Numerical and Experimental Studies of a Capillary Channel

M. Xu[1], X. Wang[*2], and Z. Wu[2]

[1]Department of Precision Instruments, Tsinghua University, Beijing, China
[2]Institute of Microelectronics, Tsinghua University, Beijing, China
*Corresponding author:
wxh-ime@tsinghua.edu.cn

Abstract: Capillary flow is commonly seen in microfluidic systems. Because of large surface-to-volume ratio, flow inside microchannels can be driven automatically by capillary effect without any external means. This can be applied in biochemical analysis, where capillary flow is used for the transport of liquid and mixing enhancement. In other applications like drug delivery, DNA analysis, and protein crystallization, capillary effect is introduced to precisely guide minute amount of liquid towards targeted reservoir. In this paper, we design a capillary channel for transporting methanol in fuel cell, and investigate its performance both numerically and experimentally.

Keywords: capillary flow, methanol, COMSOL Multiphysics.

1. Introduction

Liquid flow in the micrometer or nanometer scale has some characteristics distinguishing from that on a macro scale, among which many have laid the foundation for the rapid development of microfluidic technology and devices. As these devices work with small amount of reagent, reaction time could also be dramatically reduced compared with traditional way of chemical or biological analysis. They also exhibit the potential to integrate various laboratory operations on to a single chip smaller than a fingernail.

One of the challenges among microfluidics research now exists in the precise control of reagents, including pre-concentration, mixing, separation, reaction. To control flow of liquid inside microfluidic systems is an essential step in chip-based analysis or device.

To achieve this, the most common way is to control the direction or velocity of fluid flow in the channel by changing the channel structure at different location or time. Hence flow can be controlled by hydrodynamic force. Another way to achieve this goal is to apply electric and magnetic field or laser in the microfluidic chip. By applying various magnitude or direction of field, liquid will be dragged and stopped.

Due to the large surface-to-volume ratio of flows inside microchannels, there's another phenomenon called capillary effect that we can use to guide liquid on the microfluidic chip. It's common in microfluidics as most of the microchannels are initially filled with liquid driven by capillary force. This is an automatic process without applying any external means. In biological or chemical analysis, capillary flow is used for the transport of liquid and mixing enhancement. It's also applied to drug delivery, DNA analysis, and protein crystallization, where minute amount of liquids are precisely guided towards targeted reservoir.

This principle can also applied in fuel cell, where capillary force drives fuel to fill the reservoir so that reaction could continue. In this work, we design a capillary channel for transporting methanol in fuel cell, and investigate its performance both numerically and experimentally.

2. Governing Equations

To study capillary flow, we need to consider two phase flow and focus on the interface first. The fluid interface is controlled by the following equation:

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \gamma \nabla \cdot \left(\varepsilon \nabla \phi - \phi(1-\phi) \frac{\nabla \phi}{|\nabla \phi|} \right)$$

The parameter Φ represents the volume fraction of one phase flow, or methanol in our model. The parameter ε is the thickness of the interface. The parameter γ determines the amount of reintialization.

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Another governing equations are Navier-Stokes equations, which describe the transport of mass and momentum.

$$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\cdot[-p\mathbf{I} + \eta(\nabla\mathbf{u} + (\nabla\mathbf{u})^T)] + \mathbf{F}_{st} + \rho\mathbf{g}$$

$$\nabla\cdot\mathbf{u} = 0$$

3. Model

As illustrated in Figure 1(a), our design consists of a capillary channel between two reservoirs, represented by loading pad and vent respectively and connected to the main channel through micro parallel channels.

Once loaded on the pad, methanol will automatically move towards the vent driven by capillary force. An SEM photo of typical structures is shown in Figure 1(c).

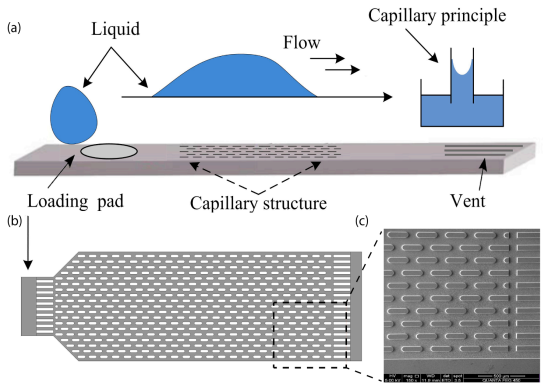

Figure 1. (a) Principle of the capillary channel: once loaded on the pad, methanol will automatically move towards the vent driven by capillary force; (b) Simulation model in COMSOL; (c) SEM photo of a typical part of the capillary channel.

