Flow Batteries for Microfluidic Networks: Configuring An Electroosmotic Pump for Nonterminal Positions

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S Supporting Information

ABSTRACT: A micropump provides flow and pressure for a lab-on-chip device, just as a battery supplies current and voltage for an electronic system. Numerous micropumps have been developed, but none is as versatile as a battery. One cannot easily insert a micropump into a nonterminal position of a fluidic line without affecting the rest of the fluidic system, and one cannot simply connect several micropumps in series to enhance the pressure output, etc. In this work we develop a flow battery (or pressure power supply) to address this issue. A flow battery consists of a +EOP (in which the liquid flows in the same direction as the field gradient) and a −EOP (in which the liquid flows opposite to the electric field gradient), and the outlet of the +EOP is directly connected to the inlet of the −EOP. An external high voltage is applied to this outlet−inlet joint via a short gel-filled capillary that allows ions but not bulk liquid flow, while the +EOP's inlet and the −EOP's outlet (the flow battery's inlet and outlet) are grounded. This flow battery can be deployed anywhere in a fluidic network without electrically affecting the rest of the system. Several flow batteries can be connected in series to enhance the pressure output to drive HPLC separations. In a fluidic system powered by flow batteries, a hydraulic equivalent of Ohm's law can be applied to analyze system pressures and flow rates.
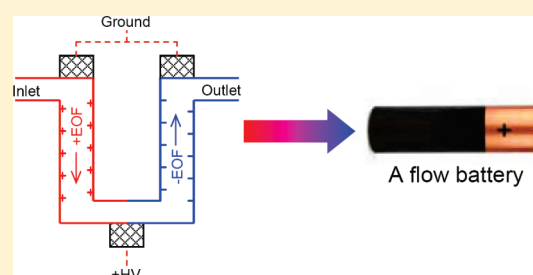
Electrical circuits can use electron sources deployed at one or more desired locations. Such devices can be unit power sources (cells), combinations thereof (batteries), or more complex variable voltage supplies. Microfluidic networks (μFNs) are the heart of lab-on-chip devices that perform complex chemical processes in nanoliter scales;[1−3] numerous applications in chemistry, biology, and other fields exist.[4−6] Controlled flow is critical in the vast majority of μFNs. Precise manipulation of such flows get increasingly complex as the μFN complexity increases. Despite the fact that hydraulic and electrical circuits are analogous in many ways,[7] the deployment of flow sources in a μFN is not as simple as putting electron sources in an electrical circuit. Several micropumps such as membrane-based pumps[8,9] and electrolysis pumps[10] have been successfully used on-chip and one of the major micropumps is an electrosmotic pump (EOP).[11−14] Simultaneous deployment of multiple EOPs on a chip especially in nonterminal locations is exceptionally complex because of interaction of the electrical fields, aside from problems of electrolytic gas evolution at such locations.

Here we describe a new class of self-contained EOPs, flow batteries, to overcome these problems. A unitary EOP battery comprises of two open tubular capillary EOPs: one with walls coated with a positively charged polymer (+EOP, in which the liquid flows in the same direction as the field gradient from

