# GATE CONTROLLED HIGH EFFICIENCY BALLISTIC ENERGY CONVERSION SYSTEM

**Yanbo Xie, Diederik Bos, Hans de Boer, Albert van den Berg and Jan C.T. Eijkel**
*BIOS/Lab on a chip group, MESA+ Institute for Nanotechnology, University of Twente, The Netherlands*

## ABSTRACT

Last year we demonstrated the microjet ballistic energy conversion system[1]. Here we show that the efficiency of such a system can be further improved by gate control. With gate control the electrical current generation is enhanced a hundred times with respect to the current generated from the zeta potential. A maximum efficiency of 48% is obtained using a 30µm pore. Energy was still lost on viscous flow, surface production and air friction. The higher droplet charge density using gate control can also be used to decreases the required target voltage. Thus a 12% efficiency was achieved with 500V target voltage using a 10µm pore and voltage gating.

**KEYWORDS:** Energy conversion, liquid jet, high efficiency, electrokinetics

## INTRODUCTION

With the rapid growth of the economy and population in the past decades, the electrical energy consumption increases rapidly.[2] To meet the demands of energy consumption, new energy sources are under research and development, and this has become one of the most important research topics. In particular, novel environmentally-friendly energy conversion systems are required. To increase the energy harvesting efficiency thereby is one of the most important goals.[3] Electrokinetic phenomena, such as streaming current, can be used to convert the kinetic energy of liquids into electrical energy, as first proposed by Osterle.[4] Highest efficiencies of conventional systems (around 5%) were obtained using nanochannels with overlapping electrical double layers (EDL).[5, 6] Subsequently for a micro liquid jet Duffin and Saykally showed that the efficiency can be over 10%.[7]

Our experiments and analysis showed that the efficiency of microjet systems can be further improved, and that the mechanism is radically different from the traditional energy conversion from streaming potential.[1] The conversion proceeds as follows. Pressure forces liquid though an orifice forming a jet. Due to the Rayleigh-Plateau instability, the liquid jet breaks up into droplets, containing net charges from the EDL. The droplets deliver the charges to a bottom target, which is connected to ground with a high value resistor, generating a high electrical potential. Thus, the charged droplets move against the electrical field generated, converting kinetic energy to electrical energy when landing on target. This is a simple and straightforward method to convert mechanical energy to electrical energy ('ballistic' energy conversion).

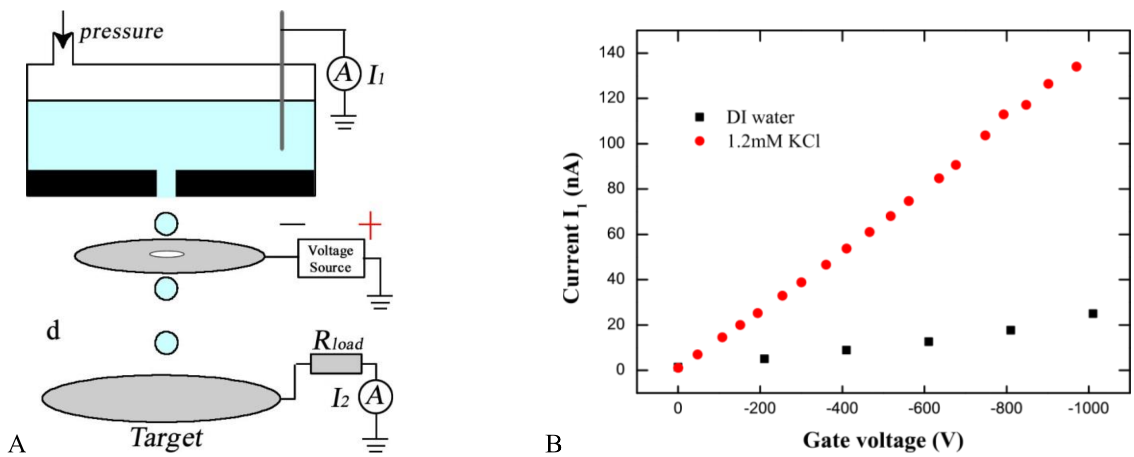


*Figure 1. A. Schematic of the gate controlled setup. Charges are electrostatically introduced in the droplets by a gate metal ring connected to a voltage source. B. The upstream current $I_1$ linearly increases with gate voltage (no load resistor connected). Higher currents are obtained with a salt solution than with demineralized water. Pore diameter 10 µm, pressure 2.2 bar.*

