OPTIMIZING LIQUID WATER JET ON ENERGY CONVERSION PERFORMANCE

Yanbo Xie, Lennart J. de Vreede, Albert van den Berg and Jan. C. T. Eijkel
Bios group, MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands
*Presenting Author: Y.Xie@utwente.nl

Abstract: Charged surface in liquid will attract counterions near the surface. Motion of liquid will drive these mobile counter ions, which represents the electrical current. This provide us a method to convert mechanical energy to electrical energy. Duffin and Saykally showed that high energy conversion efficiency could be obtained by liquid jet. In this paper, we discuss this phenomenon and study the energy conversion performance as function of height. In our experiment, we found the maximum outpur power could be obtained, when downstream reservoir receiving the break droplets of liquid jet. A quantitative explanation was given on the streaming current generation as function of height.

Keywords: Energy Conversion, Liquid jet, Streaming Current

INTRODUCTION

Electro-kinetic phenomena, such as streaming current, convert electrical energy into mechanical energy.[2] In this paper we consider to use the streaming potentials to convert mechanical energy into electrical energy. Most solid surfaces in contact with an aqueous solution become electrically charged, due to the dissociation of charged groups on the surface. Any charged surface in liquid attracts mobile counter-ions near its surface to form an Electrical Double Layer (EDL). If we apply an external pressure difference between the ends of a liquid-filled channel, the mobile ions move within the flowing liquid, thereby creating an electrical current. By placing electrodes at the two ends of the channel, we can capture the electrical energy. As a result, mechanical energy can be converted into electrical energy in a straightforward and effective manner.

In the past, investigators have studied the performance of such fluidic energy conversion systems using single phase (water) flow.[3] Yang et al. [4] noted that the streaming current in fluidic channels could be a simple and effective energy conversion system, but in the examples they considered the energy conversion efficiency was less than 0.05%. Subsequently many researchers have tried to enhance the energy conversion efficiency by using nano-channels with EDL overlap, and efficiency has reached about 3 to 5% in single nano-channels[5] and nanopores[6] respectively. Recently, Duffin and Saykally [7,8] used microjets to enhance the energy conversion efficiency to above 10%. Because of the liquid water jet will break up into small droplets by Rayleigh plateau instability in air, which is almost zero conductivity, the conduction current could be eliminated. Hence, output power will be greatly increased. In our experiment, we found that the size and distribution of the jet or droplets will be a key factor that limit the maximum efficiency. From our preliminary experiment results, we could find the optimal conditions for energy conversion.

Figure 1 shows the scheme of our experimental setup. Well cut fused silica tubing (INDEX upchurch) with a length of 1.7cm and an internal diameter of 100 μm was connected to a pressurized reservoir. A Gas source (99% N_2) was used to drive liquid and the pressures was controlled using a high accuracy gas pressure pump (Fluigent MFCS). A liquid water jet was generated through the short tubing, breaking up into droplets by the Rayleigh Plateau instability when above a certain critical length. There are two pico-ammeters (Keithley 6487) connected with Ag/AgCl electrodes, which inserted in the liquid reservoirs, to measure the conversion current. Ammeter 1 is connected with the pressurized reservoir to measure the current generated without any load resistors, which can be considered the upstream current I_{S1}. Ammeter 2 (measuring I_{S2}) is inserted in the receiving reservoir, placed in series with large load resistors to calculate the output power by multiplying the I_{S2} and the value of resistance. A 0.1mM KCl solution (bulk conductivity 15±5 S/cm) was prepared from diluted 1M KCl and the pH adjusted to 8.5. Figure 1 show that with the different distance between tubing exit and downstream reservoir, we could receive the liquid as break droplets from liquid jet instability (a) and straight liquid jet (b). To compare the energy harvest in traditional method, we also measure the streaming current in single phase flow (c).

