Proceedings of IMECE2005:
2005 ASME International Mechanical Engineering Congress and Exposition
November 5-11, 2005, Orlando, Florida USA

IMECE2005-81198

HIGH FLOW RATE PER POWER PUMPING OF AQUEOUS SOLUTIONS AND ORGANIC SOLVENTS WITH ELECTROOSMOTIC PUMPS

Daejoong Kim **Jonathan D. Posner** **Juan G. Santiago**
Department of Mechanical Engineering
Stanford University, Stanford, CA 94305 USA

ABSTRACT

We present experimental investigations of porous glass electroosmotic pumping of various low conductivity solutions. We evaluate pump pressure, flow rate, and current for sodium borate buffer, deionized water, deuterium oxide, methanol, and acetone. We present data for several figures of merit associated with steady state pumping, and present selected transient data measurements.

INTRODUCTION

Electroosmotic (EO) pumps have the potential to impact a variety of applications including electronics cooling [1] and miniature drug delivery devices [2, 3]. EO pumps generate significant flow rate and pressure differentials in a compact structure with no moving parts. Key figures of merit for pump performance are pressure, flow rate, power, and thermodynamic efficiency. Another important parameter is flow rate per applied power. The latter is particularly important for applications with relatively low pump pressure demands or cases where there is little benefit to increasing working pressure past a minimum required level (e.g., as in drug delivery applications).

One way to improve EO pumps in terms of the flow rate per power is to use low conductivity working electrolytes such as organic solvents or deionized water. Organic solvents have been used as working electrolytes in various electrokinetic devices including capillary electrophoresis [4] and electrochromatography [5]. [6] and [7] reported electroosmotic mobility of pure methanol, acetone, acetonitrile, 2-butanone, N,N-dimethylformamide, N-methylformamide, Dimethyl sulfoxide, ethanol, formamide, ethyl acetate, tetrahydrofuran, 1-propanol, and morpholine. Several organic solvents exhibit electroosmotic mobilities and flow rate per power values comparable to and higher than water.

In this work, we investigated porous glass EO pumps with high flow rate per power using low ion density aqueous solutions and organic solvents. We also present selected results for the transient pump performance of these systems.

NOMENCLATURE

$Q_{\max}$	Maximum flow rate
$I_{\max}$	Maximum current
$\Delta p_{\max}$	Maximum pressure generation
V_{app}, V_{eff}	Applied voltage and effective voltage
ψ, τ	Porosity, tortuosity
A, L	Area and thickness
ε, μ, σ_0	Permittvity, viscosity, ionic conductivity
ζ	Zeta potential

MODEL FOR POROUS GLASS EO PUMP

Yao et al. [8, 9] presented an analytical model for EO pumps with porous pumping structures and validated the model with an experimental parametric study. In that model, flow rate and current are determined by key pump characteristics such as pumping structure porosity (ψ), tortuosity (τ), and macroscopic geometry (A, L).

A key set of parameters is determined by working electrolytes chemistry including permittivity (ε), viscosity (μ), ionic conductivity (σ_0)and surface zeta potential (ζ). Also important is the electric double layer (EDL) thickness relative to pore diameter. For low ion density working liquids and order one micron pores, finite EDLs can significantly impact and dominate flow rate, pressure, and flow rate performance.

$$Q_{\max} = -\frac{\psi}{\tau}\frac{\varepsilon}{\mu}\zeta A \frac{V_{eff}}{L} f . \qquad (1)$$

$$I_{\max} = \frac{\psi}{\tau}\sigma_0 A \frac{V_{eff}}{L}\frac{f}{g}. \qquad (2)$$

f and g are determined by the distribution of ions in the EDL [8]. These tend toward unity when the pore radius is much greater than the EDL thickness. Combining Eqs 1 and 2, we can derive the maximum flow rate per maximum current as,

$$\frac{Q_{\max}}{I_{\max}} = -\frac{\varepsilon}{\mu}\frac{\zeta}{\sigma_0} g \,. \qquad (3)$$

In order to improve EO pumps in terms of flow rate per power, this suggests that we should increase electroosmotic mobility, $\varepsilon\zeta/\mu$, and decrease ionic conductivity irrespective of macroscopic geometry of pumping structures.

