of this produced water may be helpful in increasing the cell performance by hydrating the membrane and improving its proton conductivity and some other portion may transfer into anode by back diffusion or even evaporate into the gas channel. Any excess amount of liquid water fills open pores in the gas diffusion layer (GDL). As the amount of liquid water within the GDL increases, it ultimately saturates the GDL and
blocks the transport of reactants to the catalyst layer. This phenomenon is known as flooding and significantly deteriorates the cell performance. Flooding mostly happens at high current densities when the water production rate is considerable, but it may also occur at low current densities under certain conditions such as low temperature and low reactant flow rates. Accumulated liquid water within the GDL emerges from the GDL surface forming droplets. In general, liquid water removal from GDL surface follows two modes, depending on water production rate as well as superficial gas velocity, defined as the bulk velocity of gas flowing within the channel cross sectional area [2]. If the superficial gas velocity is high, the shear force from core gas flow detaches droplets from the GDL surface. When the superficial gas velocity is moderate, droplets grow in size until they touch hydrophilic channel walls and spread over them. In this case capillary flow drains the liquid water through the corners and forms annular film flow. For high water production rate and/or low superficial gas velocity that corner flow is not capable of draining all liquid water, liquid film grows in size and ultimately clogs the gas channel. This eventually stops the cell from producing electricity.

It is a common practice to treat GDLs with a hydrophobic agent such as polytetrafluoroethylene (PTFE) for better liquid water transport within the GDL [3]. Many works have targeted the effect of GDL treatment on cell performance [4, 5, 6, 7, 8, 9] as well as its effect on liquid water behavior within the cell [10, 11, 12]. Although all these works agree on improved cell performance with the cost of adding some amount of PTFE to the raw GDL, a common conclusion about the role of PTFE in GDL on liquid water transport has not been drawn. While some researchers report that increasing
PTFE content in GDL lowers liquid water transport rate through the GDL [5, 13], some other researchers confirm that a GDL with a slight amount of PTFE content shows significantly lower water wetting compared to an untreated GDL but adding more PTFE does not affect water wetting on the GDL surface [14, 15]. Although applying PTFE in GDL mainly affects water behavior within the cell, its impacts on other parameters also should be considered for an appropriate cell design. It has been found that increasing PTFE content within the GDL have some drawbacks such as decreasing electrical conductivity [9, 16], thermal conductivity [17], permeability [5, 9] and porosity [9, 18, 19].

Within the last few decades, different experimental approaches have been taken to study liquid water transport and distribution in PEFCs. Methods such as neutron imaging [20, 21], gas chromatography (GC) [22, 23] and X-ray techniques [24, 25] have enabled in-situ observation of liquid water distribution within PEFC. Other than the complexity and the high cost issues coming with these methods, they are either limited in spatial and temporal resolution (neutron radiography) or are not applicable to the situation with abundant amount of liquid water (GC). Direct optical visualization, on the other hand, is probably the simplest and the least expensive method to monitor liquid water behavior in a PEFC. Depending on the optical setup used, it can also benefit from high spatial and temporal resolution.

Although many works have been done on direct optical visualization [2, 10, 12, 26, 27, 28], there have been very few published reports regarding droplet growth and detachment on GDL surface with different wettabilities.

Theodorakakos et al. [29] made a direct visualisation experimental setup
and recorded droplet’s side view behavior upon detachment. Measuring the
dynamic contact angle, they correlated the droplet detachment diameter with
air velocity and found that the superficial gas velocity should be greater than
a critical value for a given droplet size to be able to detach. Bazylak et al. [30]
studied droplet growth and detachment on GDL surface by using fluorescence
microscopy and concluded that the breakthrough location changes over time,
suggesting an interconnected network of water pathway within the GDL.
They also noticed that detaching droplets leave a layer of residual water
on the GDL surface which provides pinning site for other droplets. Since
they only used one GDL sample with constant wettability, the influence of
surface energy on droplet behavior cannot be understood. Kumbur et al.
[26] used direct visualization and measured contact angle hysteresis as a
parameter determining the instability of the droplet under the influence of
a shear gas flow. They found that contact angle hysteresis increases with
PTFE content up to the point the adhesion energy between GDL surface
and droplet becomes insufficient to hold droplet on the GDL surface. Very
recently, Das et al. [31] studied droplet detachment from GDL surface by
measuring sliding angle and noticed that liquid columns formed underneath
the droplet and within the GDL pores assist droplet’s adhesion to the GDL
surface.

