HIGH EFFICIENCY ENERGY CONVERSION FROM LIQUID JET FLOW

Yanbo Xie, Lennart de Vreede, Trieu Nguyen, Hans L. de Boer, Ad Sprenkels, Albert van den Berg, Jan C.T. Eijkel

BIOS lab on chip group, MESA+ Institution of Nanotechnology, University of Twente

ABSTRACT

We investigate the performance of a microfluidic energy conversion system using jetting flow. Preliminary results indicate that a voltage can be generated of several kilo-Volts and energy efficiencies can reach 15%. Such values are by far the highest obtained for electrokinetic conversion systems and open new perspectives for energy conversion.

KEYWORDS

liquid jet, energy conversion; streaming potential.

INTRODUCTION

The energy crisis is one of the most pressing topics due to the rapid increase of electrical power consumption and projected decreasing availability of traditional sources of energy such as fossil and fuels. Novel sources of electrical energy, such as fuel cells and solar cells are therefore developed to replace the traditional sources of energy. Such new energy sources should preferably cause less harm to our environment than traditional ones, for example by not producing carbon dioxide or toxic chemicals. A relative little know method of energy conversion is electrokinetic conversion of fluidic mechanical energy to electrical energy.[1]

Electrokinetic energy conversion relies on the transport of the layer with net charges that is present close to most solid/liquid interfaces. When this charged layer is transported in a channel, an ionic current is generated (streaming current) as well as a potential difference between the channel ends (streaming potential).[2] In the past ten years, many investigators have tried to enhance electrokinetic energy conversion efficiency using micro- or nanochannels. The highest experimental efficiencies reached were about 5%[3-5] when nanopores were used in which double layers of opposing walls partially overlapped. Theoretical predictions using numerous assumptions predicted maximal efficiencies in such systems of 40%. [6]

Recently, Duffin and Saykally reported on the use of a microjet for energy conversion. [7] Under high pressure water was forced through a membrane orifice, forming a jet which broke up into droplets. The droplets were charged due to the electrokinetic phenomenon described above, and the charged droplets were collected by a downstream electrode. These authors found an energy conversion efficiency of around 10% in this two phase system.

In their analysis, Duffin and Saykally attribute the enhancement of efficiency in their two-phase system with respect to the values in traditional single phase systems to the occurrence of low resistance fluidic entrance flow in the pore due to its short length and high pressure applied, as well as to electrical isolation offered by the air which prevented back flow of current. In this paper, we however show that the energy conversion mechanism of this jetting flow is radically different from the traditional electrokinetic energy conversion mechanism. We show it relies on a direct conversion of the kinetic droplet energy conversion potential energy. This knowledge of the conversion mechanism allowed us to minimize the loss factors and obtain a conversion efficiency of 15%.

Setup

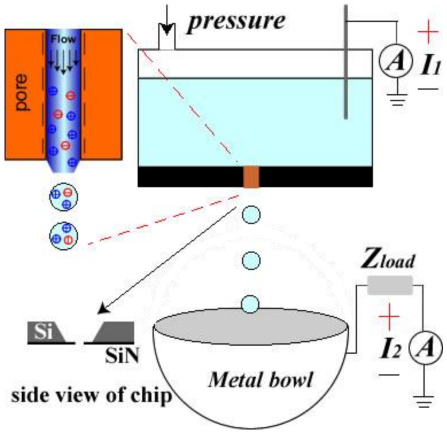

Figure 1: A liquid jet produced by pressure applied across a Si_3N_4 membrane pore breaks into (charged) droplets which are collected in a stainless steel bowl. Streaming current I_1 flows through the pore and current I_2 flows through

978-0-9798064-5-2/µTAS 2012/$20©12CBMS-0001

large electrical resistors. Both are measured by a pico-ammeter.

Figure 1 shows the scheme of our experimental setup. A silicon nitride membrane was machined with a thickness of 650nm containing a single pore with a diameter of 10 μm. The chip was mounted with a pressurized reservoir and liquid was expelled through the pore using a gas source (99% N_2) controlled with a high accuracy gas pressure pump (Fluigent MFCS). The liquid jet produced from the pore broke into droplets, which were received by a stainless steel bowl. Droplets were charged due to the streaming current generated in the pore. Two pico-ammeters were used to measure the generated upstream streaming current (I_1) as well as the current (I_2) flowing from the bowl to ground. Series connected resistors (4 × 500GOhm; 4 × 400GOhm and 2 × 100GOhm resistors with voltage ratings 1KV) were used to generate the electrical output power, which was calculated by multiplying I_2 with the generated voltage $V=I_2 \times Rload$.