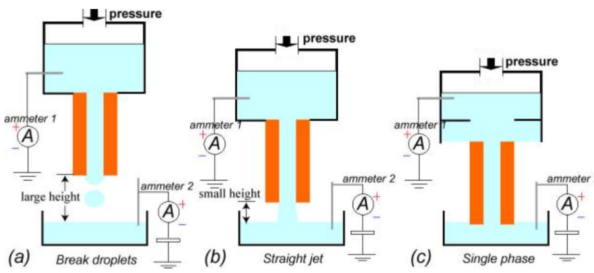
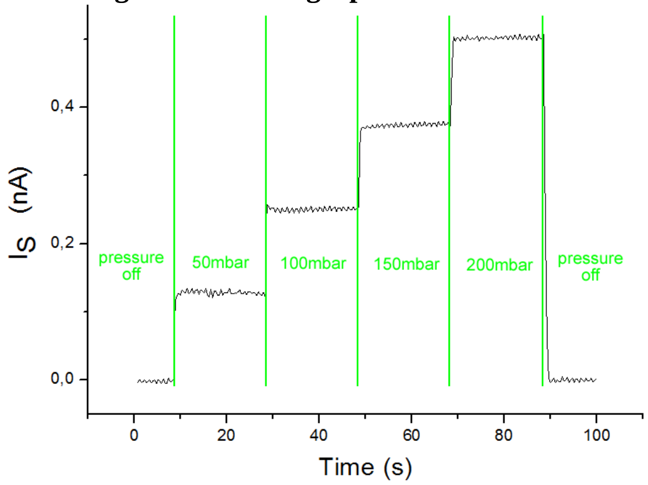


Figure 1 The pressurized reservior (top) push liquid out of the short tubing. (a) Liquid stream break into charged droplets and falling to the bottom reservior with large height between exit og tubing and downstream reservoir. (b) While in short height, straight liquid jet will shoot into the

downstream reservoir. Two pico ammeters measure the generated current (I_{S1}) and current received (I_{S2}).

EXPERIMENTAL RESULTS

Streaming current in single phase flow



Fugure 2 shows the streaming current generated in single phase flow. Streaming current increases linearly with gas pressure, which varies from 50mbar to 200mbar (green letters).

First, we measure the streaming current in single phase flow, which means the exit of tubing immersed inside the downstream reservior and contact with solution (figure 1c). In this case, the upstream current I_{S1} equals to downstream current I_{S2}. The results shown in figure 2 been pressured step by step from 50mbar to 200mbar. This result indicate the linear relation between applied pressure and generated convection streaming current. So, we could extract the streaming conductance (streaming current per unit bar) of our system from this figure 1, which was 2.5 nA/bar. This value fits the theoretical value very well by equation (assuming zeta potential is -60mV):

$$I_S = -\varepsilon\varepsilon_0 \zeta r^2 \Delta P / \eta L \qquad (1)$$

where η, r, L are viscosity of fluid, radii and length of channel, respectively. ε_0 is the permittivity of free space, ε the relative permittivity of the fluid and ζ the electrical (zeta) potential at the shear plane of the channel walls; pressure difference ΔP is linear function with streaming current in single phase flow.

Instability of the current

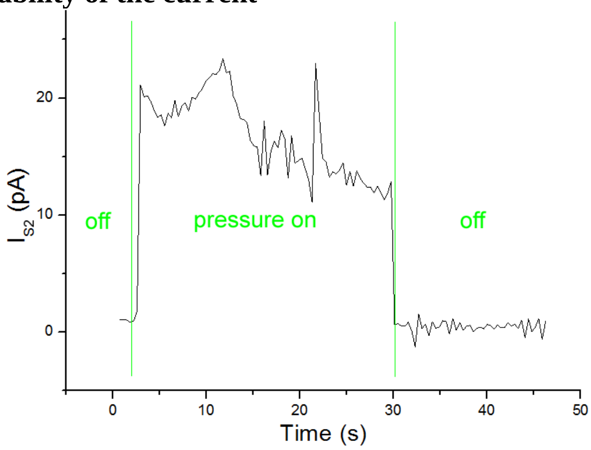


Figure 3. shows the instability of the current I_{S1}.

