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Short communication

Capillary driven electrokinetic generator for environmental energy harvesting

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ABSTRACT

We propose a novel electrokinetic generator driven by the capillary force. By coupling the capillary with water evaporation, the generator can output power as long as water evaporation exists, thus it can harvest environment energies from waste heat, wind power to solar energy. Experimental results show that a capillary driven electrokinetic generator, with evaporation area of 4.9 cm^2 and fluidic channel area of 2 mm^2, can output maximum electrical voltage of ~40 mV and current of 9.6 μA. The voltage and current can both be greatly enhanced by reducing the area of fluidic channel, approaching maximum power of 0.22 mW according to the theoretical calculations. In addition, a live-tree driven electrokinetic generator with an output electrical power of 2.7 μW is demonstrated. These results show that the capillary driven electrokinetic generator is of promising potential in self-powered systems.

1. Introduction

Efficiently producing electricity from renewable sources is a crucial goal of current energy research. Recently, the energy conversion in micro- and nanofluidic devices have attracted increasing attention [1]. Many studies have focused on the electrokinetic phenomena known as streaming currents and streaming potentials, which arise when a pressure driven fluid flows through a narrow channel [2–4]. Some researchers employed porous materials to generate streaming currents [4,5], while others concentrated on the electrical properties of single well-defined channel [6–11]. A microjet structure is also proposed to improve the efficiency of energy conversion [12–14]. However, the fluid flows in the mentioned devices are all driven by external pressure force, which consumes lots of high-grade energy and cannot be employed to supply power for self-powered systems.

Capillary force which exists inherently on curved liquid interface is a convenient driving force for the creation of pressure-driven flow in micro- and nanofluidic channel. Passive flow in narrow channels can be realized by utilizing menisci either external or internal to the channels [15–18]. Because of the dependence of the capillary pressure on the characteristic radius of the air/liquid interface curvature [19], systems using internal menisci offer the ability to create very high pressure difference along channels and have been successfully applied to single channels and heterogeneous arrays to supply near-constant continuous flow. Isolate internal menisci whose positions move with time are impractical to utilize, because it cannot last for a long time. However, static air/liquid menisci can be produced by coupling with transpiration, which can provide sustaining capillary force and thus continuous liquid flow [20].

In this paper, an electrokinetic generator driven by capillary force using coupled capillary/transpiration effects is proposed. The whole system is driven by the transpiration of water, which could be induced by temperature difference, blowing or sunlight illumination, etc. Thus, different kinds of environmental energy can be harvested simultaneously. Experiments are carried out to demonstrate the performance of the generator by employing alumina nanoporous membrane as fluidic channel to generate streaming current and transpiration surface to supply capillary force. Theoretical analysis on the output voltage and electrical power are also presented based on a Poisson-Boltzmann description of electrostatic potential and a Navier-Stock description of the flow in the nanochannel. At last, by utilizing the capillary force of the leaves of a live tree, we demonstrate a live-tree-driven electrokinetic generator for the first time.

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2. Experimental details

2.1. Electrode fabrication

Thin layer of Ag and AgCl are deposited directly on the two sides of the nanoporous alumina nanoporous membrane to work as electrodes. The fabrication procedure is illustrated as shown in Fig. S1. Firstly, a layer of Cr (about 15 nm) is deposited on one side of the alumina membrane to enhance the adherence between the membrane and the latter deposited Ag. Then the Ag layer (~100 nm) is deposited via magnetron sputtering (MS). After that, a silver wire is attached on the Ag film with silver paste to work as an extending for easier connection. AgCl layer is electrodeposited on the surface of the silver film by cycle voltammetry in the solution containing 0.1 M HCl, with continuous stirring. Then, the other side of the membrane is deposited with Cr and Ag layer (also 15 nm and 100 nm respectively) and attached to a silver wire, following the same procedure as the first side. Here the membrane is processed side by side to avoid electro-deposition (ED) occurs on both side of the membrane during AgCl deposition.

2.2. Tree generator

We fabricate a live tree generator by connecting the electrokinetic generator with a twig. During the process, two key points should be achieved: i) perfect sealing to ensure the liquid continuum; ii) remove the noncondensable gas in the liquid to avoid bubble occurrence when the liquid pressure decrease. Firstly, the incision of the twig and all the equipment are boiled in the NaCl solution for about an hour to remove the noncondensable gas. Then we quickly connect the twig and the generator under the boiled liquid. At last, the whole setup is fixed up for the measurements after temperature of solution recovers to room temperature. During the cooling process, a thin layer of oil is dropped on the top of the solution to avoid the noncondensable gas dissolving into the solution again.

