International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 0533

Ex-situ experimental study on dynamic contact angle evolution of droplet in PEMFC flow channel

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ABSTRACT

An ex-situ visualization experimental system was established to study the growth and deformation process of a single droplet in a rectangular channel for the proton exchange membrane fuel cell (PEMFC). The droplet morphology was observed and recorded by a CCD camera. Three different methods for automatically obtaining droplet size and contact angle information were developed. The influence of air flow velocities on droplet dynamic process was analyzed.

Keywords: Dynamic contact angle, Visualization, Proton exchange membrane fuel cell, Image processing

1. INTRODUCTION

Proton exchange membrane fuel cell (PEMFC) is a kind of clean energy conversion device. Water management is one of the biggest engineering challenges to the broader implementation of PEMFCs [1]. Hence, the research of the phenomenon of droplets detaching from the solid surface and the transport mechanism of liquid in micro-channels is very important for PEMFC.

Theodorakakos et al. [2] established a visual experiment to study the dynamic process of droplet shape deformation before detachment from the diffusion media surface. Incorporation of dynamic contact angle change as part of the numerical solution has allowed for relatively successful predictions of the experimental observations of the droplet shape at different air velocities. Kumbur et al. [3] focused on the prediction of the effects of operational conditions on the contact angle hysteresis (a measure of droplet instability) of a droplet on the diffusion media surface, in order to discern conditions leading to droplet removal by establishing a visual experiment; Qin et al. [4] developed a theoretical method that coupled the sliding angle and the dynamic contact angle for calculating the contact angle hysteresis of a moving water droplet on the gas diffusion layer (GDL) surface in a PEMFC. Meanwhile, some researchers have summarized the effect of operating parameters on the interaction between slug flow and solid surface in a channel for PEMFC [5, 6].

The contact angle is the key indicator to understanding the phenomenon of droplets detaching from the solid surface, which is considered to be a measure of the amount of wetting of the solid surface by liquid. What's more, the contact angle hysteresis is a measure of the magnitude of the droplet deformation and it also significantly affects the adhesion force from the solid surface [7]. Therefore, due to its importance, it is very important to take a clear picture of the dynamic process of the droplet from the experiment and take reasonable post-processing method to obtain accurate contact angle information.

In this study, we designed a transparent single model cell to create a visual experimental platform to investigate the dynamic interaction process between droplet and solid surface. In order to accurately obtain the change rule and growth characteristics of droplet contact angle, we designed three automatic image processing algorithms based on MATLAB script, and compared the advantages and disadvantages of three different methods. The effect of different gas velocity on the droplet dynamic process was also investigated.

2. EXPERIMENT

The schematic of the visual test system is shown in Fig. 1. The 2 mm square channel in an acrylic block which simulates the gas flow channel of a fuel cell. Firstly, un-humidified gas was generated by the air generator (GA-2009) with a maximum supply pressure of 0.4 MPa. Rated gas flow controlled by the air mass flow meter (YJ-600CD-AIR-10SPLM) is fed into the 120 mm long channel. A fine gage needle was used to create a 100 μm diameter hole through GDL, the method is also used in Ref. [6]. The deionized water is injected into the water tank under the GDL through a syringe pump (Harvard Pump 11 Elite) connecting a capillary tube. The liquid water at the bottom slowly seeps out through the holes on the GDL and grows gradually. Under the action of air flow, the droplets deform. An LED light source is added behind the model cell. The whole process of droplet growth, deformation and detachment is observed and recorded by using a CCD camera (FASTCAM SA1.1, PHOTRON) with a telecentric-lens.

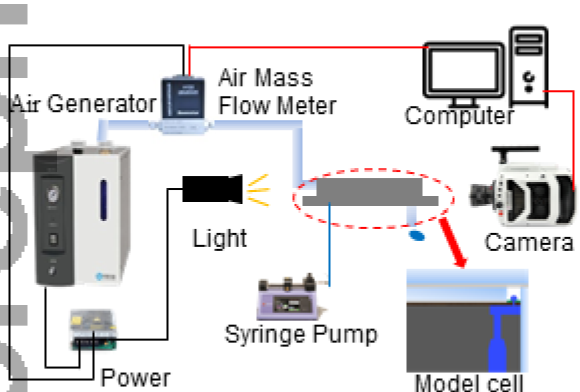


Fig 1 Schematic of the experimental system.

