MICRO STRUCTURED FLOW FIELD FOR PASSIVE WATER MANAGEMENT IN MINIATURIZED PEM FUEL CELLS

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ABSTRACT

In this work a novel flow field for the passive water management in Proton Exchange Membrane Fuel Cells (PEMFC) is described. A triangular micro channel forces condensing water droplets to detach from the Gas Diffusion Layer (GDL) in order to ensure proper oxygen supply. Water droplets are lifted into a secondary channel, and transported out of the fuel cell by capillary forces. Different droplet shapes inside the channels are identified. Preferred shapes cover the GDL only slightly and can be attained for contact angles typical for fuel cell materials.
The new channel design was compared in a test fuel cell to standard square channels in particular in the starting phase of the cell at low working temperatures (22°C). The new channel design keeps the cell at 95 % of its initial performance compared to 60 % when using the standard design.

1. INTRODUCTION

This work deals with a major challenge in the design of PEMFC flow fields: The removal of abundant water from the cathode. In the low temperature range (20 °C to 65° C) up to 95 % of the water is present in the liquid phase [1]. In conventional flow fields this water can block channels and prevent proper oxygen supply. In particular parallel channels lead to an inhomogeneous performance as single channels can be clogged by process water [1;2]. Today's common approach is to remove the water by purging the cathode flow field [3]. For that reason the flow fields consist of long meandering channels [2]. In order to ensure a homogenous distribution of oxygen, humidity and temperature high flow rates are required [4;5]. Relatively high pressure gradients and eventually special strategies like periodically purging the channel system are necessary.
In the presented flow field tapered channel walls separate the liquid from the gaseous flow by capillary forces in a completely passive way. The concept ensures air supply even if a large amount of water is produced.

2. WORKING PRINCIPLE

The considered flow field consists of parallel channels with a tapered cross section as depicted in Fig. 1. The surface of the flow field channels can be assumed to be hydrophilic with typical contact angles $60° > \theta_1 > 0°$ for electrode materials (graphite, gold, stainless steel etc.). The MEA or GDL of the fuel cell seals the channels at the bottom and exhibits a hydrophobic surface $120° > \theta_2 > 70°$.
At the edges where the hydrophobic and hydrophilic walls meet (Fig.1, detail A), the interfacial tension pulls droplets towards the channel walls as soon as they touch one of them. Depending on contact and opening angles three different shape modes can be attained (Fig. 2). These will be referred to as edge mode, wall mode and droplet mode.

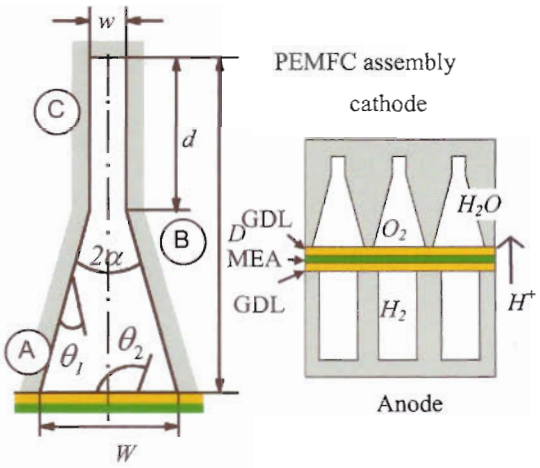
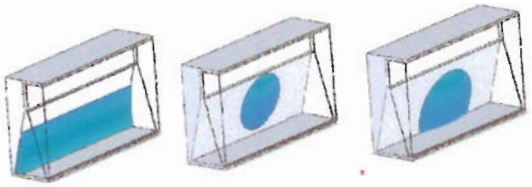


Fig. 1: Schematic of the channel design (left) and PEMFC assembly (right)



a) Edge Mode b) Wall Mode c) Droplet Mode

***Fig. 2**: Attainable modes for droplet shapes.*

The shapes of the droplets can be predicted by the theory of Canthotaxis [6] as displayed in Fig. 3. In the edge mode the liquid spreads along the edge as depicted in Fig. 2a if

$$\theta_1 + \theta_2 < \alpha + \tfrac{\pi}{2}$$

is fulfilled. The wall mode (Fig. 2 b) is attained for a very high contrast of wetting conditions between GDL and channel walls. The droplet doesn't wet any part of the GDL for

$$\theta_2 > \theta_1 + \alpha + \tfrac{\pi}{2}.$$

Between these extreme conditions the droplet mode is attained (Fig. 2 c) if

$$\theta_2 + \theta_1 > \alpha + \tfrac{\pi}{2}.$$

Only a part of the GDL is wetted and the liquid stays compact in form of a droplet (Fig. 2 c).