## SETUP

Figure 1a shows the schematic picture of the setup. A silicon-enriched silicon nitride membrane (less than 1µm thick) machined with a single micropore was mounted in a chip holder. Pressure drives aqueous solution through this pore forming a liquid jet in air. A hollow metal ring was placed under the position of jet breakup with a DC voltage source (Keithley 2410), electrostatically inducing charges in droplets. A metal target collects these charged droplets and the current flows via resistors (GOhm to TOhm) to ground. Pico-ammeters were connected to reservoir electrode and target for current measurements upstream ($I_1$) and downstream ($I_2$), respectively. Hence, electrical power will be produced and is calculated from measurements. We performed experiments using larger pores than previously reported (30µm instead of 10µm[1]), due to theoretically expected lower frictional energy losses in larger pores, creating larger droplets. The charge induction using the electrostatic gate compensates for the lower droplet charging due to the streaming potential when larger pores are used due to the lower surface-to-bulk ratio, and thus decreases the required target voltage to produce the same output power: $P_{out} = dq/dt \cdot V$, where dq and V are droplet charge and target voltage respectively. In addition, the decreased target voltage will reduce electrical energy losses by corona discharge and electrospray. The experimental efficiency will be determined by $P_{out}/(\Delta P \cdot Q)$, where ΔP is applied pressure, Q is flow rate and $P_{out} = V \cdot I_2$. The target was connected to ground via an 1 TOhm resistor. This setup is quite comparable with an electrospray setup.[8, 9] It must be remarked that no current passes through this gate ring (unless droplets are deflected to the gate), so that there will be no electrical energy dissipated by a gate ring current. The energy conversion efficiency is as normal defined as the ratio of electrical output power to mechanical input power.

## RESULTS AND DISCUSSION

Figure 1B shows that the upstream current $I_1$ increases linearly with gate voltage when 2.2 bar pressure was applied over a 10µm diameter pore. Two different solutions (DI water and 1.2mM KCl) were used in the measurements. Here, we define the induction rate $C_{ind}$ as the induced current per applied gate voltage $C_{ind} = I/U_g$, which is the slope of the data points obtained by a linear fit. A high solution conductivity helps to increase the induction rate. Assuming droplets of homogeneous size are generated with a volume flow rate of 1.1µL/s, the maximum droplet charge density $\rho_e$ is calculated as current divided by observed volume flow rate (I/Q) of droplets and is 123C/m$^3$. This is close to the Rayleigh limit of 153C/m$^3$ in 10µm diameter droplets. The Rayleigh limit describes the maximum quantity of charge in a droplet $q^2 = 64\pi^2\varepsilon\gamma R_{dr}^3$, where q, ε, γ are the quantity of charge, vacuum permittivity and surface tension. [10, 11] Higher droplet charge quantities create droplet instability or explosion by the Coulomb force.[12] Our working current shown below is generally much lower than this limit, so the effects of a high charge density on droplets will not further be discussed.