Table 1. Experimental conditions and parameters

Parameters	Values
Channel length, L	120 mm
Channel width, W	2 mm
Channel cross section	2 mm X 2 mm
Pore diameter, d	100 μ m
Environment temperature, T	25 ℃
Environment pressure, P	1 atm
Static contact angle, θ	145°±2°
Density water, ρ_l	998.2 kg m^{-3}
Viscosity air, μ_g	1.899e^{-5} kg s m^{-1}
Surface tension, σ_{lg}	0.066 N m^{-1}
Liquid volume flow rate, Q_w	0.6 μL s^{-1}
Gas volume flow rate, Q_{gas}	400 ml min^{-1} 800 ml min^{-1}
Gas volume flow velocity, V_{gas}	1.67 m s^{-1} 3.34 m s^{-1}
Frame rate	2000 Hz
Shutter rate	1/10000 sec

3. RESULTS

3.1 Image processing methods and comparison based on MATLAB script

Fig. 2 (a) shows the evolution process of droplet when the gas flow rate is 400 ml min^{-1}. It can be seen that the morphology of the droplet has changed obviously. When the droplet grows at 6200 ms, the droplet has obvious forward tilt. Meanwhile, the sum of the surface tension of the droplet, the shear force and the pressure difference generated by the air flow will reach the equilibrium state, making the droplet on the GDL unstable.

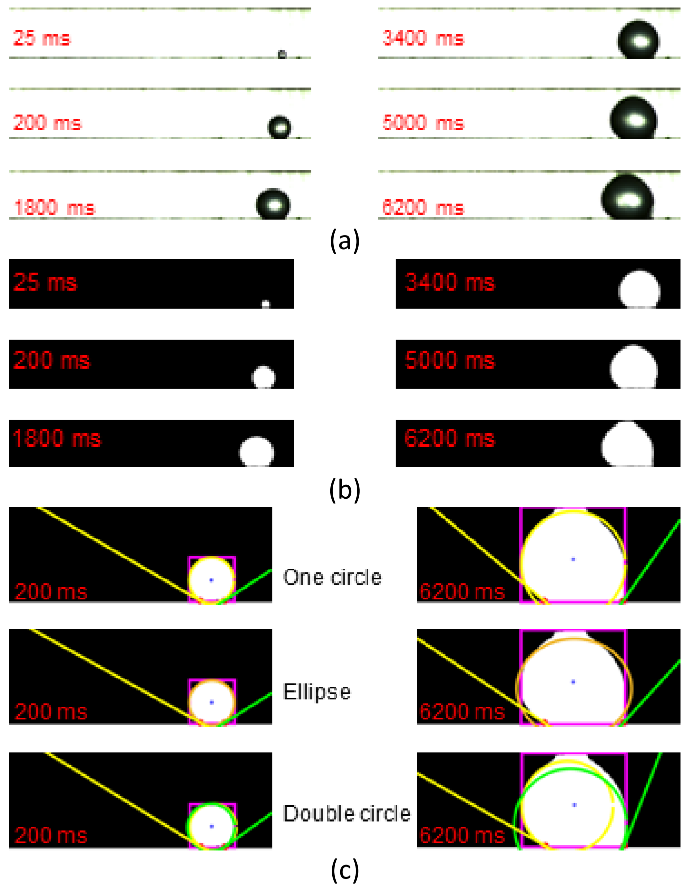
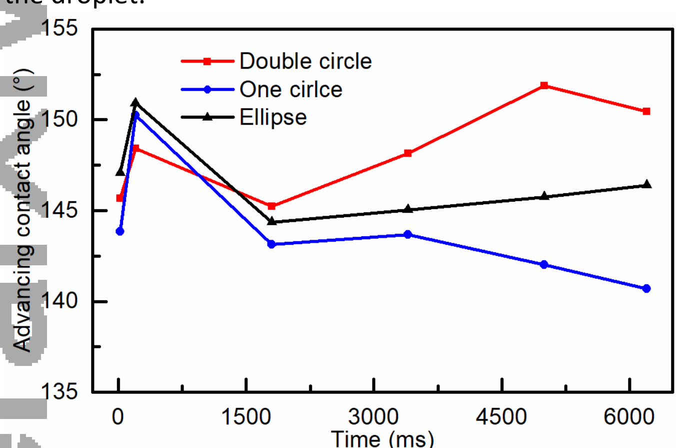
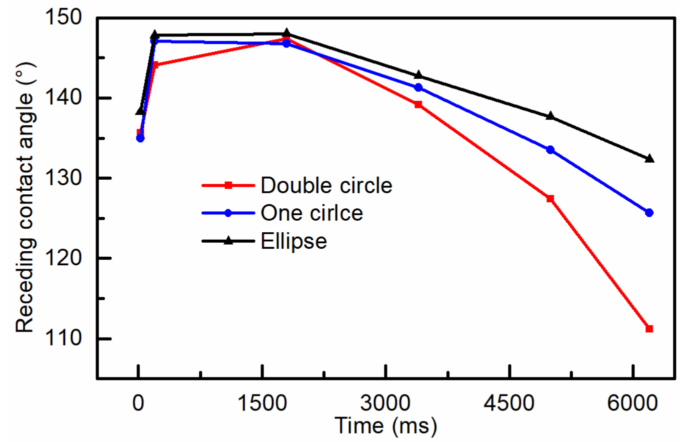