The inclined channel walls (Fig.1, detail B) with half opening angle α transport the water droplets into the secondary channel, minimizing their surface energy. This principle works if the Concus Finn Condition [7] is fulfilled, i.e.

$$\theta_1 + \alpha < \tfrac{\pi}{2}.$$

On top of the inclined channel, a rectangular channel with high capillarity transports the liquid out of the flow field. At the end of the removal channel non-woven material can be applied to suck the liquid out of the cell and to evaporate the water from there.
The efficiency of the water removal depends strongly on the shape mode the liquid attains. Edge mode is undesired as it fills a whole channel slowly but

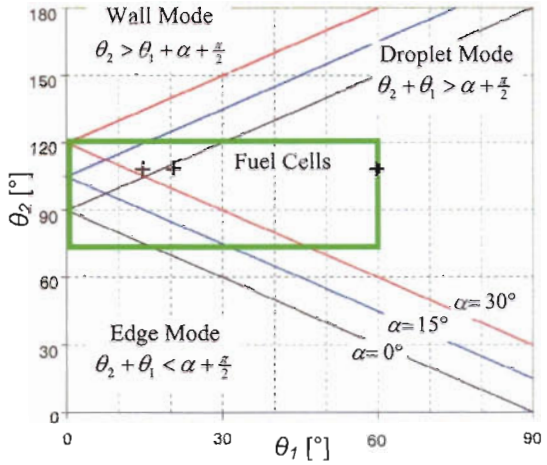


***Fig. 3**: Attainable modes for droplet shapes as a function of contact angles for opening angles α=0°, 15°, 30°. Realistic contact angle values for fuel cells are marked by a rectangle. The situations in the experiments and the CFD simulation are marked by a cross (α = 15° and α = 7.5°)*

steadily, blocking the active GDL region near the electrodes along the whole channel from air supply. Droplet mode and in the best case wall mode are preferred conditions for the application in fuel cells because only relatively small areas of the GDL are blocked. Furthermore the droplets are lifted into the removal channel as soon as they touch both walls. The small amount of liquid from a single droplet typically does not overstrain the capacity of the removal channel.

3. SIMULATIONS

The described working principle for passive droplet removal was first studied by computational fluid dynamic (CFD) simulations [8]. Simulations where performed for channels with opening angles 2α = 15° and 2α = 30°. Liquid was introduced into the channel from the bottom through a small inlet at a constant flow rate of 26 µl s^{-1}. This is the typical situation in fuel cells when water is flooding through a hydrophobic GDL along a constraint path [9]. The

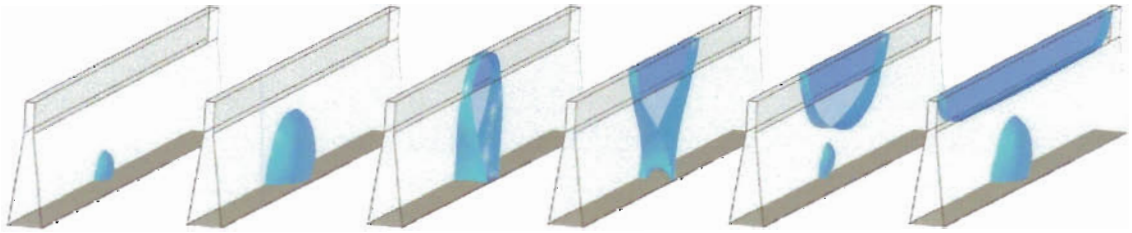


***Fig. 4**: CFD simulation of a droplet growing from the hydrophobic channel bottom (θ_2=120°) along the channel walls (θ_1=60°). As soon as the droplet touches the opposite wall capillary forces lift the water into the upper channel. (Dimensions: W= 1400um, D=3000um, w=150um, 2α=15°)*