PUMPING LIQUID CHEMISTRY AND EXPERIMENTAL SETUP

We investigated the effects of working liquid chemistry on flow rate per power. We evaluated the performance of porous glass EO pumps using the following working liquids: 1 mM sodium borate buffer, deionized (DI) water, heavy water (deuterium oxide), methanol, and acetone.

We measured ionic conductivity using the current monitoring method [10] in a 100 μm diameter round capillary. We estimated conductivity in this same setup from applied voltage and current measurements with a sourcemeter (Keithley 2410, Cleveland, OH). We measured EO mobility using neutral markers (Rhodamine B) in borofloat cross chips (Micralyne, Edmonton, AB, Canada). The latter channel material is a material similar (e.g., same glass composition) to the glass frits that we use (described below), although such measurements should be interpreted as an approximate predictor of performance in the glass frit systems. Table 1 summarizes our measurements of ionic conductivity and electroomotic mobility.

Table 1. Pumping liquid chemistry.

Solvents	Conductivity [S/m]	EO mobility [m^2/V/s] average	EO mobility [m^2/V/s] error	zeta potential [mV]
Buffer	7.73E-03	5.69E-08	1.48E-10	-73.1
DI water	2.00E-04	4.77E-08	1.73E-10	-61.2
Deuterium oxide	1.00E-03	4.48E-08	3.23E-09	-71.0
Methanol	8.90E-05	3.66E-08	6.29E-09	-68.9
Acetone	9.40E-06	4.62E-08	9.50E-10	-76.3

Fig. 1 shows the schematic of our EO pump. As methanol and acetone are strong solvents, we fabricated pump housings using Teflon and sealed these with ethylene propylene O-rings and a special adhesive (3M 2216, St. Paul, MN). The pumping structure was 4.8 mm thick porous borosilicate glass frits (ROBU ultrafine frit, Hattert, Germany) with a diameter of 4 cm.

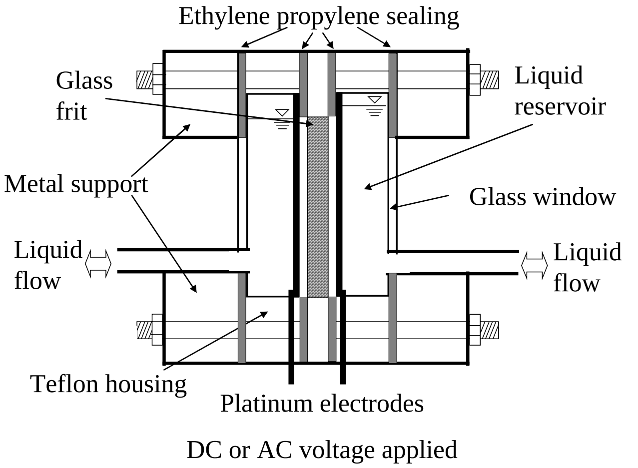

Fig. 1. Schematic of EO pump device. Pump housing is machined from Teflon to allow flexibility in working liquids and fitted with a glass window. AC voltages of 0.02 to 0.1 Hz are applied.

Fig. 2 shows the experimental setup. The very low frequency (0.02 to 0.1 Hz) voltage signals were generated with a data acquisition (DAQ) card (National Instruments PCI-6220, Austin, TX) and amplified with a voltage amplifier (Trek PZD350, Medina, NY). We measured flow rate by visually tracking the menisci of liquids in outlet Teflon tubes. The current was measured with the same DAQ card. Before each measurement, we rinsed the frit with electroosmotic flow with the solvent of interest. For the heavy water experiments, we connected the outlet tubes to a 250 cm^3 inert gas reservoir is to prevent solvent evaporation and, more importantly, to prevent absorption of atmospheric gases (deuterium oxide is very hydroscopic).

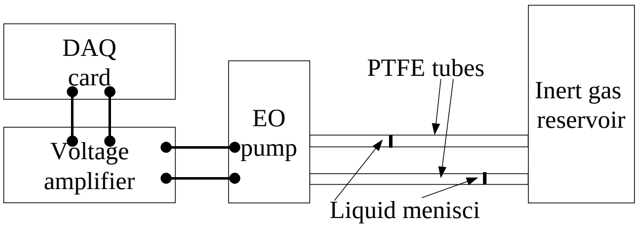

Fig. 2. Experimental setup for flow rate, and current measurement. Liquid is pumped using an AC field. In the case of heavy water measurements, outlet tubes were connected to a 250 cm^3 reservoir with a nitrogen gas cap.