Fig 2 (a) the original picture of the droplet morphology change process at different times when the air flow rate is 400 ml min^{-1}; (b) the binary image of the droplet morphology change process at different time points when the air flow rate is 400 ml min^{-1}; (c) the angle formed by the yellow line and the horizontal plane is the advancing contact angle, the included angle between the green line and the horizontal plane is the receding contact angle, and the purple box in the figure is the area occupied by the maximum connecting area of the marked droplet.

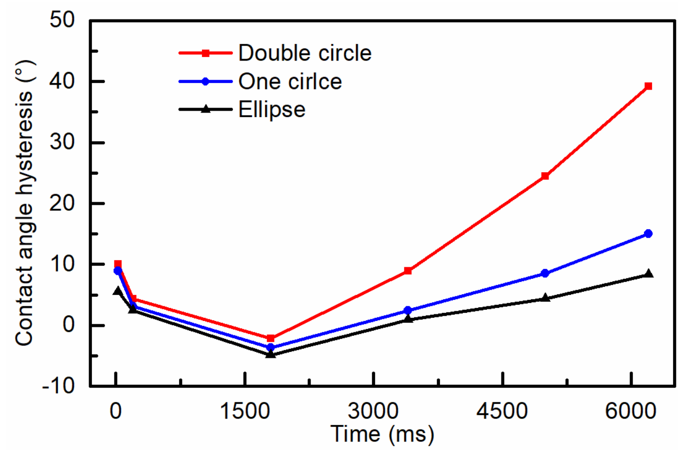
In order to quantitatively describe the deformation of the droplet, it is necessary to extract the contact angle value of the three-phase interface of solid, liquid and gas, that is, to obtain the advancing contact angle and receding contact angle of the droplet. In previous studies, most of the manual extraction methods were used, that is, the contact angle was obtained by subjective evaluation, which made the error very large. As shown in Fig. 2 (b), the white part is the droplet, and the contour of the droplet is approximately an arc. Therefore, when obtaining the contact angle value, it is necessary to fit the contour to find the tangent intersecting with the three-phase contact point. As shown in Fig. 2 (c), the included angle between the yellow line and the horizontal plane is the forward contact angle, and the angle between the green line and the horizontal plane is the backward contact angle. As it is shown in Fig. 3, when the droplet is small, i.e. before 1500 ms, the advancing contact angle, receding contact angle and contact angle hysteresis obtained by the three methods are close to each other. Meanwhile, because the droplet is in a relatively stable state, its shape is symmetrical, which is similar to that in Fig. 2 (c). When the droplet is in the unstable state at 6200ms shown in Fig. 2 (c), the curve of single circle fitting and ellipse fitting can not correspond to the droplet profile. At this moment, the advancing contact angle value is relatively small, and the receding contact angle value is too large, which can not truly reflect the droplet deformation. Therefore, the double circle fitting method should be used in the whole growth period of the droplet.