positive potential to ground), serially connected to one with walls coated with a negatively charged polymer (−EOP, in which the liquid flows opposite to the electric field gradient). As illustrated in Figure 1a, if we apply a positive high voltage to the junction of the two capillaries while their free termini are grounded, there will be flow from the free terminus of the +EOP (inlet) to the free terminus of the −EOP (outlet). We thus have an electroosmotically driven flow battery where both the pump inlet/outlet are at ground potential while there is finite flow through the system. Further, no gas is present in the pump fluid. The junction between the two is shown in more detail in Figure 1b. Both the inlet and outlet and this junction are actually in the form of a tee rather than a union: an immobilized polyacrylamide gel-filled capillary connects the main fluid channel to the external electrolyte reservoirs where either high voltage (HV) or ground electrodes are placed. The gel-filled capillaries complete the electrical connection by allowing ion flow but not bulk liquid flow.[15] Any gas evolution occurs in the electrode liquid reservoir separated from the flow channels of interest. (Note: Isolation of electrolysis-generated bubbles from pump channels has been implemented
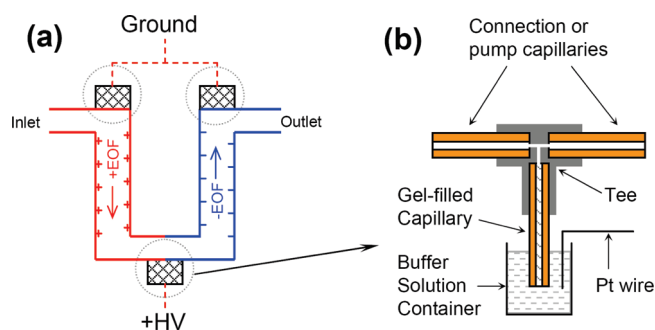
Figure 1. Schematic configuration of flow battery: (a) configuration of a basic pump unit. For a positively charged wall, the electroosmotic flow is from ground to +HV and for a negatively charged wall the flow is from +HV to ground. (b) The circled area is shown expanded, the cross-hatched area in part a is the gel-filled capillary in part b. The gel-filled capillary prevents bulk liquid flow but allows electrical connection through the ion flow.
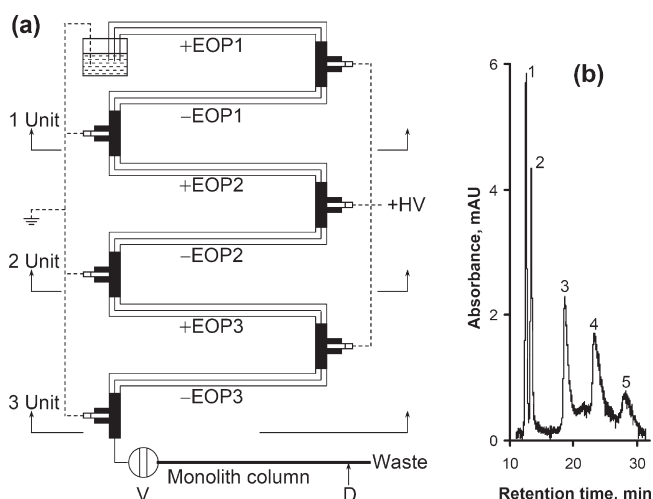

Figure 2. Serially connected flow battery for HPLC: (a) A capillary HPLC system configured with serially connected flow batteries. Each EOP contained 52 parallel pump capillaries (1 m length × 4.8 μm i.d.). HV, +20 kV; V, 4 nL injector; 20 cm length × 75 μm i.d. acrylate monolith column; D, on-capillary UV absorbance detector at 215 nm. (b) Typical chromatogram: eluent, 0.1% TFA 15:85 CH$_3$CN–H$_2$O; 2 ng of (1) Gly-Tyr, (2) Val-Tyr-Val, (3) Met enkephalin, (4) Leu enkephalin, and (5) angiotensin II; 30 kV, pump flow 56 nL/min; pressure ~1.8 MPa.

before.[16−18]) Not only is there no potential difference between the pump unit inlet and the outlet, both are at ground potential. Incorporating one or more flow batteries anywhere in a μFN does not therefore cause interaction between electric fields. They can therefore be used as flow/pressure sources, singly, in series, and in multiple nonterminal locations. A μFN "powered" by such sources can be fully modeled by hydraulic Ohm's laws.[7]

Obviously, the unit flow battery is most efficient when the flow rate of the +EOP exactly matches that of the −EOP. Applying different voltages to each is not possible without creating an inlet/outlet potential difference. Rather than tailoring coating compositions or capillary bores for each EOP, the most convenient way to achieve this is to use some uniform formulation of +EOP and −EOP coatings that will provide a stable electroosmotic flow (EOF) with the desired pump fluid and then adjust the capillary length for the −EOP relative to that of the + EOP, to match the flow at the same voltage applied. This unit flow battery is efficient; the total flow/pressure generated by it is linearly related to the magnitude of the HV applied to the unit. This then acts as a linear transducer, converting voltage to flow, acting analogous to a variable voltage supply in an electrical circuit but without a potential difference between the inlet and the outlet. The magnitude of the HV can be varied without affecting the fields in all regions outside the battery. Unit batteries can also be serially connected to achieve an increase in pressure (voltage).

