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PRESSURE DRIVEN CONTINUOUS FLOW IN CLOSED-OPEN-CLOSED LIQUID MICROCHANNELS

Jessica Melin, Wouter van der Wijngaart, and Göran Stemme
Royal Institute of Technology, Department of Signals, Sensors, and Systems,
Microsystem Technology, SE 100 44, Stockholm, Sweden

Abstract
This paper introduces a closed-open-closed liquid microchannel that allows direct interfacing with on-chip continuous liquid flow and studies its performance and robustness. The novel component was successfully tested for flow performance, sample addition, and gas bubble removal and compares well with the theoretical model. The novel component behaves as a fluidic transistor where the open channel inlet, the open channel outlet and the air correspond to the source (P_s), drain (P_d), and gate (P_g=P_D), respectively. If P_g-P_D<0, the component acts as a fluidic diode.

Keywords: pressure driven, open channel, micro-channel, fluidic interfacing

1. Introduction
Surface fluidic systems, e.g., microarrays, are commonly interfaced by direct access to the external macro surroundings; however, open systems are vulnerable to evaporation and contamination and do not easily allow liquid control or waste product removal. Closed microchannel systems reduce evaporation, minimize contamination, and allow active fluid control via integrated or external pneumatic actuation. However, basic fluidic operations such as joining liquid samples or reagents in closed on-chip systems typically require integration of active fluid components such as pumps or valves [1]. Tube interfacing consumes space, introduces dead volume and often causes bubbles during priming [2]. Open capillary channels have been presented earlier, including capillary driven surface flow on hydrophilic microstripes [3], capillary filling of open channels [4], as well as gravitationally driven [5], and evaporation driven open microchannel flow [6].

2. Device Functionality
The component carries a continuous flow of liquid and comprises a closed inlet channel and closed outlet channel where the section in between is an open channel exposed to the environment, see Figure 1. Surface tension prevents channel overflow.

Figure 1. Schematic of a closed-open-closed channel geometry.
Liquid samples were successfully introduced to a constant flow in the open channel (Fig. 1). In addition, bubble removal was tested by introducing bubbles at the fluid inlet. The bubbles disappeared as they entered the open channel.

The closed-open-closed channel can be modeled as a transistor as can be seen in Figure 2. If the system is open to atmosphere ($P_G = P_{atm}$), pneumatic flow control is either upstream (overpressure; $P_G > P_{atm}$) or downstream (suction; $P_G < P_{atm}$). The liquid curvature and static pressure are fixed by the relation $r(x) = r(x)$ at any location in the open channel. The liquid-air surface wicks up when $P(x) > P_G$ and wicks down when $P(x) < P_G$.

The threshold pressure $P_T$ is defined as the pressure difference $P_G - P_S$ which induces liquid to enter the channel. Capillary priming occurs if $P_G < P_T$, while pressure is required for priming if $P_G > P_T$. Surface tension of the open liquid-air interface prevents the liquid from overflowing (failure mode #1) for moderate pressures. Channel overflow can only occur during larger upstream pneumatic overpressure and starts at the channel source. Viscous losses cause a pressure drop $P_{SD} = P_S - P_D$ along the open channel, resulting in a change in liquid surface curvature $1/r(x)$, as is qualitatively depicted in Figure 2. In many applications of interest, the kinematic pressure drop is negligible: $P_{SD} = P_S - P_D$. The pressure inside the liquid channel determines the cross section of the liquid in the open microchannel, see Figure 3. If the surface radius $r(0)$ at the source is forced beyond the minimum ($r_{min} = w/2$), overflow occurs. If the design is suboptimal, overflows occur due to wetting of the top surface of the open channel. Thus, appropriate geometrical design allows system optimization in terms of overflow robustness. For pressures $P_G - P(x)$ below a value $P_{sat}$, the air-liquid-solid 3-phase line detaches from the channel edge and moves downwards to the bottom of the channel (the fluid transistor moves from linear to saturation regime). The exact position of the 3-phase line depends on the cross-sectional channel geometry. When $P_D$ drops below a pinch-off pressure $P_{pinch}$, part of the channel near the drain becomes pinch off (dry). At this point, the transistor “saturates” with pressure-flow characteristics depending on the exact channel cross-section. Even further decrease of $P_D$ eventually results in introduction of gas bubbles through suction at the drain (failure mode #2). However, the latter effect can be avoided by geometrically ensuring large capillary forces at the drain as is schematically illustrated in Figure 1.

![Figure 2](image1.png)  
**Figure 2.** Schematic circuit representation of the component (top). The open liquid channel for varying $P_D$ and constant $P_S$ and $P_G$ (bottom).

![Figure 3](image2.png)  
**Figure 3.** Liquid curvature vs. liquid pressure.
3. Device Characterization

Experiments were performed using a PDMS-glass closed-open-closed microchannel and hydrostatically controlled water pressure as shown in Figure 4. As can be seen from Figure 5, where $P_{in}$ was constant and $P_{in}-P_{out}$ was varied, and from Figure 6, where $P_{i}$ and $P_{out}$ were kept constant while $P_{in}$ was varied, measurements verified the theoretical flow performance for the open micro-channel. The open channel is modeled as open plate flow. Note the fluidic diode characteristics of the device when $P_{in}=P_{out}$ (Fig. 6).

![Figure 4. The closed-open-closed microchannel in its experimental set-up.](image)

![Figure 5. Measured values (squares) and theoretical model (solid curve) of the gate pressure $P_{in}$ vs. flow for the microchannel.](image)

![Figure 6. Measured values (squares) and theoretical model (solid curve) of the inlet pressure $P_{in}$ vs. flow for the microchannel.](image)

4. Conclusions

This novel component can be used for applications including introduction of samples in flow-through microsystems or removal of gas bubbles in liquid flow. Further studies are currently in progress on developing a more complete theoretical model and understanding how the channel geometry affects the pressure-flow characteristics of the novel fluidic transistor.

References