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Oral

PRESSURE CHARACTERISTICS MODELLING FOR THE RAPID DESIGN OF CAPILLARY MICROFLUIDIC SYSTEMS

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Abstract

For the first time we present a novel **modeling approach** for the **rapid design of microfluidic systems** which rely on the **control of plugs and gas bubbles by capillary forces**. Systems are represented as a **generic network** of **equal nodes and channel segments**. **The capillary pressure** of the network is calculated and plotted **versus an x-axis accounting for the volumes** of the segments. The behavior of liquid plugs or gas bubbles in complex capillary systems can be qualitatively and quantitatively predicted by shifting a “virtual” volume along the volume axis of the graph and deducing the pressure drop. **Pressure characteristics were calculated for two complex microfluidic capillary systems and compared to experiments**. **The approach is simple but efficient to** optimize elements (e.g. valves or metering structures) in capillary systems. This **enables a rapid but reliable design of capillary microfluidics for microTAS**.

Working Principle

The proposed pressure characteristics model represents a microfluidic system as a linear network of generic channel segments and the connecting nodes (Fig. 1). At each node the capillary pressure of the upstream and downstream channel as well as the pinning pressures of a meniscus entering the node are calculated by a basic set of equations (Fig. 2) following [1] and interpolated along the channels. The pressures are plotted against the volumes of the segments as shown for some common examples in Fig. 3 (a, b, c). Complex shapes and networks of arbitrary channel combinations are approximated by multiple channel segments. By using a volume scale as x-axis, the capillary pressure drop over a fluidic compartment – gas bubble or liquid plug - can be read out at any position by shifting a constant ”virtual” volume along the graph. From the interception of both ends of the volume with the graph the capillary pressure difference can be taken directly from the graph’s y-axis. Thus capillary forces and movement can be directly evaluated (Fig. 3 (d)).

Applications

The modeling approach was used to analyze two capillary systems. A micro structured system for the passive water management in a fuel cells cathode [2] is analyzed in Fig. 4: A tapered channel at the beginning leads to a falling slope in the pressure characteristics. Liquid is sucked towards the lower pressure and stored left from the capillary valve visible by the step in the graph. The maximum storable liquid volume can be simply read out from the graph. If this volume is overcome the valve discharges excess liquid to the right. In Fig. 5 a pressure driven diagnostic chip [3] using three hydrophobic valves is analyzed. Each valve prevents the liquid plug to move onto the right until it is pushed forward by an external pressure pulse. After the pulse terminates the plug settles between two neighbouring valves. Pinning barriers are visible as singularities in the plot.

Conclusion

The presented pressure characteristics model is a systematic and efficient tool for the rapid design of capillary microfluidic systems for microTAS. While here only the application to liquid plugs is shown it can be applied to gas bubbles as well. More sophisticated effects like buoyancy and contact angle hysteresis can be implemented straight forward.

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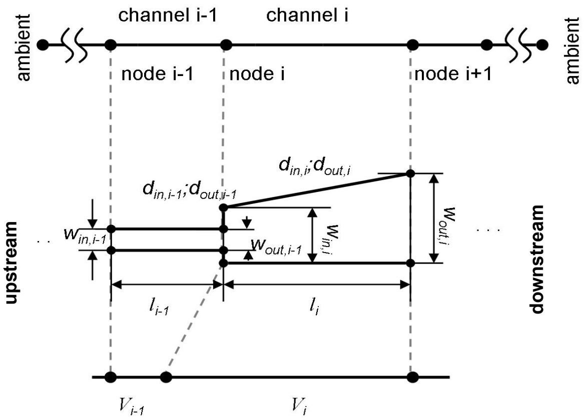

Fig. 1: A network model for the calculation of pressure characteristics is given by elementary channel segments connected by nodes. Channel segments are defined by inlet and outlet width and depth w_{in}, d_{in}, w_{out}, d_{out}, the length l_i and contact angles θ. The volume of every segment is plotted on a x-axis below.

$$p_{cap}=\begin{cases} p_{up,i} & \text{for} \quad x<x_i \\ p_{pin,down,i} & \text{for} \quad x \xrightarrow{downstream} x_i \\ p_{pin,up,i} & \text{for} \quad x \xrightarrow{upstream} x_i \\ p_{down,i} & \text{for} \quad x>x_i \end{cases} \quad (1)$$

$$\Delta p_{cap}=-2\sigma\frac{1}{A}\int_U \cos\theta\, ds \quad (2)$$

$$V_i=\frac{l}{3}\left(w_{in}d_{in}+w_{out}d_{out}+\sqrt{w_{in}d_{in}w_{out}d_{out}}\right) \quad (3)$$