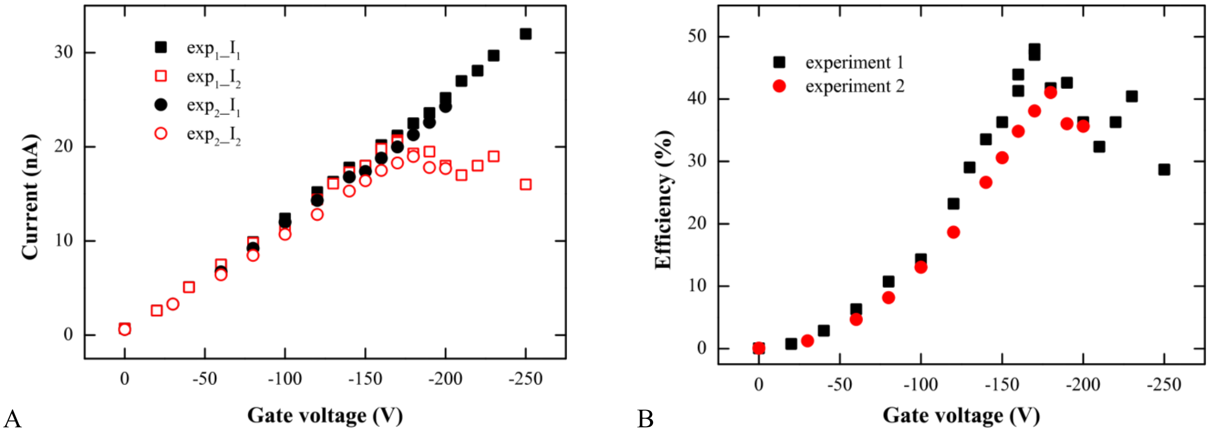


*Figure 2 A. Both the variation of upstream current $I_1$ and downstream current $I_2$ as a function of gate voltage. B The efficiency as function of gate voltage. A 10mM KCl solution was used in these experiments and a 30 µm diameter pore.*

Figure 2A shows two typical measurements using a 30µm pore with addition of KCl (10mM) in the aqueous solution. A 1.01TOhm resistor was connected in the downstream circuit. The negative gate voltage was tuned from 0V to -250V to increase upstream current $I_1$. Downstream current $I_2$ increases with $I_1$ at increasing gate voltages and then starts to decrease around a target voltage of 20kV. The deflection of droplets and electrojetting were then observed from target to gate ring. This voltage value is also about the limit of our system given the target shape and corona discharge commences between target and gate ring according to Peek's equation $U_c = m_v g_v r \ln(d/r)$, which describes the voltage breakdown limit between two targets, where $U_C$, $m_v$, $g_v$, d and r are the corona inception voltage, irregularity factor of surface smoothness, "visual critical" electric field, distance between target and gate ring, respectively.[13] The limit of target voltage in our system is about 24kV (d=3cm and r=1.4mm). With measurements of pressure (1.38bar) and flow rates (6.65µL/s), the calculated efficiencies of these two experiments are shown in figure 2b. The maximum efficiency is 48%, which is still lower than our theoretical prediction (63%) possibly because the required target voltage is higher than the actual limit of our target collector.

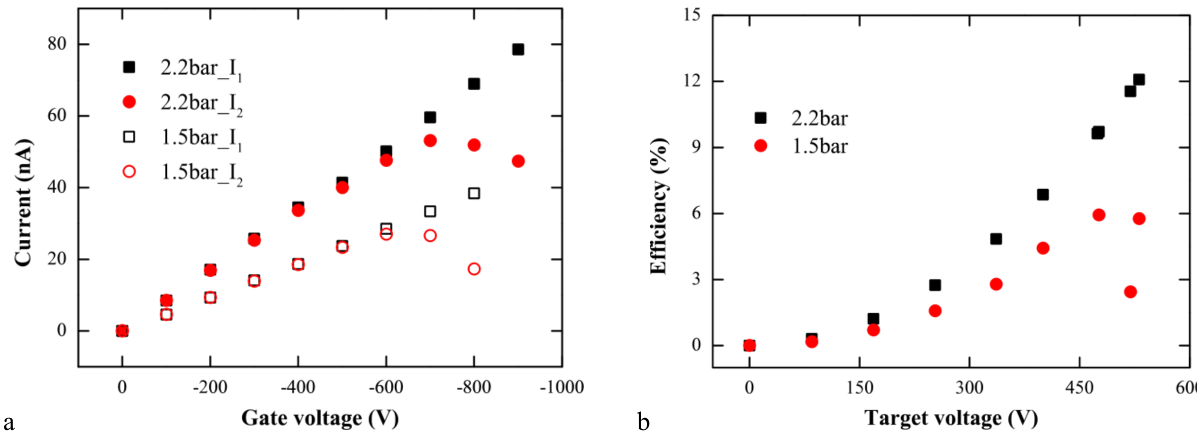


*Figure 3. a. Upstream ($I_1$) and downstream ($I_2$) currents as function of gate voltage. b. The efficiency as function of generated target voltage.*