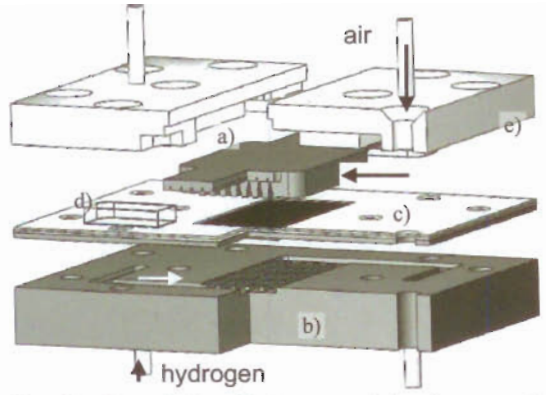


Fig 5: Test fuel cell (cut at right front) with: a) exchangeable cathode flow field; b) graphite anode; c) MEA, GDL and sealing assembly; d) observation window; e) polycarbonat frame .

flow rate corresponds to the liquid produced in the GDL area of the whole simulated channel (20 mm x 1.1 mm) at a constant current of j = 800 mA/cm².

The results displayed in Fig. 4 show that the droplet grows at the channel wall. When reaching the opposite wall a liquid bridge is formed and the water is lifted. The droplet breaks up and a small secondary droplet remains at the wall while the liquid bridge moves upwards and spreads along the water removal channel. The overall time to lift a single droplet of 2.6 µl is evaluated to be less than 100 ms.

The desired water removal from the GDL is observed in simulations for contact angles of $\theta_1 = 15°$, $\theta_1 = 20°$ and $\theta_1 = 60°$ for the channel walls and $\theta_2 = 105°$ for the channel bottom (cf. Fig. 3).

4. MATERIALS AND FABRICATION

For in situ experiments a fuel cell employing the new channel design was fabricated as depicted in Figure 5. The cathode as well as the anode flow field (Fig. 5a,b) were milled into graphite (Ringsdorff R7340 [10]). A contact angle for water of 60° was measured on the material. To increase the wetting tendency, the cathode flow field was grafted at the channel walls with PEG (polyethylenglycol) leading to a contact angle $\theta_1 \sim 15°$. The MEA/GDL sandwich (Fig. 5c) was pressed between the flowfields. The MEA consists of Naphion® N112 with catalyst layers of Platinum 0.3 mg Pt cm^{-2} at the anode and 0.6 mg cm^{-2} Pt at the cathode [11]. Carbon paper Sigracet 10CC [10] was used as gas diffusion layer, grafted with 10 % weight Teflon to reach hydrophobic [11] behaviour. Contact angles of 105° were measured. The design contains a window (Fig. 5d) which allows for visual inspection of the cathode flow channels. Water movement in perpendicular directions to the gas flow can be observed.

For the cathode flow field channels were fabricated with opening angles of 2α 15°, 20° and 30 °. The total channel depth was D = 4000 µm in all cases with a removal channel w = 300 µm and d = 1000 µm. Furthermore a reference flow field was built having three channels with rectangular cross sections (width 1000µm depth 2320 µm) for comparison.

5. EXPERIMENTAL RESULTS

Test channels

Beside the graphite flow field for the fuel cell single channels were milled into transparent PMMA. The channels were plasma treated ($\theta_1 = 20°$) and sealed with hydrophobic PDMS ($\theta_2 = 105°$). Compared to the graphite flow field they enabled a better insight into the channel. To observe the principle of droplet removal (cf. Fig. 6) water was brought into these channels by pumping through a 200 µm pipe from the bottom of the PDMS sealing.

Fig. 6 shows growth and removal of water in the droplet mode. A droplet of 4.3 µl is removed within less than 400 ms.

Fuel Cell Experiments

The fabricated fuel cell (Fig. 5) was run with class 5 hydrogen at the anode and ambient air at the cathode. A working point of about 10 mbar air pressure and 50 mbar hydrogen pressure was set at a temperature of 22 °C. The current was kept at 900 mA cm^{-2} using a current controlled standard power supply. This working point was found to support high liquid generation. Experiments were performed with pure graphite ($\theta_1 = 60°$) and PEG grafted surface ($\theta_1 \sim 15°$). The capillary removal of liquid was observed for the coated channels for all validated opening angles $2\alpha = 15°$, 20° and 30°. The liquid formed droplets on top of the GDL which did soon attach to the hydrophilic channel walls and moved upward as soon as they got in contact with both channel walls (Fig. 7 a-c). The lift times for droplets varied from 1 to 15 seconds which is an order larger than for the PMMA channel.

