CAPILLARY PUMPING WITH A CONSTANT FLOW RATE INDEPENDENT OF THE LIQUID SAMPLE VISCOSITY AND SURFACE ENERGY

*Weijin Guo, Jonas Hansson, and Wouter van der Wijngaart**
KTH Royal Institute of Technology, Stockholm, SWEDEN

ABSTRACT

We introduce and experimentally verify a capillary pump design that, for the first time, enables autonomous pumping of sample liquid with a flow rate constant in time and independent of the sample viscosity and sample surface energy. These results are of interest for applications that rely on a predictable flow rate and where the sample fluid viscosity or surface energy are not precisely known, e.g. in capillary driven diagnostic lateral flow biosensors for urine or blood sample, where large variations exist in both viscosity and surface energy between different patient samples.

INTRODUCTION

Capillary action plays an important role in the liquid transport on micro- and nanoscale, and has widely engineering applications. In biomedical engineering, capillary pumping is utilized in biomolecules pattern on the chip surface [1], and sample liquid pumping in lateral flow immunoassay [2].

Capillary devices with constant cross-section exhibit the well-known Washburn behavior, characterized by a flow rate that depends on the square root of time [3-5] and that depends on the fluid properties with a factor $\gamma.\cos(\theta)/\mu$, in which γ is surface energy, θ is contact angle, and μ is viscosity. The variation of liquid properties, including the surface energy and viscosity, can induce a variation in flow rate. In lateral flow tests, there exists person-to-person variation in the properties of the sample liquids (e.g. blood and urine). This is a problem for diagnostic applications that rely on a predictable flow rate and where the sample fluid viscosity or surface energy is not precisely known.

Constant capillary flow can be obtained by introducing a large up-stream liquid resistance that dominates the viscous losses in the capillary device [6, 7]. Constant and sample viscosity independent capillary pumping can be obtained by introducing a downstream fluidic resistance for the displaced air that dominates the viscous losses in the capillary system [8]. Capillary pumping independent of sample surface energy has not been reported previously.

CONCEPT

We propose a capillary pump design (Figure. 1) that is primed with a well-characterized *pump liquid* of our choice before use. When *sample liquid* with unknown fluid properties is added at the pump inlet, the chosen pump liquid is triggered to capillarily imbibe the downstream section of the pump and thereby pull along the unknown sample plug.

The pump is designed such that the capillary pressure at the leading edge of the pump liquid dominates the capillary suction: $P_{c,pl} >> P_{c,pr}$, $P_{c,sl}$ and $P_{c,sr}$. Moreover, a fluidic resistor in the pump liquid section is designed to have orders of magnitude higher fluidic resistance, R_R, than the rest of the device. These design features ensure that the flow rate of the entire pump is dominated by the capillary pressure over, and the viscous losses of, the well-characterized pump liquid, hence the pump operates independently of the unknown sample liquid properties. The constant capillary pressure drop over the pump liquid plug and the near constant fluidic resistance of the entire device, $R_{total} \approx R_R$, ensure a time independent flow rate.

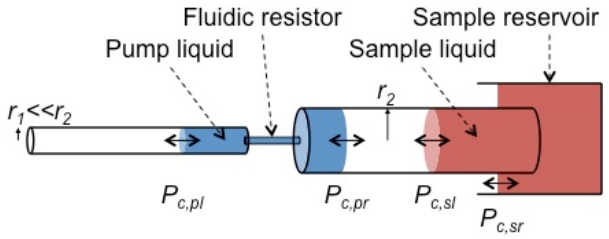

Figure 1: Schematic of the capillary pump principle.

EXPERIMENTS

Figure 2 shows the capillary pump prototype, consisting of two 2.5 mm ID glass capillaries (Sigma-Aldrich, Switzerland) that form the pump liquid section and sample liquid section and that are coupled together by a geometric capillary valve, consisting of an ID 4.7 mm plastic capillary (cut from 1 ml NORM-JECT®, HENKA SASS WOLF, Germany) using OSTE glue (Ostemer 220, Mercene Labs, Sweden). The length of the glass tubes and plastic tube are 62 mm and 21 mm respectively. The plastic capillary acting as a geometrical valve can prevent contact of the pump and sample liquids with one another and with the same solid surface. Nitrocellulose paper (Hi-Flow Plus HF075, Merck Millipore) is cut by a xurograph (Cutting Plotter CE5000-60, Graphtech) to have a narrow tip that forms the fluidic resistor, and which tip fits into the capillary. Pump liquid (DI water in our experiments) is prefilled from the exit of the pump liquid section. To start sample pumping, i) the entrance of the sample liquid section of the capillary tube is immersed in the sample, and ii) the narrow tip of the nitrocellulose paper is inserted in the exit of the pump liquid section. We use a camera (Canon EOS 600D, Japan) to capture the whole filling process, and analyze the video to get the time-distance/pumped volume curve of the sample liquids.

We choose some household chemicals in the lab as the sample liquids, including DI water (18 MΩ cm, Millipore), ethanol (99.5%, Analytical Grade, Solveco, Sweden), isopropanol (LC-MS Chromasolv, Sigma-Aldrich, Germany), mineral oil (Mineral oil, light, 330779 Sigma-Aldrich, USA), and glycerol (ACS reagent, ≥ 99.5%, Sigma-Aldrich, USA). We also performed the test without sample liquid, namely we use the pump to pump air. These sample liquids have large variation in the surface

energy and viscosity, shown in Table 1. For the control experiment, we did the filling experiments of the sample liquids in a length 62 mm, ID 2.5 mm glass tube, the same as the glass capillary we used in the novel pump.