(a)



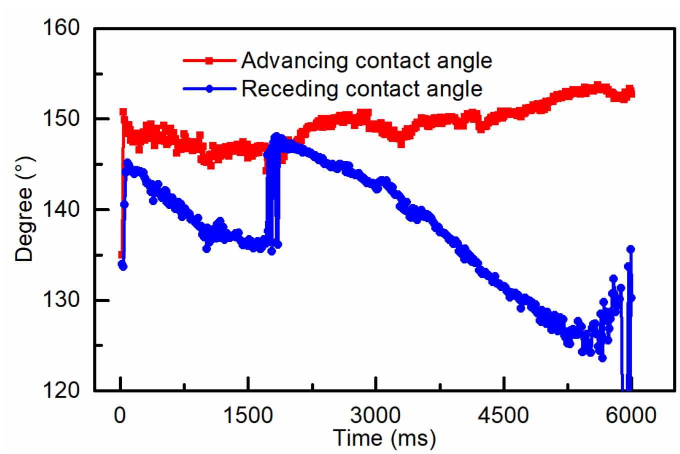
(b)



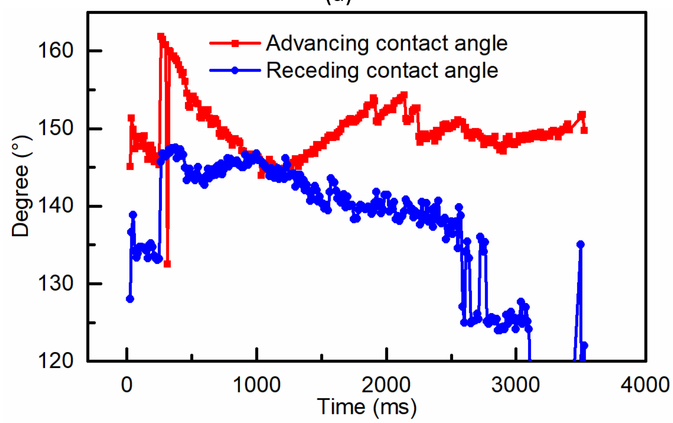
(c)

Fig 3 The influence of three different methods based on single circle contour fitting, double circle contour fitting and ellipse contour fitting on droplet advancing contact angle, receding contact angle and contact angle hysteresis at different time when the air flow rate is 400 ml min^{-1}: (a) the droplet advancing contact angle; (b) the droplet receding contact angle; (c) the contact angle hysteresis.

3.2 Evolution of droplet size and contact angle at different gas velocities



(a)



(b)

Fig 4 Evolution of droplet size and contact angle at different gas velocities: (a) gas flow rate is 400 ml min^{-1}; (b) gas flow rate is 800 ml min^{-1}

Figure 4 (a) and (b) show the time-dependent curves of the contact angle values extracted by the double circle fitting method when the air flow rates are 400 ml min^{-1} and 800 ml min^{-1}, respectively. Generally, the advancing contact angle increases slowly with time regardless of the air flow velocity. In the later stage, with the increase of droplet volume, the increasing rate of advancing contact angle becomes slower. This is because the resultant force of the droplet in the unstable state is gradually close to the adhesion force between the droplet and the diffusion layer. At this moment, the deformation degree of the droplet on the leeward side reaches the maximum, and the advancing contact angle increases As shown in Fig. 4 (a), the hysteresis of the maximum contact angle can reach 30° when the air flow velocity is 400 ml min^{-1}, and when the air flow rate is 800 ml min^{-1}, the maximum contact angle hysteresis is about 25 °. So, with the increase of air velocity, the contact angle hysteresis decreases, the deformation degree of droplets is small, and the shape of droplets is close to symmetry, which is conducive to removal.

4. CONCLUSIONS

Contact angle is an important parameter reflecting the force and wetting characteristics of liquid water in the flow channel of proton exchange membrane fuel cell (PEMFC). It is related to many parameters and can indirectly guide the water management of PEMFC. The liquid water advancing contact angle, receding contact angle and contact angle hysteresis are successfully extracted using the double circle fitting method from the images captured by CCD camera. It is found that in the process of droplet growth, the advancing contact angle increases monotonically with time, but the receding contact angle decreases monotonically with time. The receding contact angle decreases gradually with time, and the deformation of droplet on windward surface increases with the air flow rate. This can reduce the contact angle hysteresis and promote the separation of droplet from the gas diffusion layer (GDL).

ACKNOWLEDGEMENT

This work is financially supported by the National Natural Science Foundation of China (Grant No. 51706153).

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