Loss factors

Several factors can be identified in this process, which can be split in two stages. Firstly during the pore passage the input energy is incompletely converted to kinetic energy due to the friction with the pore wall. We can define the efficiency for this conversion as a power ratio:

$$eff_1 = P_{kin}/P_{in} = \left(P_{in} - P_{pore\ fric}\right)/P_{in} \tag{1}$$

where P_{kin} and P_{in} (J/s) are droplet kinetic power and hydrodynamic input power, respectively. Here and $p_{pore\ fric}$ is the power dissipation by pore friction. Subsequently, during the passage of the droplets through the air, the kinetic energy is in completely converted to electrical energy due to air friction and by charge evaporating from droplets. We can define efficiency for this second conversion as:

$$eff_2 = P_{el}/P_{kin} = \left(P_{kin} - P_{air\ fric} - P_{evap}\right)/P_{kin} \tag{2}$$

where P_{el} is electrical output power; p_{air} is the power dissipation by friction with air and P_{evap} is the power loss due to charge evaporating from the droplet. The final energy conversion efficiency then can be calculated from multiplying the efficiencies of both separate processes: $eff = eff_1 \cdot eff_2$.

Experimental results

Charged droplets were collected by the bowl. They generated electrical current from the downstream reservoir through the large resistors to ground, creating a voltage, which produced an electrical field. Since the polarity of voltage and droplets are the same, droplets needed to overcome this electrical field to reach the bowl, while being subject to other energy dissipation processes, such as air friction and evaporation.

The dissipation by air friction will decrease the velocity of droplets. Hence, to reach the bowl the kinetic energy of droplets has to be larger than the sum of electrical energy and air friction energy dissipation. The latter can be estimated from drag force: $F_D = 0.5 \cdot \rho u^2 C_D A$, where ρ is mass density of fluid, C_D is drag coefficient; A and u are reference area and velocity of droplet. Since $P_{air\ fric}$ equals $\int F_D dx$, the droplets trajectory length (h), is directly related to the air friction power dissipation, making it quite more important.

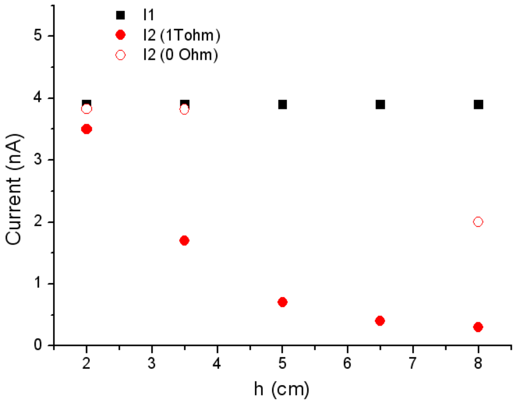

Figure 2. Current I_1(black) and I_2(red) as function of droplets trajectory distance h. I_2 decreases quickly as h increases, when a 1 Tohm resistance is connected. This decrease is much smaller without a resistance connected.

Figure 2 shows an experiment where we obtained the current (1.9bar applied pressure) as a function of distance h. Current I_1 is generated at the top reservoir and independent of the distance h, but I_2 (both with and without a 1TOhm resistance connected) decreases with increasing distance h. I_2 however decreases much faster when 1 TOhm resistance was connected. This is probably due to the increase in the droplets trajectory time spent in the electrical field generated in the bottom circuit: the voltage generated on the bowl will decelerate the droplets, causing the charge and droplets to evaporate more.

To prevent the charge loss in air, in another experiment we kept the trajectory length h around 3cm and studied the influence of the resistance. Upstream (I_1) and downstream (I_2) current are shown in figure 3a as a function of load resistance (R_{load}). Both I_1 and I_2 decreased slightly with increasing load resistance. The upstream current was always larger than the downstream current, which can be explained by droplet loss in the air.