The hereby illustrated literature review highlights the lack of in-depth
studies of droplet behavior on GDL surface with different PTFE content. In
this work, droplet growth and detachment on GDLs with different PTFE
content and superficial gas velocity are quantitatively studied. A scaled-up
channel was designed to eliminate the wall effect. Although channel walls
may affect the growth and detachment mechanism within a gas channel in an actual fuel cell, droplet behavior under the influence of core gas flow was intended to be studied in this work.

2. Experimental

2.1. Apparatus design

An ex-situ direct visualization apparatus was designed and fabricated to study liquid water droplet emergence, growth and detachment on GDL surface as shown in Figure 1. The experimental apparatus includes a 100 mm long, 2.5 mm wide single gas channel machined on a 1 mm thick aluminum plate and sandwiched by two polycarbonate plates. Air or hydrogen were supplied within the gas channel through an inlet port machined on one of the polycarbonate plates, aligned with gas channel on its entrance, and were discharged from another port machined at the end of the gas channel. GDL sample was placed between polycarbonate plate 1 and aluminium plate (Figure 1). Deionized liquid water was injected by a syringe pump on the backside of the GDL (the side facing to polycarbonate plate 1) through a capillary tube with 250 µm inside diameter (U.111, Upchurch). Droplet emergence, growth, and detachment on GDL surface was monitored through polycarbonate plate 2. Teflon sheets were used between polycarbonate plates and the aluminum plate to prevent any possible gas leakage from the apparatus.

Toray carbon papers (TGP_060) with manufacturer-specified thickness and porosity of 190 µm and 76%, respectively, were used as a GDL. Toray carbon papers were loaded with PTFE based on the procedure given in [32] and described as follows. The substrates were dipped in PTFE emulsion (60
wt.% dispersion in $H_2O$, ALDRICH) for ten hours and then they were dried at $120^\circ C$ for one hour. According to [32] in order to make a uniform distribution of PTFE within the GDL substrates, the substrates were sintered at $360^\circ C$ for one hour. PTFE weight percent loaded on GDL was controlled by the PTFE concentration in the emulsion.

In order to study the aging effect on GDL surface energy, a batch of GDL samples were aged by dipping in deionized water at $60^\circ C$ for twenty four hours and were put in furnace at $60^\circ C$ for four hours.

Figure 2 shows the amount of PTFE content in GDL as well as loaded GDL areal mass based on PTFE concentration in emulsion. PTFE content in GDL was calculated by comparing GDL mass before and after PTFE treatment. Samples with nominal PTFE loadings of 10 wt.% , 25 wt.%, 35 wt.% and 55 wt.% were tested in this study. Table 1 summarizes measured and calculated physical properties of the samples used in this study.

For a better clarification of droplet behavior on GDL surface in cathode and anode of an actual fuel cell, separate experiments were conducted with air and hydrogen being supplied in the channel. Two different rotameters of FL_3802C and FL_3804ST (Omega) were used to supply desired volumetric gas flow rate at low (max. 1200 ml min$^{-1}$ for air and 4200 ml min$^{-1}$ for hydrogen) and high (max. 4500 ml min$^{-1}$ for air and 16000 ml min$^{-1}$ for hydrogen) range, respectively. All experiments were run in atmospheric pressure and room temperature. GDL surface temperature was measured at $59^\circ C \pm 1^\circ C$ using a hand-held infrared thermometer (Optex). This relatively high temperature came from two light sources used during the experiments. Table 2 lists the conditions of each run in the series of experiments. Three
runs were conducted for each case to ensure the repeatability. In order to provide same condition for each run, GDLs were dried before each test by purging nitrogen at 3000 mℓ min$^{-1}$ for 20 minutes while two light sources were kept on.

The schematic of experimental setup consisting of experimental apparatus, gas cylinder, rotameter, syringe pump and high speed camera controlled by PC is shown in Figure 3.

2.2. High speed imaging

Droplet growth and detachment on the GDL surface in the gas channel was recorded using a high speed camera (50KD2B2, Mega Speed) controlled with a PC. Navitron TV Zoom Lens 7000 18.180 mm was attached to the high speed camera that provided a spatial resolution of 10 µm pixel$^{-1}$. Visualizing window had a resolution of 640 × 480 pixels with approximately 250 pixels for the channel width, ensuring a proper resolution for image analysis. Image analysis was done by Mega Speed AVI Player software provided by the camera manufacturer. Two 300-W tungsten lamps (Lowel Omni) were used as the light source to provide proper illumination.