The uncoated graphite with the small opening angles of $2\alpha = 15°$ and $2\alpha = 20°$ showed only poor performance as the liquid tended to pin at the corner

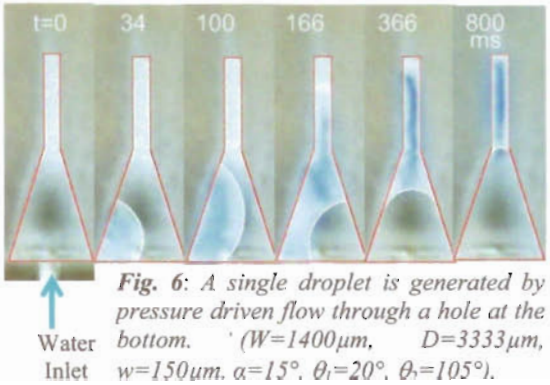


Fig. 6: A single droplet is generated by pressure driven flow through a hole at the bottom. (W=1400µm, D=3333µm, w=150µm, α=15°, θ_1=20°, θ_2=105°).

where the inclined channel reaches the removal channel.

The performance during the cold start (T=22°C) of the cell using different flow fields is shown in Fig. 8. In the first few minutes both configurations show decay in performance of about fifteen to twenty percent. The power output of the reference cell successively decreases to 60 % of the initial value in the following 15 minutes. The stepwise decline is correlated with observed sudden blocking events of two of the three channels of the flow field. For the tapered channels the cell regained its peak performance after about ten minutes. The channels were never blocked completely during the cold start and droplets moved away from the GDL as soon as they became large enough.

CONCLUSION

A new channel design for cathode flow fields of PEMFC was presented enabling passive removal of liquid water. The proposed flow field design has been successfully validated in a test fuel cell proving liquid water removal. From theory and experiments it can be concluded that surfaces with low contact angles for the cathode walls as well as opening angles larger than $\alpha = 10°$ are more likely to provide save water removal. Thus, the new channel design enables cost efficient PEMFCs without the need for external water removal components like pumps or similar.

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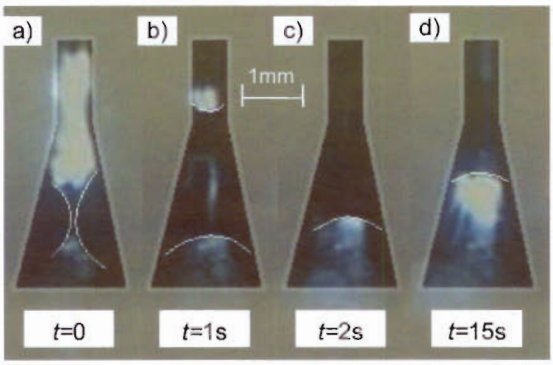

Fig 7: Water removal from the GDL in the fuel cell assembly. Two droplets growing on opposite channel walls (a) merge and move upwards (b, c). After about 15 seconds the main channel is cleared (d). ($D = 4000\mu m$; $W = 2032\mu m$; $w = 300\mu m$; $2\alpha = 30°$; $\theta_1 = 5°$; $\theta_2 = 105°$; $j = 900\ mA\ cm^{-2}$)

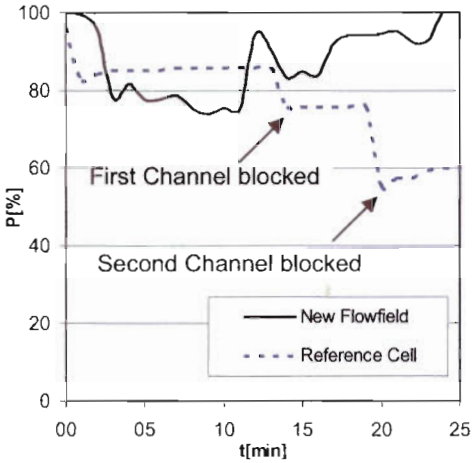

Fig 8: Performance during cold start of the fuel cell applying different flow field designs. ($\theta_1 = 5°$; $\theta_2 = 105°$; $j = 900\ mA\ cm^{-2}$)

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