Then, we start to move the tubing out of downstream reservoir (figure 1b without any resistance connected) with short distance (height = 0.3 cm). I_{S2} as a function of time was shown in figure 3. When the pressure applied, current generated immediately. However, the streaming current was not stable while the pressure keeps 1 bar constantly. The magnitude of streaming current is a complicated function of time. This instability probably due to the liquid fluctuation at the exit of tubing which will be discussed in next paragraph. The data shown below in this paper are average values of the current. As gas pressure been turned off, the streaming current decreases immediately.

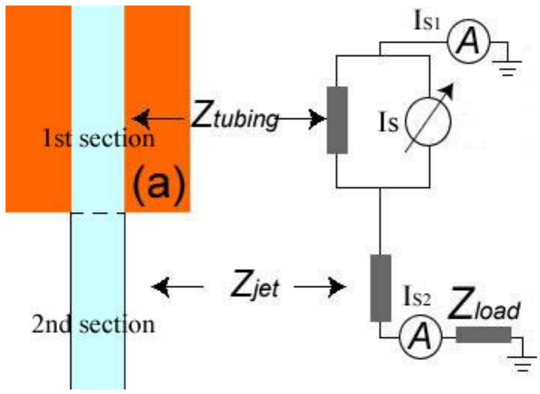


Figure 4. a shows the schematic piture of liquid jet. The electrical equavalent circuit was shown in b.

Schematic picture of liquid jet in short distance was shown in figure 4a. We define the liquid jet into two sections: first section is the liquid inside tubing; second section is the liquid outside of tubing. Electrical equivalent of circuit was shown in figure 4b. Since the streaming current only generated within surface charged area (inside tubing in our case), first section could be considered as a constant current source parallel connected with internal resistance (Z_{tubing}). The second section is liquid stream exposed in the air. There is no streaming current generated between the liquid and air interface. But since the shape of section 2 is still like a tube, it also contribute to the total internal resistance of the system (Z_{jet}).

According to Kirchhoff Laws the streaming current of system could be expressed as:

$$I_{S2} = \frac{I_{S1} Z_{load}}{Z_{tubing} + Z_{jet} + Z_{load}} \qquad (2)$$

By equation (2), even assuming the streaming current generation keeps constant, any change of resistance in the system will make I_{S2} changes accordingly. It is possible that the fluctuation of the liquid jet make Z_{jet} changes very quick with time. Then fluctuation of Z_{jet} makes I_{S2} (figure 3) instable.

Current as function of height

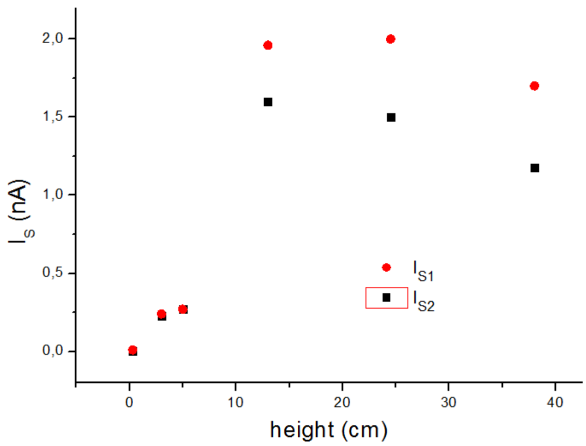


Figure 5. The streaming current I_{S1} (black) measured in ammeter 1 is a little higher than the current I_{S2} (red) flow through large resistor (100Gohm). The energy conversion efficiency could reach 0.1%. With larger resistors, the current could even obtained higher.

As we know, water will break into droplets according to Rayleigh plateau instability. By adjusting the height between tubing exit and downstream reservoir, we could obtain different liquid jet mode: break droplets (figure 1a) and straight liquid stream (figure 1b). We study the energy conversion performance as a function of height, which were shown in figure 5. 1bar was applied on the upstream reservoir and 100 Gohm was connected in the downstream electrical circuit to obtain the output power. As can been seen, when height is quite short, both IS1 and IS2 are very small. One possible reason is that in straight liquid stream mode, the liquid stream directly connect to the downstream as shown in figure1b. This connection create a straight way for conduction current. When huge load resistance connected at downstream, the liquid stream in section 2 will create conduction current, which flow against the streaming current. This conduction current will balance most of the streaming current then make streaming current of system almost zero. Another possible reason is that current flow through huge resistance will generate voltage and this generated voltage will create static electrical field toward liquid jet. From knowledge of electrostatics, the electrical field is function of reciprocal of height. Hence, long distance will decrease the influence of generated voltage.

