BALLISTIC KELVIN'S WATER DROPPER FOR ENERGY HARVESTING

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ABSTRACT

In this paper, we introduce a microfluidic self-excited energy conversion system inspired by Kelvin's water dropper but driven by inertia instead of gravity. Two micro water jets are produced by forcing water through two micropores, breaking up into microdroplets which are inductively charged by electrostatic gates. Targets and electrostatic gates are cross-connected in a way similar to Kelvin's water dropper. To prevent overcharging of the droplets, a voltage divider using inversely connected diodes was introduced in our system to control the charge induction. Maximal 18% energy conversion efficiency was obtained with the diode-gated system.

KEYWORDS: Energy conversion, micro-droplets, Kelvin's water dropper

INTRODUCTION

As one of the renewable energy conversion methods, microfluidic energy conversion is relatively less known to the public. Recently we demonstrated a new form of microfluidic energy conversion named as "ballistic", which is both an efficient and powerful method to generate electric power. We showed that with a single-jet system a maximal conversion efficiency of 48% could be obtained.[1] In this conversion method water is accelerated by pumping it through a micropore, where it forms a microjet breaking up into fast-moving (>10 m/s) charged droplets. Droplet kinetic energy is subsequently converted to electrical energy when the charged droplets decelerate in the electrical field that forms between membrane and a metal target. In our original device we also employed an electrostatic gate to charge the droplets and obtained a stable and adjustable current generation that is independent of the membrane zeta potential. With a well-controlled applied voltage and proper design of the gate, theoretically the droplet charge density can be increased until the Rayleigh limit, so that the target potential required for high efficiency can be decreased to the order of daily-use range.[1] However, for an electrical energy conversion device an external voltage source is cumbersome to implement. Instead, a self-excited energy conversion system will be much more convenient for applications. Here we report on such a self-excited device.

Lord Kelvin invented an electrostatic high voltage generator by water dripping in 1876, generally named the 'Kelvin water dropper'.[2] In Kelvin's design, two metal buckets with an opening in the bottom drip water. The falling water drops pass through hollow metal rings and are collected by two other metal buckets. The hollow metal rings through which the droplets pass are cross-connected with both bottom buckets (a setup as in figure 1b). As a result, any tiny charge on the water drops (e.g. a positive charge) that left the left-top bucket will charge the bottom left bucket and hence the right side ring. The metal ring on the right side will then attract more negative charges to the water drops on the right side, so that more net negative charges will be collected by the bottom right bucket and the negative voltage increases on the left ring. Hence, a positive feedback exists and the two downstream buckets will continue this charging process until voltage breakdown occurs between the two bottom buckets, or drops are repelled and fall outside of the buckets. The Kelvin water dropper is thus a self-excited positive feedback system that charges water droplets and delivers charged droplets at high electrical potential driven by gravity.[3] However, the Kelvin water dropper itself has not been further improved as energy harvesting device since the droplets are easily been overcharged inducing much deflection (loss) of droplets on energy collection.

Besides, the generated voltage is far too high for practical applications, and the harvested currents are very small with regard to the amount of water consumed.

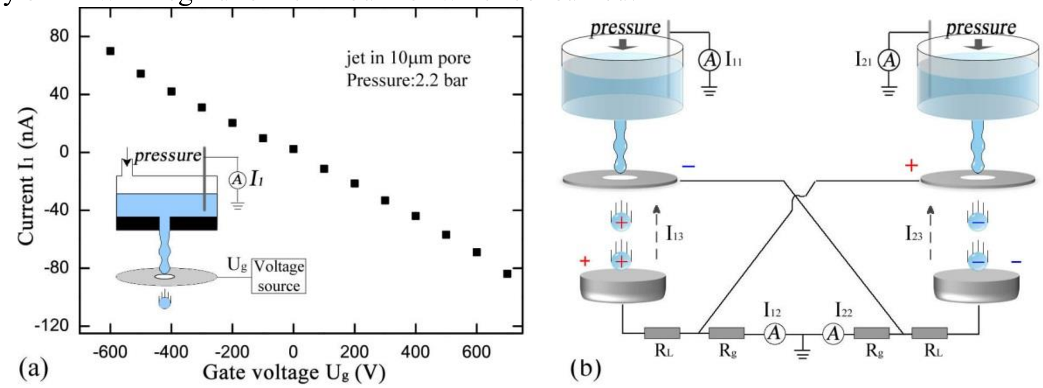

Figure 1: (a). The principle of controlling the upstream current by gate induction. The polarity of current I_1 can be controlled by applying a proper gate voltage. Solution: 0.1M KCl, pore diameter: 10 μm, applied pressure: 2.2 bar. (b). Our self-excited ballistic energy system driven by pressure. Resistors form a voltage divider to separate the gate voltage from the target voltage.