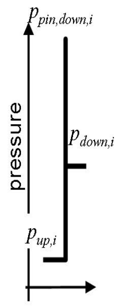

Fig. 2: In the vicinity of a node (index i, position x_i) four capillary pressures must be distinguished (1): The capillary pressures of upstream and downstream channel ($p_{up,i}$, $p_{down,i}$) and the pinning pressures of an arriving meniscus $p_{pin,down,i}$ and $p_{pin,up,i}$. The values are calculated by the integral theorem (2) and the theory of canthotaxis [1] in dependence of channel parameters. Volumes V_i are calculated by the trapezoid formula (3). (U circumference; A area σ surface tension)

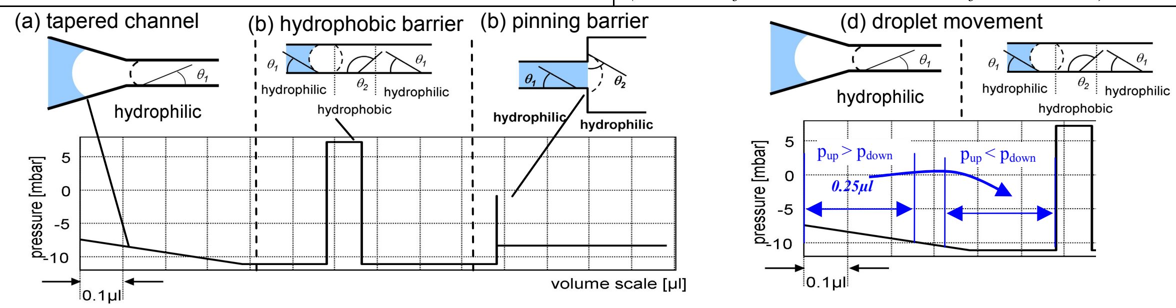

Fig. 3: Fundamental elements in capillary driven systems and their pressure characteristics evaluated by the generic model: (a) a tapered channel; (b) a hydrophobic barrier; (c) a pinning barrier (downstream). The movement of a given liquid volume can simply be predicted by shifting a constant virtual volume (arrows) along the pressure characteristics (d). As long as the pressure values on the left and right side of the volume are different, the plug will move.

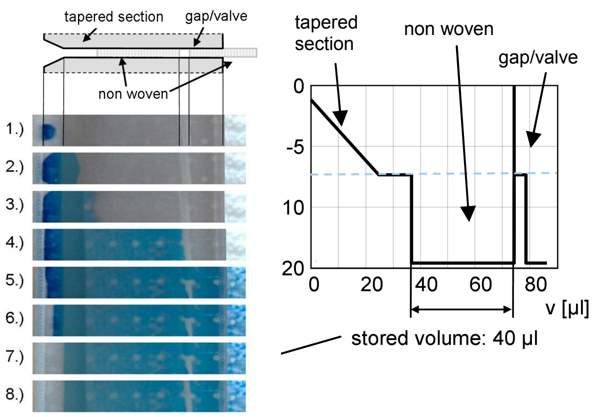

Fig. 4: Capillary system for the passive water management in a fuel cells cathode and pressure characteristic. The non woven material constitutes a local minimum that must be filled before liquid can overcome the overflow valve. At the volume axis one can read out the storable volume before the overflow gap is flooded. (Minimum channel dimension is 200µm. Length 25 mm)

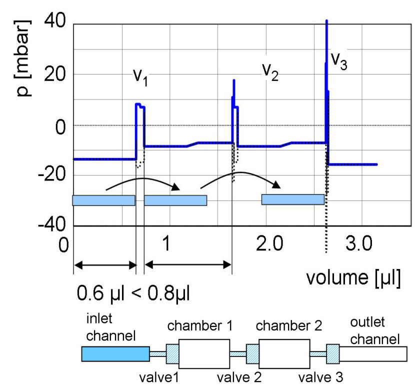

Fig. 5: Pressure characteristics of a complex, pressure driven diagnostic chip that can be capillary primed and uses three hydrophobic barriers as valves (v_1,v_2,v_3). Liquid plugs can are forced to overcome the valves by a short external pressure pulse. In-between the valves the plugs stay at the position. Right: Fabricated chip with channel diameters down to 50µm

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[3] M. M. Mielnik, et al. Proc. µTAS 2007, p. 1512-1514, 2007