However, if we raise the height, larger streaming current could be obtained. This is possibly due to the liquid jet break into small droplets, then there will be no way for charges to move back. This means by block of air, the charges in droplets cannot form the conduction current. According to equation (2), we could obtain the more current in load resistance. This streaming current are quite close to the streaming conductance in single phase flow, which also means not much electrical energy loss during the energy conversion process. But long distance will make more chances to loss the droplets in the air. This is the reason the difference between IS1 and IS2 become larger when height is over 30cm. It is need to be noted that IS1 (red points) is always larger than IS2 (black points). This also probably because of the droplets missing in the air.

Current as function of load resistance

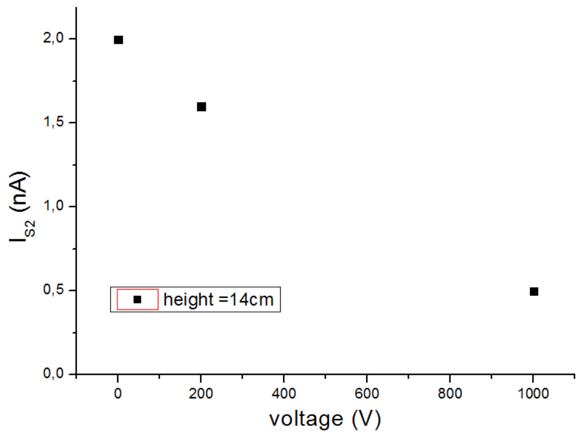


Figure 6. shows the IS2 perform as a function of load resistance.

Then we fix the height at 14cm, study the influence of load resistance. We can obtain the maximum current without any load resistance connected. When the generated voltage increases, higher electrical field will decrease the current in system. As can be seen, when generated voltage comes to 1KV, IS2 will be one quarter of it without load resistance. Assuming this decreasing trend of IS2 is linear, we could obtain the maximum output power approximately 0.6 μW. With measurement of flowrate (Q = 3.6mL/min), we could calculate the input power by $\Delta P \times Q$. Then we could estimate the efficiency (*eff*) by *eff* = P_{out} / P_{in}. The maximum efficiency we could obtain is around 0.1% from the short tubing.

DISCUSSION

We contribute the decrease of IS1 and IS2 in quite short height to the Rayleigh plateau instability. But this liquid stream still cannot explain the decrease quantity of streaming current. This is need to be further studied. Other factors such as wettability of tubing; droplets possibly influence between each other; repel from the downstream vessel by generated voltage and so on.

CONCLUSION

In this paper, we study the energy conversion efficiency in three different mode: single phase flow; straight liquid jet and break droplets. We give a quantitative explanation on current instability by equivalent electrical circuit analysis. Then current as function of height was studied. Current IS2 with long distance (height) is much larger than it with short distance. This possibly related with generated electrical field. Then we find the current will decrease with generated voltage increase.

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] Olthuis W., Schippers B., Eijkel J. C. T., Albert van den Berg, Sensors and Actuators B: Chemical 111-112, 385-389 (2005)

[4] Yang, J., F.Z. Lu, L.W. Kostiuk, and D.Y. Kwok, J. Micromech. Microeng. 13 (6), 963-970 (2003).

[5] van der Heyden, F.H.J., D.J. Bonthuis, D. Stein, C. Meyer, and C. Dekker, Nano Letters 7 (4), 1022-1025 (2007).

[6] Xie, Y.B., X.W. Wang, J.M. Xue, K. Jin, L. Chen, and Y.G. Wang, Appl. Phys.Lett. 93 (16), 163116 (2008).

[7] Duffin, A.M. and R.J. Saykally, J. Phys. Chem. C 112 (43), 17018-17022 (2008).

[8] Duffin, A.M. and R.J. Saykally, J. Phys. Chem. C 111 (32), 12031-12037 (2007).