Previously we demonstrated the single microjet ballistic system discussed above. [1] In the present paper, we apply an electrostatic charge self-induction mechanism inspired by Kelvin's water dropper to this inertia-driven (ballistic) energy conversion system and show that the disadvantages of Kelvin's water dropper can be overcome. The droplet charge will be derived from the same inductive charging mechanism as in Kelvin's droplet generator, employing two separate systems and cross-connecting targets and induction rings. One of the disadvantages of Kelvin's water dropper is that it uses a positive feedback system that is inherently unstable. In our ballistic system overcharging of droplets will also result in droplet repulsion from the target. The deflection of these overcharged droplets causes a lower efficiency.[1] To overcome the disadvantages of Kelvin's positive feedback mechanism, we therefore introduce non-Ohmic voltage dividers by reversely connecting diodes in the system to properly control the induction voltages thus enabling a stable current generation and energy conversion as a self-gated system.

Figure 1b shows a schematic picture of our ballistic Kelvin's water dropper energy conversion device. Two silicon nitride membranes with a single cylindrical pore with a diameter of 30 μm were mounted in pressurized PMMA reservoirs with rubber O-rings. The reservoirs contained degassed ultrapure 10m KCl solution. A layer of 150nm thickness Pt was sputtered at the back side of the chip for electrical connection with instruments via four metal pins. The mechanical input power can be calculated by measurement of the flow rate (Bronkhorst Cori-flow flow sensor) and pressure (Sensortechnics CTE 8016 GY7 pressure sensor). Two pieces of aluminum foil with a thickness of 0.2mm were attached under the chip holders to function as induction gate. Upstream currents are denoted as I_{11} and I_{21}, and the harvested currents as I_{12} and I_{22}. The currents, including the current generated by deflection of droplets from the target to the gate ring (I_{13} and I_{23}) can be measured by either a pico-ammeter (Keithley) or a multi-meter in voltage mode, showing the voltage difference over its integrated 10MOhm resistor induced by the current flow. Two stainless steel cups functioned as targets and were placed beneath the chip holders to collect charged droplets. The load resistance connected between these targets and ground was divided into two sections: resistors for electrical power generation and resistors for induction of the other jet, named R_L and R_g respectively.

EXPERIMENTAL RESULTS

To induce a stable current and consequently obtain a stable energy conversion, we decided to introduce elements with a non-linear resistance behavior for the electrostatic gating in the circuit. We applied reversely connected diodes for this purpose, which exhibit an ohmic behavior at low currents and a constant voltage drop at high currents. The benefits of adding these reversely connected diodes are that the induction voltage now can become a constant independent of target voltage (or downstream current), while the induction mechanism will still work. As a result, the gate voltage can stay in a constant suitable range preventing overcharging the droplets.

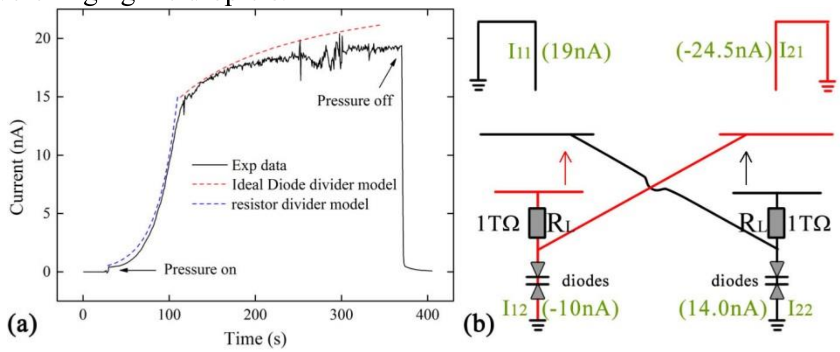

Figure 2. a. The rise of current I_{11} as a function of time when the feedback circuit with diodes is used as shown in b. Blue dashed line shows the theretical prediction using ohmic resistor ($R_g/(R_L+R_g)=0.02$). Red dashed line shows the prediction by using reversly connected diode divider ($nC_{ind}=0.05nA/V$, $C_L=12pC$). b. Scheme of the electrical circuit and values of the measured currents.

In the setup we furthermore added a second forward connected diode in series to prevent random charging of the two microjets (figure 2b). When the pressure was turned on, the initial current was less than 1nA and was generated by the microjet due to the sum of the streaming current and initial induction current (figure 2a). The current then rapidly increased when the current flow through the diodes generated an induction voltage. Above 15nA the current started to saturate, finally reaching a plateau around 19nA. Figure 2a also shows two fitted curves (dashed lines) obtained from a resistor divider model and a diode divider model respectively. From the measured flow rate for the two microjets (12μL/s) and the applied pressure (1.40bar), we then calculate that the total efficiency of the self-excited system is at least 18%. There is still space to improve the performance of this device, such as by changing the orifice diameter of the gate ring, optimal design of the target and optimizing the choice of the diodes.

CONCLUSION

Inspired by Kelvin's water dropper, we apply the electrostatic charge self-induction mechanism to an inertia-driven (ballistic) energy conversion system, and show the disadvantages of Kelvin's water dropper do not any more apply. The droplet charge thereby is derived from the same inductive charging mechanism as in Kelvin's droplet generator, employing two separate systems and cross-connecting targets and induction rings. To prevent overcharging of the droplets by the inductive mechanism and consequent droplet loss by repulsion from the target, we use voltage dividers, to enable stable energy conversion with a self-induction system. With reversely connected diodes, experimentally maximal 18% energy conversion efficiency was obtained with the diode-induced system.

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