2.3. Contact angle measurement

Static contact angles on fresh and aged GDLs were measured using a setup already made for this purpose [33]. The procedure and theory can be found in [34] and are summarized as follows. The setup consists of an illumination source that provides a beam of light with equal intensity, a series of lenses to converge the beam, a labjack (Thorlabs L200) enabling X,Y,Z alignment of the sample and a long distance microscope (Infinity K2/S) coupled to a CCD.
camera (PULNIX TM-1325CL). Ten droplets with diameters in the range of 1 – 3 mm were placed on the GDL surfaces and images were captured. The images were then analyzed using a computer code based on Young-Laplace equation developed for this purpose to solve for the contact angle on the two sides of the droplets. Mean value of contact angle for ten images was considered as the contact angle of droplets on each GDL surface.

2.4. Flow condition

The surface area of the capillary tube ($4.908 \times 10^{-4}$ cm$^2$) used to inject liquid water on GDL surface can be considered as the water production area in an operating fuel cell. Water production rate during oxygen reduction reaction can be obtained by Faraday’s second law of electrolysis:

$$
\dot{n}_{H_2O} = \frac{iA_{act}}{2F}
$$

where $\dot{n}_{H_2O}$ is the molar rate of water produced, $i$ is the current density, $A_{act}$ is the active area, and $F$ is the Faraday constant. Assuming all water produced is in liquid phase, the liquid water production rate for current density of 2 A cm$^{-2}$ and active area of $4.908 \times 10^{-4}$ cm$^2$ is 0.33 $\mu$ℓ h$^{-1}$. In order to be able to run the experiment in a reasonable time without secondary effects such as evaporation, higher water flow rate of 350 $\mu$ℓ h$^{-1}$ was chosen as was done in [35].

Air and hydrogen were supplied at different ranges as given in Table 2. These flows result in Reynolds numbers ranging from 336 to 1345 for air and from 252 to 672 for hydrogen.
3. Results and discussion

3.1. Contact angle

Liquid contact angle is a measure of wetting ability of a solid surface by liquid and depends on the interfacial energy along the three phase boundary. In water management with application in PEFC, contact angle is an important parameter characterizing many dominant properties. Surface adhesion force, drag force, capillary pressure, and even the shape of a droplet sitting on GDL surface are some of the properties contact angle affects. Surface adhesion force that is the consequence of molecular interaction between liquid and solid adheres droplet on solid surface and resists droplet detachment caused by core gas flow. It has been shown that the contact angle hysteresis (the difference between advancing and receding contact angle) is a key parameter in defining the adhesion force and instability of a droplet under the influence of shear gas flow [26, 36]. Increasing gas flow rate increases the dynamic contact angle hysteresis and moves the droplet towards an unstable condition [26]. The contact angle of a droplet on PTFE treated GDL depends on parameters such as porosity, macroscopic roughness of fibers ridges, microscopic roughness of the individual fibers, and chemical heterogeneity of carbon and PTFE surface in GDL [15]. In this study, static contact angle was measured and used as parameter defining surface energy of GDLs.

Sessile droplets on treated and untreated GDLs are shown in Figure 4. GDLs were aged by dipping in deionized water at 60°C for twenty four hours. Figure 5 shows contact angles of droplets on fresh treated, aged treated, and fresh untreated GDLs. Error bars shown represent standard deviation of
the measured contact angles. While adding some amount of PTFE to an untreated GDL significantly increases the contact angle, it can be observed that droplets show similar contact angles on GDLs with different PTFE content. Similar observation was reported by Benziger et al. [37] for TGP-H-120 Toray carbon paper. Lim and Wang [6] calculated contact angle based on capillary meniscus height measurement and observed that contact angle does not change significantly by adding Teflon from 10 wt.% to 40 wt.% PTFE. Fairweather et al. [14] used pore size distribution obtained from MIP to estimate effective contact angle distributions on untreated and treated GDLs, and observed that contact angle increases by applying 5 wt.% PTFE to a raw GDL while any further addition of PTFE was found not to have any effect on the contact angle. Since contact angle does not change with PTFE content in GDL, it is suspected that most parts of PTFE particles penetrate through the GDL and agglomerate within the pores rather than on GDL surface. Measured contact angles in the same range for treated fresh GDLs (152°) and treated aged GDLs (147°) support the possibility of higher PTFE agglomeration within the GDL rather than on its surface. However, there are still some PTFE particles sitting on the surface of the GDL since the contact angle is significantly different between an untreated GDL and 10 wt.% PTFE treated GDL. PTFE particles are small enough (50 − 500 nm) to be able to pass through GDL pores (10 − 30 µm) and accumulate on inner layers of GDL. The smaller standard deviations of contact angles on treated GDLs shown in Figure 5 represent more uniform contact angles on treated GDLs compared to untreated one. It can be thought that PTFE particles fill open pores on GDL surface and make a smooth surface with shorter contact line
between droplet and fibers. PTFE distribution through the GDL is under study by the authors and the results will be reported after this work.