RESULTS AND DISCUSSIONS

Measured flow rate and current are summarized in Fig. 3. Flow rate and current show a linear dependence on applied voltage as expected.

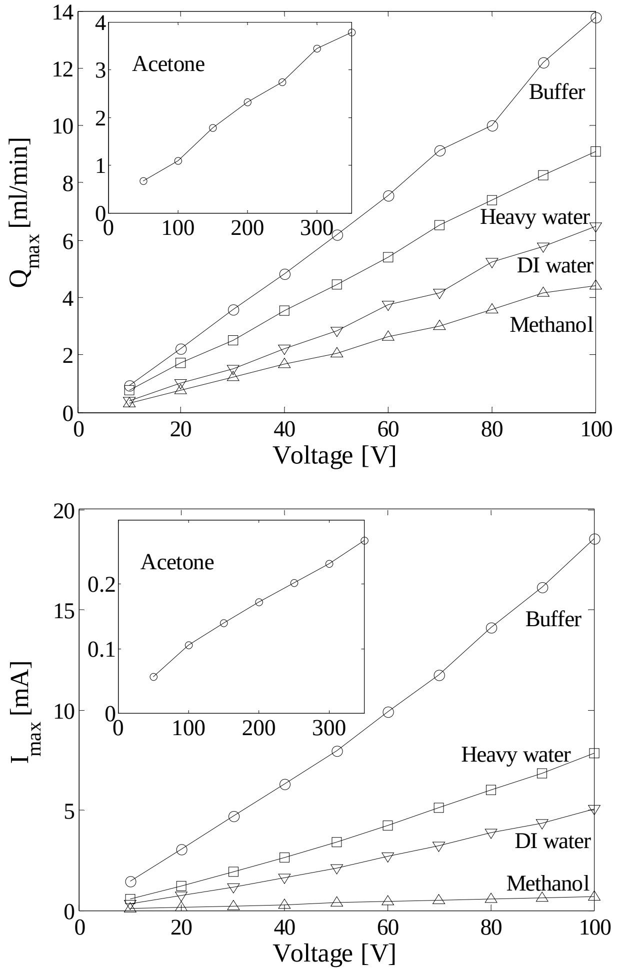

Fig. 3. Flow rate and current versus applied voltage for five working liquids. Insets show extended voltage range for acetone.

The slope of flow rate versus voltage for different solvents is roughly in the order of their electroosmotic mobility in the borosilicate chip systems measurements shown in Table 1. The one exception is the data for acetone. The relatively low effective mobility value for acetone is probably due to finite EDL effects lowering the parameter f . Acetone has very low (although measurable) ionic strength with an ionic conductivity two or three order lower than aqueous solvents. The acetone system's Debye length is therefore expected to be thicker, compared to the pore radius. We estimate a value of f = 0.03.

Flow rate normalized by current data are shown in Figure 4. Acetone shows the best performance with twelve times higher flow rate per current than the aqueous buffer. Although not shown here, we have also made maximum pressure measurements for each case. Typical pressure per applied voltage values are 7.6×10^{-3} atm/V, 3.7×10^{-3} atm/V, 1.7×10^{-3} atm/V, and 4.0×10^{-4} atm/V for buffer, DI water, methanol, and acetone systems, respectively. The resulting estimates for thermodynamic efficiency are 0.24%, 0.21%, 0.41%, and 0.22% for buffer, DI water, methanol, and acetone systems, respectively. These relatively low values (e.g., compared to 1.3% for DI water and 0.3% for buffer, maximum values reported by Zeng et al. [11] and Yao et al. [9], respectively) are due to the fact that *f* and *g* in these systems are relatively low. That is, although low conductivity can lead to significantly high values of *Q/I* and flow rate per power, low ion density also lead to relatively low values of hydraulic power output due to finite EDL effects.