A CFD simulation is carried out with COMSOL Multiphysics, using the Two-Phase Flow, Laminar, Level Set application mode. This application mode uses the Navier-Stokes equations to describe the momentum transport, including the surface tension and the conservation of mass, and also a reinitialized level set method to represent a discrete fluid interface between the air and methanol.

Figure 1(b) presents the model defined in COMSOL, which is smaller than that used in the experiment to reduce the calculating time. An incompressible, laminar, Newtonian fluid represented by methanol and air act as the two phase in this model. The boundary condition of each inside wall is set as wetted wall with contact angle at 15 degrees. Initially the main channel is filled with air and a methanol volume fraction value of unity and zero is specified at the inlet and outlet respectively.

A hyperfine triangular mesh is applied in the main channel in order to get a more accurate calculation of capillary force. So is the inlet and outlet of the main channel. If the mesh were not precise enough, the calculated capillary force would not be enough to pull the liquid forwards. The reservoir part is of less importance; hence the simplest mesh is good enough in this simulation. Here the disconformity of flow over depth is not considered since the model is based on laminar flow. In certain situations, for example, where the top or bottom of the channel has chemical reactions, a 3D model should be introduced to take this disconformity into account.

4. Numerical and Experimental Results

Figure 2(a) extracted from simulation movie shows the movement of the methanol-gas interface. During the capillary filling process the moving speed of the interface is about the same, with a drastically changed surface shape. Initially due to the trapezoid inlet, the meniscus interface has a convex shape, which gradually disappears as more methanol filled in. When half of the channel is filled with methanol, the interface is almost straight. The capillary flow speed is a little bit faster in both sides than that in the central, since liquid in the center could go both way forwards while liquid beside the wall could have only one direction. Consequently when this is achieved, the meniscus interface gets a concave shape. The channel is tested with water and methanol respectively and the results are consistent with experiments as shown in Figure 2(c). Note that in Figure 2(b) no concave front is observed, possibly because the channel is not long enough to present the entire process.

It takes a considerably longer time to fill the channel with water than methanol mainly due to different contact angles of these two liquids. To further investigate this assumption, we test the channel with methanol solution of different concentration in COMSOL and experiment, as