3.2. Droplet growth

Liquid water finds its path with least transport resistance through the GDL and emerges at the preferential locations, forming droplet [38]. Emerged droplet grows in size until it is detached via drag force from core gas flow. Figure 6 shows droplet growth on untreated and treated GDLs with different PTFE content. Spreading factor, defined as the ratio of droplet diameter $d$ to droplet detachment diameter $d_d$, is shown at different times. Spreading factor is only shown for first 100 ms for the sake of easier comparison. It can be observed that the slope of the curves increases with PTFE content, meaning that droplets need less time to reach to their final size before detachment on GDLs with higher PTFE content. Figure 6 also shows that droplets detach within 100 ms on GDLs with high PTFE content (35 wt.% and 55 wt.% PTFE) while they need more time to detach from GDLs with lower PTFE content.

3.3. Droplet detachment diameter

Zhang et al. [2] defined two modes of water removal from GDL surface; droplet detachment by shear force and capillary wicking of liquid water into more hydrophilic channel walls. Droplet detachment is the characteristic of high superficial gas velocity while capillary wicking occurs at lower gas flow rates. Droplet detachment from GDLs with different wettabilities is the subject of study in the present work. Droplet detachment can be studied by considering all of the forces applied on a droplet under shear gas flow.
Considering droplet free body diagram in general as shown in Figure 7, these forces are; (i) gravitational force \( F_G \) (ii) surface adhesion force \( F_S \) and (iii) shear drag force from core gas flow \( F_D \).

Bond number describes the ratio of gravitational force to surface tension force and is defined as:

\[
Bo = \frac{\Delta \rho gd_d^2}{\sigma}
\]  

(2)

where \( \Delta \rho \) is the density difference between liquid and gas, \( g \) is the gravitational acceleration, \( d_d \) is the droplet detachment diameter and \( \sigma \) the interfacial surface tension. The maximum Bond number calculated in this study was 0.1 that indicates the negligibility of gravity compared to surface tension [39]. Surface adhesion force keeps the droplet on the surface while the drag force applied from the core gas flow tries to detach the droplet from the surface. Droplet detachment occurs when drag force overcomes surface adhesion force and can detach droplet from the GDL surface.

The droplet detachment diameter is an important parameter in fuel cell gas channel design. A gas channel smaller than the droplet size upon detachment will be clogged by the droplet, and an over-sized channel, on the other hand, will increase the parasitic power required to supply the reactants at the same superficial velocity to run the cell. The former stops the cell from producing energy and the latter lowers the overall energy efficiency. In this study, droplet detachment diameter from GDL surface was measured while air and hydrogen were flown in the gas channel.

In general, it was observed that droplets detach at higher hydrogen superficial velocity compared to air. Drag force (Equation 3) is a function of
gas density as well as superficial gas velocity:

\[ F_D = \frac{1}{2} \rho C_D A_P V^2 \]  \hspace{1cm} (3)

Since hydrogen’s density is much lower than air’s, higher hydrogen superficial velocity is required to provide enough drag force to detach the droplet. The density of air is fourteen times as much as hydrogen and in order to detach a droplet of equal size, hydrogen superficial velocity should be more than three times as much as air.

It was also observed that droplets leave residual liquid water particles as they detach from the GDL surface. It has been reported that these residual water particles become pinning site for future droplets and will be followed by slug formation after a while [30].

Furthermore, it was observed that the first few droplets emerge at the same location, but after a while, multiple droplets emerge in different locations on the GDL surface as shown in Figure 8. This was also reported in [30], suggesting an interconnected network of water pathways within the GDL.