To demonstrate the additivity of the components of such a flow battery in serial connections, we connected 1−3 units (indicated by the arrows in Figure 2a) and measured the overall pressure output. The pressure output, P, increased proportionally to the number, n, of supply units connected serially (see Figure S1 in the Supporting Information), indicating that it behaves similar to electrical power cells connected in series. The pressure output also predictably increased linearly with the external voltage applied, V_{app}. (P (MPa) = 0.171 ± 0.002V_{app} (kV), r^2 = 0.9992, intercept statistically indistinguishable from zero). For safety reasons, we recommend voltages ≤30 kV.

The experimental system of Figure 2 was deliberately constructed to generate significant flow at high pressures to test HPLC capability. Each EOP contained 52 capillaries, and each capillary has a length of 1 m and an i.d. of 4.8 μm. Selection of the capillary dimensions will depend on the desired flow rate, pumping pressure, and tolerance of Joule heating across the

gel-filled capillary. A battery of 3 generated a no-load pressure of 5.1 MPa, adequate to drive capillary scale monolithic HPLC. Figure 2b illustrates baseline-resolution of 5 peptides in ~30 min. The pump rate variation before and after the separation was less than 3%.

With these pump units, one can build μFNs that mimic electronic circuits and apply the fluidic equivalent of Ohm's law to calculate the fluid pressure (voltage) and flow rate (current). We use a simple fluidic system as shown in Figure 3a to define two basic parameters, flow resistance and pressure rating of a flow battery. The fluidic system contains one flow battery and one flow resistor (the load capillary).

The EOF (no-load flow) of the flow battery can be expressed by

$$Q_{eo} = n\pi \left(\frac{d}{2}\right)^2 \mu_{eo} \left(\frac{V}{L}\right) \tag{1}$$

where L and d are the length and inner diameter of the pump capillary, n is the number of pump capillaries, μ_{eo} is the electroosmotic mobility, and V is the voltage applied across the pump capillaries. When the pump outlet is blocked, the Q_{eo} will be opposed by a pressure-driven counter flow, yielding a zero net flow and a pressure, ΔP_{max}. On the basis of the Hagen–Poiseuille's equation,

$$\Delta P_{max} = \left(\frac{128\eta L}{n\pi d^4}\right) Q_{eo} = z Q_{eo} \tag{2}$$

where η is the viscosity of the pump solution. The expression of z is the definition of flow resistance,

$$z = \frac{128\eta L}{n\pi d^4} \tag{3}$$

Flow resistance has a unit of Pa s m^{-3}. We also define this unit as LΩ.
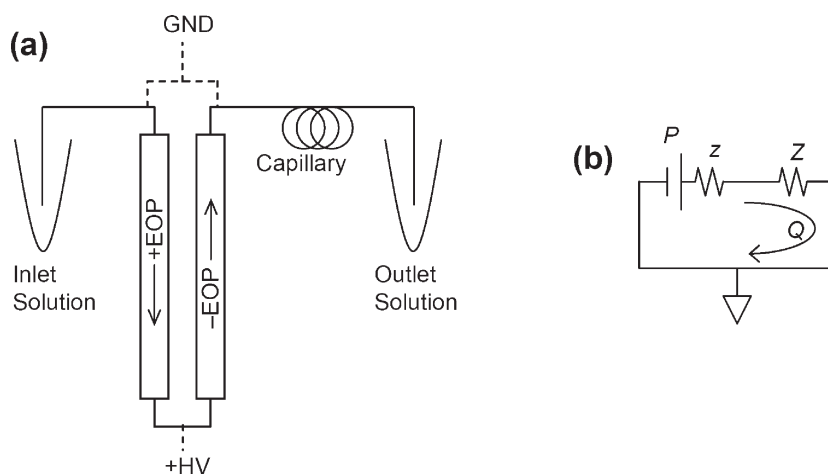
Figure 3. Electronic-circuit-like microfluidic network: (a) a simple microfluidic system with one flow battery and flow resistor, (b) an equivalent fluidic circuit diagram of part a. P and z are the pressure rating and internal resistance of the flow battery, and Z is the flow resistance of the load capillary.