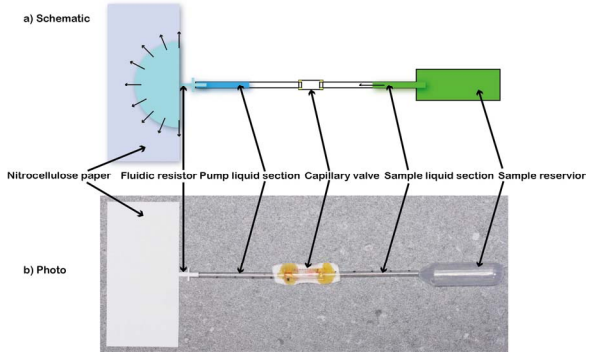

Figure 2: Schematic (a) and photo (b) of the capillary pump prototype. The pump liquid front imbibes the nitrocellulose paper, which determines the capillary suction; the fluidic resistor consists of a thin and long nitrocellulose paper section; a geometrical capillary valve separates the pump liquid and sample liquid sections, preventing cross-reactions between the two.

RESULTS

Table 1 shows the average volumetric flow rate of our novel design for all sample fluids with strongly varying fluid properties and Figure 3 shows the pumped volume versus filling time for different sample liquids. It was shown in Figure 3 that the flow rate is constant and almost the same for all the sample liquids in our novel capillary pump design, while the flow behavior in the constant cross section glass capillary can be well described by the Lucas-Washburn equation. Despite the fluid samples tested featuring large differences in viscosity (factor > 66000 difference), surface energy (factor 4.76 difference), and contact angle (in the range 15.6° to 19.4°), the flow rate delivered by our novel pump remains in the range 0.33 - 0.40 μL/s. This flow rate is relevant for point-of-care diagnostic applications. The flow variation in the novel design between largely varying samples (Figure 3a) remains < 8%, which can be compared to the factor 576 in flow variation measured for the (Washburn-like) filling of standard capillaries with the tested sample liquids (Figure 3b).

Table 1: The sample fluid properties and the measured pump volumetric flow rate.

	Pumped sample fluids with different fluid properties					
	DI water	ethanol	isopropanol	mineral oil	glycerol	air(=no sample liquid)
Viscosity μ (mPa.s)	1.00	1.07	1.96	68	1.20×10^3	1.8×10^{-2}
Surface Energy γ (mJ/m^2)	71.60	20.01	18.86	28.27	89.8	n.a.
Contact angle θ (°)	17.4	18.3	19.4	16.3	15.6	n.a.
Measured average flow rate using constant cross-section capillary (Washburn) (μL/s)	1383.4	634.0	380.4	30.4	2.4	n.a.
Measured average flow rate using novel pump design (μL/s)	0.40	0.35	0.33	0.40	0.35	0.39

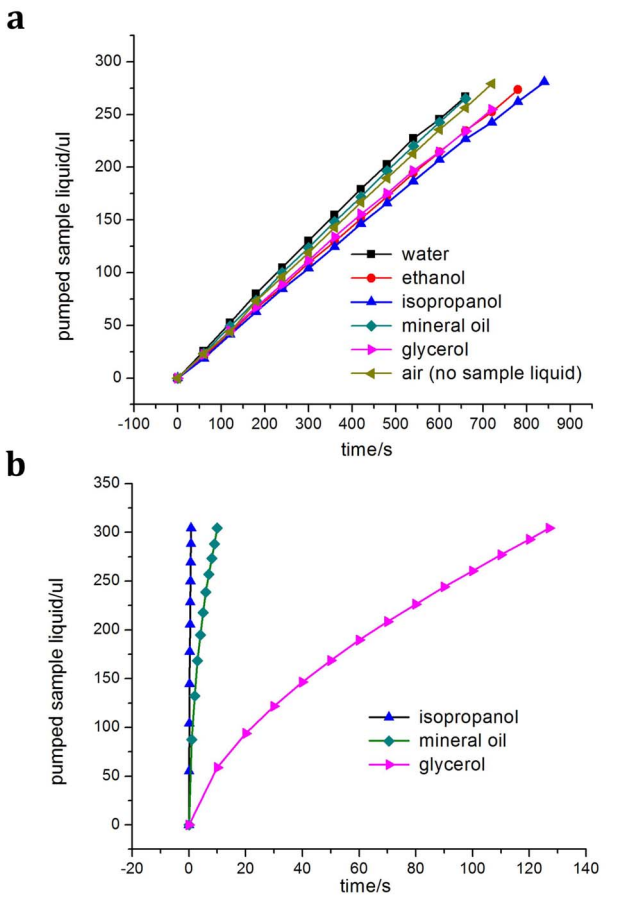

Figure 3: Pumped sample volume versus time for several sample liquids: a) in our novel capillary pump; and, b) for comparison, in a circular cross-section glass capillary tube with 2.5 mm ID (Washburn case).

CONCLUSIONS

We introduced a novel capillary pump design that can provide a constant flow rate independent of sample liquid surface energy and viscosity, and experimentally verified it. For all the sample fluids tested, the flow rate is nearly constant and independent of the sample fluid properties. This novel capillary pump has great potential in the application of lateral flow immunoassay. With predictable flow rate through the reaction zone, it may be possible to get quantitative test results, which will be a big advance compared to qualitative traditional lateral flow devices.

ACKNOWLEDGEMENTS

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CONTACT

*Wouter van der Wijngaart; phone: +46-8-7906613; wouter@kth.se