3.3.1. **Effects of PTFE content on droplet detachment diameter in cathode and anode**

Figure 9 shows droplet detachment diameter on GDLs with different PTFE content and under superficial air velocity of 11.1 m s\(^{-1}\). The mean diameters for the first ten detaching droplets are shown. It can be observed that droplets detach at smaller diameters on GDLs with greater PTFE content. As shown in Figure 5, the contact angle on GDL surface is nearly uniform regardless the PTFE content. Different detachment diameters for
GDLs with similar contact angles (similar surface energy) are an indication of the existence of a heterogeneous through-plane parameter affecting the detachment mechanism. Furthermore, although it was observed that droplets make lower contact angle on aged GDLs compared to fresh ones (Figure 5), droplet detachment diameter is assumed not to be affected by aging of the GDL since the contact angles on aged GDLs are in close range no matter the PTFE content.

Smaller detachment diameter on GDLs with higher PTFE content is justified by PTFE accumulation within the GDL. It has been reported that PTFE distribution through the GDL is not uniform and differs based on the distance from the GDL surfaces. Fishman and Bazylak [19] used high resolution microscale visualization and measured through-plane porosity of PTFE treated paper GDLs. They observed higher local porosity in the center of the GDL and lower local porosity within the GDL near the surface. Such observation was attributed to higher PTFE concentration within the GDL and near the surface and lower PTFE concentration within the GDL and in the core region of the GDL. In another study, Rofaiel et al. [40] used Scanning Electron Microscopy (SEM) energy dispersive X-ray to measure through-plane PTFE distribution within the GDL and observed higher PTFE concentration within the GDL and near the surfaces compared to core region part of the GDL. Similar results obtained from two different methods indicate higher PTFE concentration within the GDL and near the surface and lower PTFE concentration in the center of the GDL. Agglomerated PTFE particles within the GDL increase the internal contact angle $\theta$ and decrease the pore radius $r_{pore}$. This increases the capillary pressure required to intrude water into the
pores:

\[ P_c = \frac{2\sigma_{\text{water}} \cos \theta}{r_{\text{pore}}} \]  \hspace{1cm} (4)

Liquid water can pass through the pores only when its pressure exceeds capillary pressure, and for a continuous flow to happen, its pressure should also remain higher than the capillary pressure [41]. Carbon layers with high PTFE content within the GDL resist liquid water transport by acting as a barrier. Liquid water with low pressure is not able to pass through this barrier and accumulates behind it with pressure increasing until it reaches to the capillary pressure and can pass through the pores. As liquid water passes through the pores, its pressure suddenly drops and the barrier again blocks water transport through the GDL. Liquid water passed through the GDL forms a small droplet on GDL surface and since the barrier within the GDL has blocked water transport, no water column exists underneath the droplet to assist its adhesion [31]. Small droplets without liquid column in GDL can be easily swept away from the GDL surface. GDL layers with high PTFE content can be described as an on-off valve controlling liquid water transport through the GDL.

We may also justify the smaller droplet detachment diameter on GDLs with more PTFE content based on surface roughness. Droplet behavior on GDL surface is mostly controlled by the wetting characteristic of the top few monolayers of the surface as Whitesides [42] reported. Higher PTFE concentration reduces the surface roughness [19] and since droplets sitting on highly rough surfaces show less tendency to detach [30], droplets tend to detach easier at smaller diameters on highly PTFE loaded GDLs.
Although droplet detachment from GDLs with different PTFE content was observed, it was found that droplet never detached from an untreated GDL surface. Instead, they slide on its surface along the gas channel. Figure 10 shows a droplet sliding on an untreated GDL without being detached. The sliding diameter on untreated GDL is shown in Figure 9. Fairweather et al. [14] measured the capillary pressure for untreated and treated GDLs and found that liquid water intrudes more easily to the untreated GDL while adding any slight amount of PTFE to the GDL makes it easier to remove water rather than to intrude it.

Our results in this work show that increasing PTFE content in GDL enhances droplet detachment by reducing the growth time and the diameter at which droplets detach from the GDL surface. However, the way that PTFE content affects other parameters should be carefully considered for an appropriate cell design. An optimum PTFE content in GDL should be defined by considering all of the parameters affecting the cell performance. For instance, in terms of cell performance, Velayutham et al. [43] reported that the optimum PTFE content is around 20 wt.% since any further amount of PTFE within the GDL increases the electrical resistance and very low amount of PTFE, on the other hand, results in water flooding within the cell. Each of these consequences can reduce the cell performance and should be carefully avoided.