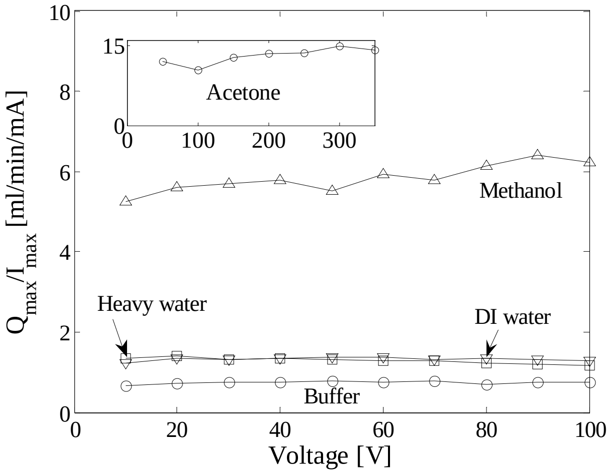

Fig. 4. Flow rate per current for four working liquids. Inset shows acetone results.

We found that pumps with low ion density working liquids also demonstrate strong current start-up transients. Figure 5 shows selected measurements of normalized current versus time for DI water, methanol, and acetone. Upon application of voltage, pump current quickly rises to a maximum value and gradually decreases to a steady state. Shown in the plot are the characteristic (first order) exponential relaxation time constants for each case. We are currently developing models for this behavior, including the effect of capacitive charge accumulation, Joule current, and Faradaic charge transfer.

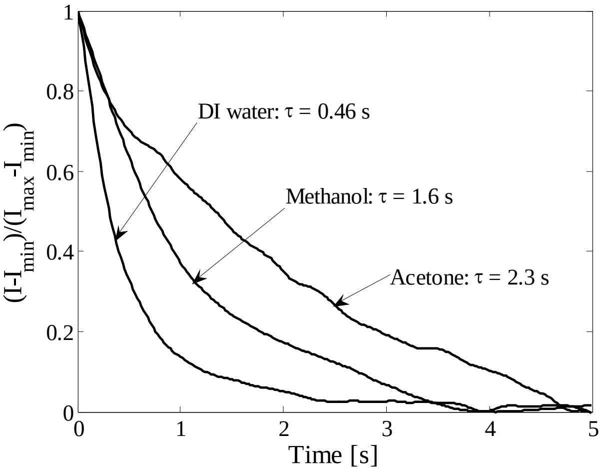

Fig. 5. Time evolution of normalized pump current with an applied voltage of 50 V for DI water, methanol, and acetone. The characteristic exponential relaxation time constants also are shown.

CONCLUSIONS

We are studying the use of low ionic conductivity working electrolytes to achieve high flow rate per power in porous glass electroosmotic pumps. Flow rate normalized by current (and flow rate per power) for acetone was twelve times higher than that of borate buffer. We found pumps with low ion density working electrolytes also show strong current transients.

REFERENCES

1. L. Jiang, J. C. Mikkelsen, J.-M. Koo, D. Huber, S. Yao, L. Zhang, P. Zhou, J. G. Maveety, R. Prasher, J. G. Santiago, T. W. Kenny, and K. E. Goodson, *IEEE Trans. Comp., Packag., Manufact. Technol.* **25**, 347 (2002).
2. V. Pretorius, B. J. Hopkins, and J. D. Schieke, *J. Chromatogr. A* **819**, 3 (1974).
3. F. Theeuwes, *J. Pharmaceutical Sci.* **64**, 1987 (1975).
4. M. L. Riekkola, *Electrophoresis* **23**, 3865 (2002).
5. M. Lammerhofer, *J. Chromatogr. A* **1068**, 31 (2005).
6. P. B. Wright, A. S. Lister, and J. G. Dorsey, *Analytical Chemistry* **69**, 3251 (1997).
7. I. E. Valko, H. Siren, and M. Riekkola, *J. Microcolumn Sep.* **11**, 199 (1999).
8. S. Yao and J. G. Santiago, *J. Colloid Interface Sci.* **268**, 133 (2003).
9. S. Yao and J. G. Santiago, *J. Colloid Interface Sci.* **268**, 143 (2003).
10. X. Huang, M. J. Gordon, and R. N. Zare, *Anal. Chem.* **60**, 1837 (1988).
11. S. Zeng, C.Chen, J. C. Mikkelson Jr., J. G. Santiago, *Sens. Actuat. B* **79**, 107 (2001).