3. Results and discussion

Fig. 1a shows the structure of the proposed generator. The central part is a traditional electrokinetic generator, in which stream currents generate in the nanoporous membrane across the fluidic channel when electrolyte solution flows through it. On the two sides of the membrane, electrodes are plated on to convert chemical energy to electricity. Unlike a normal pressure driven electrokinetic generator, the fluidic flow in this work is driven by the capillary force supplied by the air/liquid menisci (Fig. 1b) forming in the top placed transpiration surface (porous material). Continuous transpiration of water in the top surface ensures static air/liquid menisci, so as to maintain a steady flow through the channel below. Therefore, any energy that may induce water transpiration in environment can be harvested to generate electricity, such as wind power, solar energy, heat, etc.

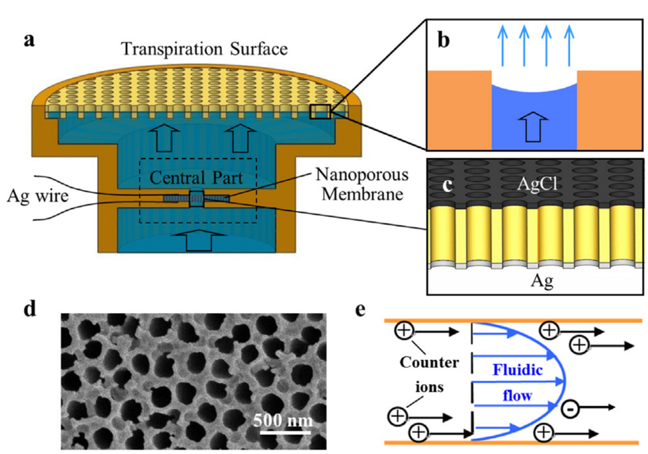

Fig. 1. Schematic of a capillary driven electrokinetic generator. (a) The structure. (b) Static air/liquid menisci formed in the porous membrane combined with transpiration. (c) Inner structure of the nanoporous membrane and electrodes. (d) SEM image of the nanoporous membrane after depositing electrodes. (e) Schematic illustration of the streaming current generate in a single nanochannel.

In the experiments, the whole device is constructed in a cylinder tube (diameter 2.5 cm) made of organic glass. Streaming currents are generated in a piece of alumina nanoporous membrane (anodic aluminum oxide) with thickness 60 μm and surface fraction 60% (Fig. 1c). As shown in Fig. 1c, the membrane consists of tens of thousands of vertical nanochannels with diameter of about 200 nm. Thin layers of Ag and AgCl (~100 nm) are plated on the two side of the membrane to work as electrodes. Fig. 1d shows the SEM image of the membrane after depositing electrodes. The streaming current generating in a nanochannel is schematically illustrated in Fig. 1d. The diameter of the fluidic channel for solution to flow through is 1.6 mm. NaCl solution of 10^{-6} mol/L is prepared as working solution, so as to get the best performance [7]. Before all the test, the electrokinetic property of the employed alumina nanoporous membrane is evaluated by a pressure driven experiment, as shown in Fig. S2. The pressure difference of 0.5 MPa will generate a streaming potential of 1.4 V. The transpiration surface (diameter of 1.5 cm) is made of the same porous membrane as used to generate streaming currents. Fig. 2a inset shows the photograph of the fabricated generator.

As shown in Fig. 2a, the generator is covered by the polyethylene film to prevent evaporation before experiments, thus it outputs a voltage of zero. When the polyethylene film is removed, the output open-circuit voltage (V) increases gradually to ~7 mV at ambient condition of 14 °C in temperature and 35% in relative humidity. When we increase the environmental wind velocity to promote the evaporation, V shows rapid increase with the wind velocity (Fig. 2b). The voltage achieves a value of 20 mV when velocity of wind is ~20 m/s. As we know, the evaporation rate of the water can also be enhanced by increasing the environment temperature and reducing the relative humidity. Thus here we also exam the output performance of the generator under different intensity of sun light irradiation and record the induced temperature and humidity variation. As shown in Fig. 2c, the output voltage increases with the increased temperature and reduced humidity as we predicted. Under an environmental temperature of 58.8 °C and relative humidity of 7.7%, the generator outputs a high open-voltage of ~ 39 mV. Plotting the relation between the evaporation rate and output voltage in the two test, we find that, the voltage has a linearly relation with evaporation rate.

To further investigate such a relation and the underlying mechanisms, theoretical analysis is carried out by employing the Poisson-Boltzmann equation [21] to characterize the streaming current and Navier-Stock equation to characterize the flow in a single nanochannel (details in Supplementary Note). Since the membrane consists of tens of thousands of the same channels, the real streaming current and internal resistance is thus:

$$R_{in} = R_0/n_0,\ I = I_0 \cdot n_0, \tag{1}$$

where R_0 and I_0 are the internal resistance and streaming current of a single nanochannel, n_0 is the number of the nanochannels available in the fluidic channel. The open-circuit voltage equals to that of a single channel. The diameter of the nanochannel is taken as 200 nm in calculation according to the size of the alumina nanopores, and the surface charge density of the channel wall (σ),