Figure 11 shows droplet detachment diameter under superficial hydrogen velocity of 40 m s\(^{-1}\) as a function of PTFE content in the GDL. Again, it can be observed that as the PTFE content increases, droplets detach at smaller diameters. As discussed earlier, comparing air and hydrogen, higher
hydrogen superficial velocity is required to detach water droplets from the GDL surface.

3.3.2. Effect of superficial gas velocity on droplet detachment diameter in cathode and anode

Superficial gas velocity plays an important role in droplet detachment from the GDL surface. For low superficial gas velocity, the drag force applied from the core gas flow (Equation 3) on droplet cannot overcome the adhesion force and droplet increases in size until it forms slug in the gas channel. High superficial gas velocity, on the other hand, leads to low reactant utilization, increased parasitic losses, and possibly membrane dehydration. Figure 12 shows the droplet detachment diameter for different superficial air velocity. As the superficial air velocity increases, droplets detach at smaller diameters on treated GDL surface. For untreated GDL, droplet sliding diameter on GDL surface is shown in this Figure.

Droplet detachment diameter as a function of superficial hydrogen velocity is shown in Figure 13. For low hydrogen superficial velocity, droplets detach at smaller diameter on the GDL with higher PTFE content (35 wt.%). However, above 40 m s\(^{-1}\) of hydrogen superficial velocity, the droplets detach at nearly identical diameter for different PTFE content. This indicates that for high superficial gas velocity, PTFE content in GDL is not the governing parameter in droplet detachment.

In reality, hydrogen velocity in anode tends to be low, because pure hydrogen is used and utilization is very high. Therefore, once droplets are formed in anode gas channel, it is extremely difficult to remove such droplets by drag force.
Droplet detachment diameter on treated fresh GDL and under the influence of shear gas flow has been studied. Although increasing both PTFE content in GDL and superficial gas velocity were observed to decrease droplet detachment diameter, the later was found to be more significant compared to the former. While droplet detachment diameter decreased from 0.86mm for superficial gas velocity of 3.7m s\(^{-1}\) to 0.35mm for superficial air velocity of 14.8m s\(^{-1}\), it only decreased from 0.61mm for 10wt.% PTFE to 0.36mm for 55wt.% PTFE under constant superficial air velocity of 11.1m s\(^{-1}\).

4. Conclusion

Water droplet behavior on GDLs with different PTFE content has been studied under different superficial gas velocity in an ex-situ setup with transparent fuel cell. Air and hydrogen were supplied within the channel and at different flow rates. The following conclusions can be drawn from this study:

1. Applying PTFE on a raw GDL increases the contact angle significantly but the contact angle does not change for different PTFE content. Furthermore, droplets show much more uniform contact angles on treated GDLs compared to untreated one. It is probably because PTFE particles fill GDL pores, making more uniform surfaces with shorter contact lines between the droplet and fibers.

2. Droplets show slightly lower contact angles on treated aged GDLs compared to fresh ones. This is an indication of PTFE degradation from the treated aged GDL surface. Since the contact angles droplets show on treated fresh GDLs and treated aged GDLs are almost similar (\(\sim 152^\circ\) for treated fresh and \(\sim 148^\circ\) for treated aged GDLs), we may con-
clude that GDL aging will not have any effect on droplet detachment diameter.

3. Droplet detachment diameter decreases as the PTFE content in GDL increases. High PTFE content within the GDL increases the capillary pressure liquid water needs to exceed to be able to pass through the GDL pores. Increased liquid water pressure provides liquid path through the pores but as liquid water passes through the GDL, its pressure instantly drops. This results in small droplets emerging on GDL surface without water columns underneath to assist adhesion. Smaller droplet detachment diameter can be also justified by smoother GDL surface for higher PTFE content, since droplets tend to detach easily from less rough surfaces.

4. Superficial gas velocity significantly affects the droplet detachment diameter. Increasing the superficial gas velocity increases the drag force applied on the droplet, and smaller droplet diameter will be required to surpass the adhesion force keeping the droplet on the GDL surface.

5. It was observed that droplets detach at higher superficial velocities of hydrogen compared to air. Hydrogen’s lower density compared to air can be named as the main reason for such observation.

6. It was observed that droplet detachment does not occur on untreated GDL, instead droplets slide on its surface. This results from lower contact angle (higher surface energy) of droplets on untreated GDLs.

7. For high superficial hydrogen velocity, PTFE content in GDL is not the governing parameter in droplet detachment. Instead, droplets detach at similar diameters no matter the PTFE content.
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