Referring back to Figure 3a, as the flow battery drives the solution through the load capillary, the flow rate (Q) is directly proportional to the pressure (ΔP) built up between the flow battery and the load capillary

$$Q = \Delta P / \left(\frac{128\eta L'}{\pi d'^4}\right) = \Delta P/Z \qquad (4)$$

where L', d', and Z are the length, inner diameter, and flow resistance of the load capillary. The ΔP is also the backpressure of the flow battery and will cause a backward flow (Q_b) through the pump capillaries,

$$Q_b = \Delta P / \left(\frac{128\eta L}{n\pi d^4}\right) = \Delta P/z \qquad (5)$$

Combining eqs 2, 4, and 5 and recognizing $Q_{eo} = Q + Q_b$,[19−21] we have

$$\Delta P_{max}/(z + Z) = \Delta P/Z = Q \qquad (6)$$

Equation 6 is the hydraulic equivalent of Ohm's law. The flow battery can be thought of as a pressure power supply with a no-load pressure rating (open circuit voltage) of $P = \Delta P_{max}$ and an internal resistance of z. If we apply the Ohm's law to the μFN in Figure 3b, the same results as eq 6 are obtained.

To demonstrate the applicability of the hydraulic equivalents of Ohm's law and Kirchhoff's law, we construct a μFN that consists of two flow batteries and two flow resistors (Figure 4a). The equivalent electronic circuit is in Figure 4b. The inlet and outlets are at the same "ambient" pressure ($P_{amb} = 1.01 \times 10^5$ Pa) that is equivalent to "ground" in an electrical circuit. The inlet flow rate must be equal to the sum of the outlet flow rates. We used eq 1 to calculate the EOFs (Q_{eo} and Q_{eo}') of the two pumps. From the dimensions of the pump capillaries, we used eq 3 to calculate the corresponding internal flow resistances (z and z') of the unit pumps and the flow resistances (Z_1 and Z_2) of the load capillaries 1 and 2. From Q_{eo} and Q_{eo}' and z and z', we obtained the EOPs' pressure ratings (P and P') as defined by eq 2. Because we measured pressure from ideal gas laws (vide infra), the absolute value of the pressure is important. Taking the finite value of P_{amb} into account, we apply fluidic Ohm's law to calculate P_1, P_2, Q_1, and Q_2. The calculated vs experimental results are listed in the third and fourth columns of Table 1, respectively. The two sets of data are in excellent agreement. We also measured P, P', z, z', Z_1,
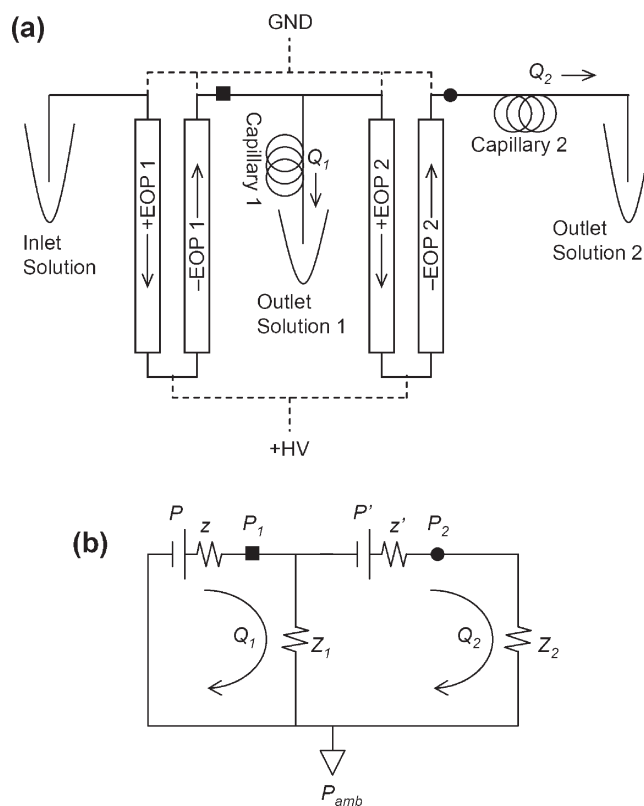