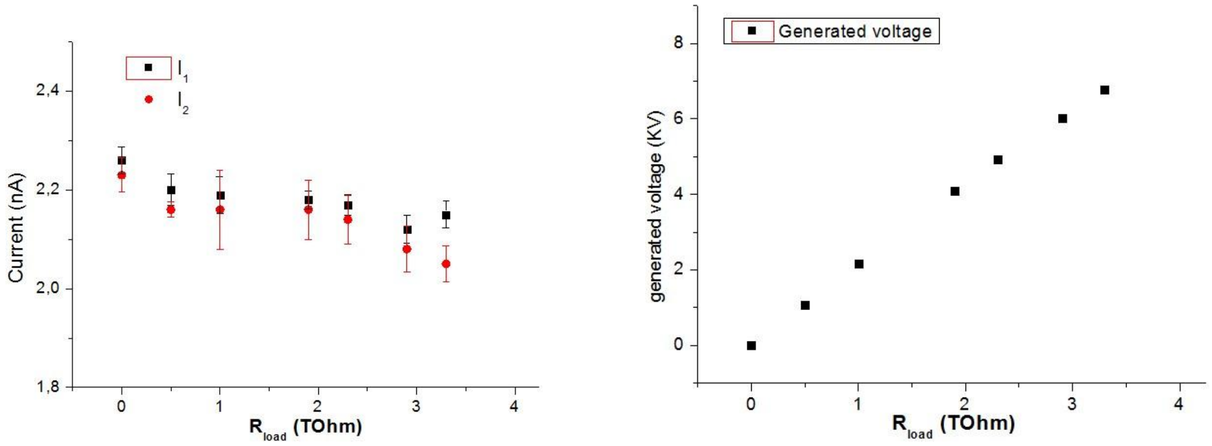

Figure 3a: Upstream (I_1) and downstream (I_2) current decreased only slightly with increasing load resistance. b. The generated voltage calculated by multiplying I_2 and load resistance, could reach 6.77KV.

The generated voltage between bowl and membrane can be calculated by $I_2 \cdot R_{load}$, and is shown in figure 3b. It increases almost linearly with resistance (maximum 6.77KV). The output power can now be estimated as $P_{out} = I_2 \cdot V$.

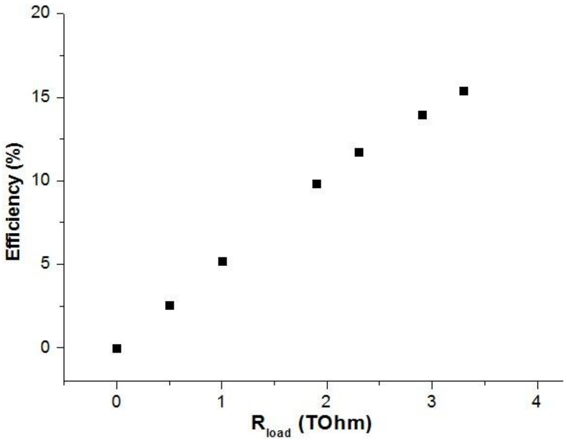

Figure 4: Energy conversion efficiency increased with load resistance, reaching 15% at a resistor value of 3.3 T.

The input power was estimated by multiplying the constant input pressure (ΔP_{in}:1.1bar) with the flow rate (Q:0.90µL/s): $P_{in} = \Delta P \times Q$. Finally, the efficiency obtained ($eff = P_{out}/P_{in}$) is shown in Figure 4. The efficiency increased with load resistance, reaching a maximum of 15%. At present experiments are performed to confirm and improve these preliminary results. The value of 15% represents the highest value obtained at present in electrokinetic energy conversion experiments.

REFERENCES:

[1] Pennathur S., Eijkel J. C. T., Albert van den Berg, Lab Chip, 7, 1234-1237 (2007)
[2] Osterle, J.F., J. Appl. Mech. 31, 161 (1964).
[3] Yang, J., F.Z. Lu, L.W. Kostiuk, and D.Y. Kwok, J. Micromech. Microeng. 13 (6), 963-970 (2003).
[4] van der Heyden, F.H.J., D.J. Bonthuis, D. Stein, C. Meyer, and C. Dekker, Nano Letters 7 (4), 1022-1025 (2007).
[5] Xie, Y.B., X.W. Wang, J.M. Xue, K. Jin, L. Chen, and Y.G. Wang, Appl. Phys.Lett. 93 (16), 163116 (2008).
[6] Y.Ren., D. Stein., Nanotechnology. 19, 195707 (2008).
[7] Duffin, A.M. and R.J. Saykally, J. Phys. Chem. C 112 (43), 17018-17022 (2008).

CONTACT

Yanbo Xie y.xie@utwente.nl
Jan Eijkel J.C.T.Eijkel@utwente.nl