Besides energy conversion efficiency, the target voltage is also quite important for application. By increasing the charge density of droplets, the target voltage can be decreased to the range of daily used voltages. Now a 10 Gohm resistance was used for energy conversion and a 2.2bar applied pressure drives 0.1M KCl solution out of a 10µm pore with volume flow rate of 1.06µL/s. The current variation and hence droplet charge density as a function of gate voltage is shown in figure 3a and the energy conversion efficiency in figure 3b. It is seen that the downstream current $I_2$ initially increases with $I_1$, and then decreases due to droplet reflection. The maximum efficiency obtained is 12% with 500V target voltage. Such relatively low efficiencies are partly due to the fact that part of the kinetic energy is consumed to overcome the potential from the gate (-700V). Another reason for this low efficiency is that the highly charged droplets repelled each other during travelling. Under some circumstances, a droplets-cone was formed when the droplets came out through the induction ring. As a result, the droplets didn't form a straight air wake and lost more kinetic energy against air friction. Besides, the flat target surface creates different transport distances for the droplets at the inside and outside of the cone. The droplets that need to travel a longer distance will be more easily deflected by the target voltage, thus the inhomogeneous distance will cause a smaller energy conversion efficiency. Further development on target electrode design can help to increase the efficiency at such low target voltage, which is in the range of daily use.

## CONCLUSION

In this paper, we improved the microjet ballistic energy conversion system by electrostatic gate control, increasing the current generation. It was found that the droplet charge density increases linearly with applied voltage. Using this approach nearly 50% conversion efficiency was obtained from 30µm pore. A higher charge density in droplets can also be used to decreases the required target voltage for maximal energy conversion efficiency. Thus a 12% efficiency was achieved with 500V target voltage using a 10µm pore and voltage gating.

## ACKNOWLEDGEMENTS

We gratefully acknowledge financial support of a NOW TOP grant (YX, AvdB, JE). Ad Sprenkels is thanked for electrical measurements assistance and Johan Bomer for cleanroom assistance.

## REFERENCES


[1]. Y.B. Xie et al. MicroTAS 2012, Chemical and Biological Microsystems Society: Okinawa. p. 198-200. 2012
[2]. P.B. Weisz, Physics Today. 57(7): p. 47-52. 2004
[3]. S. Pennathur et al., Lab Chip. 7(10): p. 1234-1237. 2007
[4]. J.F. Osterle, J. Appl. Mech. 31: p. 161. 1964
[5]. Y.B Xie et al. Appl. Phy. Lett. 93(16): 163116. 2008
[6]. F.H.J. van der Heyden et al. Nano Lett. 7(4): p. 1022-1025. 2007
[7]. A.M. Duffin, and R.J. Saykally, J. Phys. Chem. C. 112(43): p. 17018-17022. 2008
[8]. G.J. Van Berkel, and F.M. Zhou, Anal. Chem. 67(17): p. 2916-2923. 1995
[9]. S.G. Taylor, Proc. Royal Soc. London A: Mathematical, Physical & Engineering Sciences. 291: p. 145-158. 1964
[10]. L. Rayleigh, Phil. Mag. 14: p. 184–186. 1882
[11]. A. Gomez, and K.Q. Tang, Phys. Fluids. 6(1): p. 404-414. 1994
[12]. D. Duft et al. Nature, 421(6919): p. 128-128. 2003
[13]. F.W. Peek, Dielectric Phenomena in High Voltage Engineering: McGraw-Hill. p. 57. 1929


## CONTACT

*Jan C.T. Eijkel, tel: +31- 489-2839; j.c.t.eijkel@utwente.nl