Figure 4. A double-loop microfluidic network. The two flow batteries were constructed following the same procedure and using the same materials. In total, 15 parallel pump capillaries (1 m length × 4.8 μm i.d.) were utilized to build all +EOPs and −EOPs. The dimensions of capillaries 1 and 2 are 30 cm length × 4.8 μm i.d. and 50 cm length × 11 μm i.d, respectively. The ■ and ● indicate where P_1 and P_2 were measured. Q_1 and Q_2 were flow rates out of capillaries 1 and 2.

and Z_2 (see the Supporting Information for measurements of P and P' and z, z', Z_1, and Z_2) and calculated the dependent variables using these experimentally measured parameters. The calculated data are listed in the fifth column. Again, these results match the experimentally measured data well, indicating the applicability of hydraulic equivalents of Ohm's laws to these circuits.

Table 1. Comparison between Calculated and Experimentally Measured Results[a]

		calculated	measured[b]	calculated[c]
EOP	Q_{eo}	1.84×10^{-13}	1.79×10^{-13}	
	P	1.89×10^{6}	1.86×10^{6}	
	z	1.02×10^{19}	1.07×10^{19}	
EOP$'$	Q_{eo}'	1.84×10^{-13}	1.82×10^{-13}	
	P'	1.89×10^{6}	1.82×10^{6}	
	z'	1.02×10^{19}	1.05×10^{19}	
capillary 1	Z_1	2.30×10^{19}	2.28×10^{19}	
capillary 2	Z_2	1.39×10^{18}	1.36×10^{18}	
dependent variables	P_1	1.99×10^{5}	2.13×10^{5}	1.93×10^{5}
	P_2	3.39×10^{5}	3.14×10^{5}	3.21×10^{5}
	Q_1	4.21×10^{-15}	4.36×10^{-15}	4.03×10^{-15}
	Q_2	1.71×10^{-13}	1.70×10^{-13}	1.61×10^{-13}

[a] 0.1% trifluoroacetic acid in water was used as the pump solution in this test. Both positively and negatively coated capillaries had a similar electroosmotic mobility of 3.40×10^{-8} m^2 V^{-1} s^{-1} with this pump solution. The high voltage applied was 20 kV. A liquid viscosity of 0.001 Pa s was used for the calculations. SI units are used in this table: m^3 s^{-1} for Q, Pa for P, and LΩ (= Pa s m^{-3}, see eq 3 for definition) for Z. [b] The data in this column were averages of three measurements. [c] The data were calculated using the experimentally measured P, P', z, z', Z_1, and Z_2 in the 4th column.

Referring back to Figure 4a, the second flow battery was inserted in the middle of a fluidic line to raise the downstream fluid pressure. The two interface points of the flow battery to the circuit, the inlet and the outlet, are both at electrical ground; its addition had no effects on the electric field distribution to the μFN.

In principle, the inlet and outlet potentials can be the same but need not be at ground potential. If the desired insertion point in the μFN has a finite nonzero potential, the inlet and outlet can be electrically tied together but left floating. As long as the pump HV supply and the μFN supply share a common ground, the device will work fine. While combination of serially connected + and − EOPs have been attempted before, such arrangements necessarily involved the presence of voltage at one terminus.[22,23] No other pumps or electrically driven flow sources can be deployed in this unique way.

In summary, we have described a new class of micropumps that work as unit flow/pressure sources. They allow facile design of microfluidic networks which are easily modeled using traditional electrical principles, e.g., Ohm's law, Kirchhoff's law, etc. It is obvious that such laws can also be readily used to estimate pressures, flow rates, etc. in extant μFNs. Construction of flow batteries in the current capillary-format is kind of tedious and time-consuming. The batteries can be manufactured on chips, which is an ongoing project in our group and the results will be published elsewhere. A potential problem with the flow battery is the dependence of EOF on pump solution composition. Derivatizing the surfaces of the pumping elements with "strong" acid or base can alleviate this problem but cannot avoid it. This should be taken into consideration when the hydraulic equivalent of Ohm's law is used to calculate the flow rate and pressure of a microfluidic system.