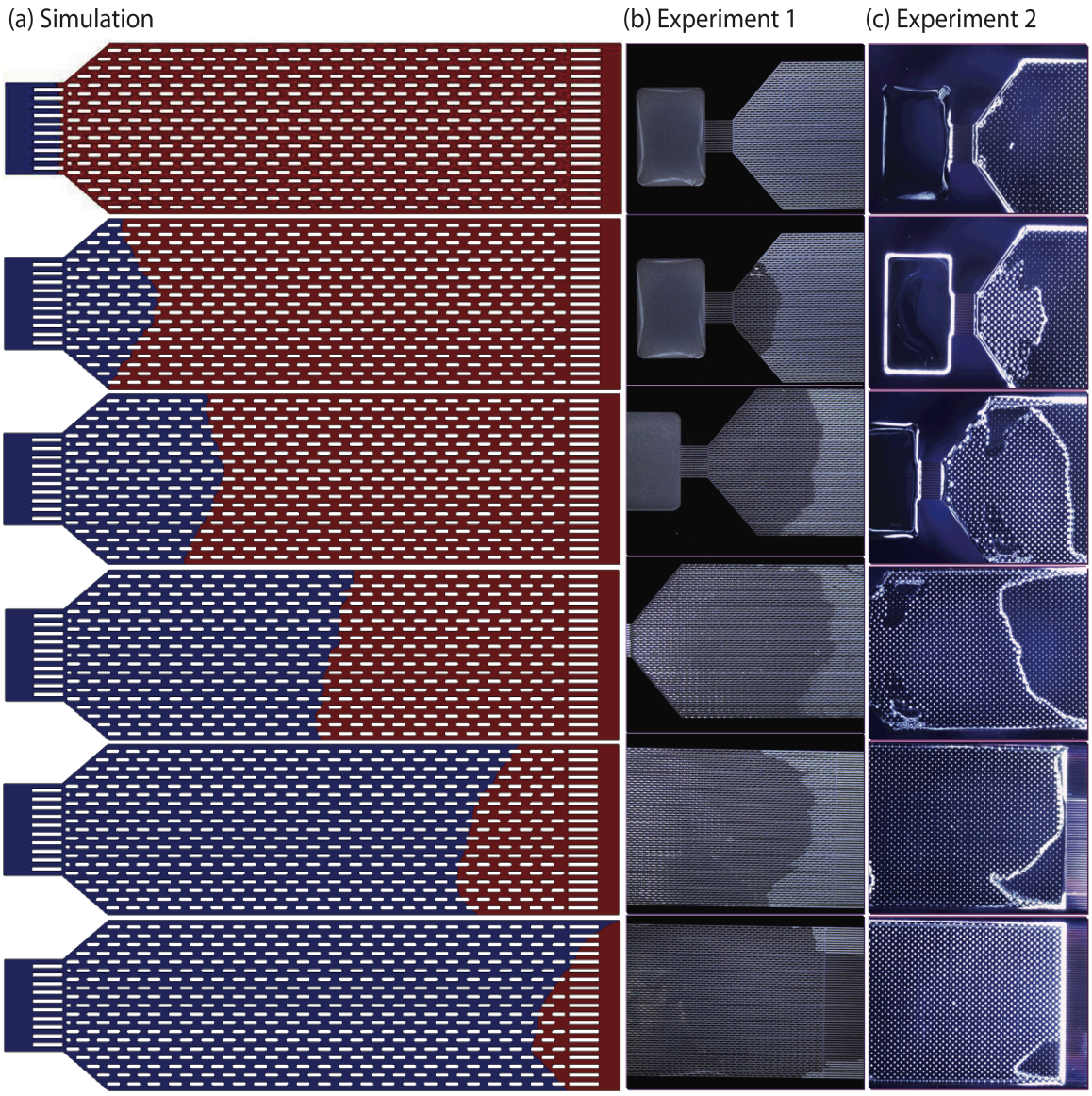

Figure 2. (a) Numerical results of capillary flow in the channel: moving speed of the interface is about the same with the meniscus interface changing from convex shape to concave shape; (b)&(c) Experimental results of capillary flow in the channel.

shown in Figure 3(a). Both flow rate and time for pure methanol to fill the channel is defined as 1.00 to better compare numerical and experimental results. The results show a good consistency in Figure 3(b) and Figure 3(c), confirming an increased flow rate with a reduced contact angle.

5. Conclusions

In this paper we design a capillary channel for methanol transport in fuel cell. Its performance is studied both numerically and experimentally. This capillary channel can also be adapted for other minute liquid transport besides methanol in other applications. And the experimental and numerical methods presented

(a)

	Pure Methanol	10M Methanol	5M Methanol	2M Methanol
Contact Angle *(Degree)*	15	22	31	49
Time *(experiment)*	1.000	1.310	1.862	2.931
Time *(simulation)*	1.000	1.163	1.581	1.744

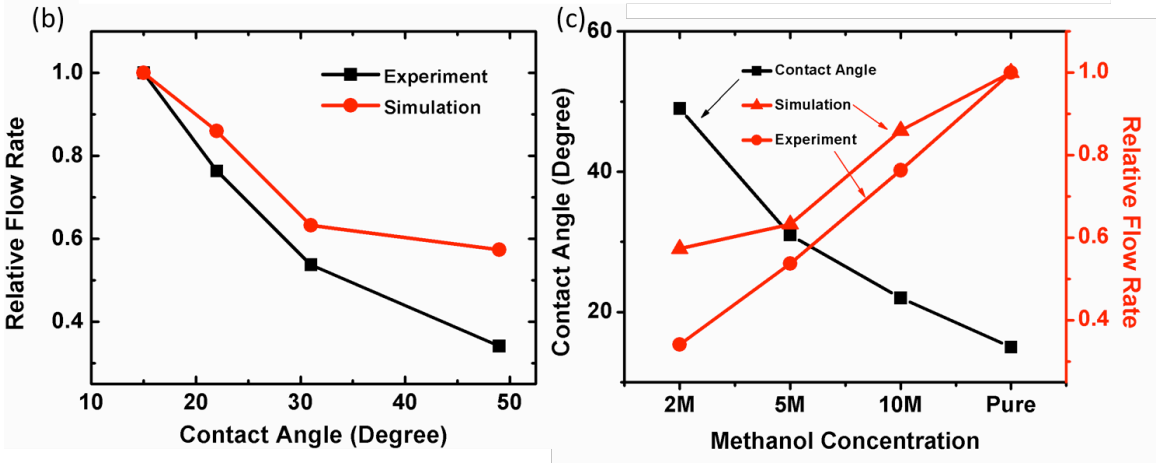

Figure 3. (a) Table of data from simulation and experiment; (b) Capillary flow rate decreases with an increasing contact angle; (c) Flow rate increases with an increasing methanol concentration.

in this work can serve as guidelines for further investigations of capillary transport.

6. References

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