■ ASSOCIATED CONTENT

ⓢ Supporting Information. Experimental, definitions of flow resistance and pressure rating of a pressure power source and derivation of the equivalent Ohm's law, and application of Ohm's law equivalent to Figure 3 (equations used for Table 1). This material is available free of charge via the Internet at http://pubs.acs.org.

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■ REFERENCES

(1) Harrison, D. J.; Fluri, K.; Seiler, K.; Fan, Z.; Effenhauser, C. S.; Manz, A. *Science* **1993**, *261*, 895–897.

(2) Unger, M. A.; Chou, H. P.; Thorsen, T.; Scherer, A.; Quake, S. R. *Science* **2000**, *288*, 113–116.

(3) Burns, M. A.; Johnson, B. N.; Brahmasandra, S. N.; Handique, K.; Webster, J. R.; Krishnan, M.; Sammarco, T. S.; Man, P. M.; Jones, D.; Heldsinger, D.; Mastrangelo, C. H.; Burke, D. T. *Science* **1998**, *282*, 484–487.

(4) Dittrich, P. S.; Manz, A. *Nat. Rev. Drug Discovery* **2006**, *5*, 210–218.

(5) Squires, T. M.; Quake, S. R. *Rev. Mod. Phys.* **2005**, *77*, 977–1026.

(6) Whitesides, G. M. *Nature* **2006**, *442*, 368–73.

(7) Esposito, A. *Machine Des.* **1969**, *41*, 173–177.

(8) Unger, M. A.; Chou, H.-P.; Thorsen, T.; Scherer, A.; Quake, S. R. *Science* **2000**, *288*, 113–116.

(9) Grover, W. H.; Skelley, A. M.; Liu, C. N.; Lagally, E. T.; Mathies, R. A. *Sens. Actuators, B* **2003**, *89*, 315–323.

(10) Bohm, S.; Olthuis, W.; Bergveld, P. *J. Biomed. Microdevices* **1999**, *1*, 121–130.

(11) Laser, D. J.; Santiago, J. G. *J. Micromech. Microeng.* **2004**, *14*, R35–R64.

(12) Lazar, I. M.; Trisiripisal, P.; Sarvaiya, H. A. *Anal. Chem.* **2006**, *78*, 5513–5524.

(13) Borowsky, J. F.; Giordano, B. C.; Lu, Q.; Terray, A.; Collins, G. E. *Anal. Chem.* **2008**, *80*, 8287–8292.

(14) Wang, X.; Wang, S.; Gendhar, B.; Cheng, C.; Byun, C. K.; Li, G.; Zhao, M.; Liu, S. *Trends Analyt. Chem.* **2009**, *28*, 64–74.

(15) Byun, C. K.; Wang, X.; Pu, Q.; Liu, S. *Anal. Chem.* **2007**, *79*, 3862–3866.

(16) Dasgupta, P. K.; Liu, S. *Anal. Chem.* **1994**, *66*, 1792–1798.

(17) Brask, A.; Kutter, J. P.; Bruus, H. *Lab Chip* **2005**, *5*, 730–738.

(18) Takamura, Y.; Onoda, H.; Inokuchi, H.; Adachi, S.; Oki, A.; Horiike, Y. *Electrophoresis* **2003**, *24*, 185–192.

(19) Lazar, I. M; Karger, B. L. *Anal. Chem.* **2002**, *74*, 6259–6268.

(20) Liu, S.; Pu, Q.; Lu, J. J. *J. Chromatogr., A* **2003**, *1013*, 57–64.

(21) Yao, S. H.; Santiago, J. G. *J. Colloid Interface Sci.* **2003**, *268*, 133–142.

(22) Razunguzwa, T. T.; Timperman, A. T. *Anal. Chem.* **2004**, *76*, 1336–1341.

(23) Arnold, D. W.; Paul, P. H.; Schoeniger, J. S. Method for eliminating gas blocking in electrokinetic pumping systems. U.S. Patent 6,287,440, September 11, 2001.

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