Enhancement of Electrokinetic Power Generation by Surface Treatment on a Porous Glass

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Abstract. A direct energy conversion technology based on electrokinetic (EK) phenomenon has attracted an increasing attention during recent years. However, an external driving source (e.g. hydrostatic pressure) is needed to produce an EK flow in microchannels. We recently have developed a novel hybrid energy conversion technique using combined principles of EK and forward osmosis (FO) which directly converts the salinity gradient energy into the electric energy without need of external pressure input. In order to further enhance the power generation efficiency of the FO-EK system, an experimental study is conducted on surface treatment of porous glass (PG) that offers microchannels for EK flow to pass through. The results show that, ultrasonic treatment gives rises to more consistent potential difference and streaming current. SDS surface treatment on PG pretreated by ultrasonic can further enhance EK power generation. In particular, PG treated by ultrasonic and SDS 12 mM yields the best power generation performance with a power density of 3.08 W/m³, an increment of 27.3 % compared to PG without any surface treatment. In addition, the generated potential difference and streaming current linearly increase with the increasing flow rate. Finally, increasing the flow rate gives rise to higher power density increment.

Keywords: Streaming potential, Streaming current, Porous glass, Surface treatment, SDS, Ultrasonic.

1. Introduction

It is well known that majority of substances can be charged once being immersed in an aqueous solution through electrochemical mechanisms of adsorption of the charged species or dissociation of the ionizable groups [1, 2]. For example, a glass capillary is usually get negatively charged when in contact with an electrolyte solution with suitable pH due to the dissociation of silanol groups, SiOH ↔ SiO⁻ + H⁺ [3]. The negatively charged surface attracts positive ions and repels negative ions, leading to the formation of an electric double layer (EDL). When a pressure driven flow passes through this glass capillary, excess counterions in the EDL are induced to flow downward, which is commonly referred to as convection current or streaming current. However, as there is no external electric connection between the inlet and exit of the capillary, the accumulation of the excess counterions at the exit generates a potential difference between the two ends which simultaneously induces a conduction current in the opposite direction through the bulk of the liquid. The electric field strength corresponding to the induced potential difference is called streaming potential [4]. Once connected with an external circuit, the generated streaming potential and streaming current can be harvested as the power source. This process is commonly referred to as the electrokinetic (EK) power generation.

All previous researchers employ external driving devices such as pumps and syringes to generate liquid flow. We recently developed a novel hybrid energy conversion system to extract energy from the salinity gradient, termed as the forward osmosis (FO) - EK energy conversion system [5, 6]. Two sub-modules are included in this system, namely FO sub-module and EK sub-module. For the overall system, a suction force generated in the FO sub-module due to the mechanism of FO draws water through a porous glass (PG) disk.
housed in the EK sub-module. When such osmotic pressure-driven flow passes across the PG, streaming potential and streaming current are generated and they can be harvested as the power source to an external electric circuit. Such hybrid energy conversion system could be more advantageous over the other EK energy conversion systems due to that the proposed system is free of extra energy input and thus more environmental friendly and cost effective.

Highly hydrophobic solid surface gives rise to high liquid velocity and thus low pressure consumption [7-10]. In addition, high surface charge density, obviously, induces high zeta potential. Enhancements in both of these two aspects can greatly improve the EK flow in microchannels and finally increase the EK power generation efficiency. However, it is known that the less polarizable the solid surface molecules are, the more hydrophobic the solid surface is. This means that the solid surface hydrophobicity can be increased by diminishment of surface charge density [11], which simultaneously reduces the zeta potential. Some approaches have been reported to address this dilemma by adding polymers [12], employing surface modification [13], applying two phase flow [14], and so on. As well known that, Sodium Dodecyl Sulphate (SDS) is an anionic surfactant, consisting of a 12-carbon tail attached to a sulfate group. The corresponding critical hemimicelle concentration (HMC) and critical micelle concentration (CMC) are around 1.6 mM and 8.2 mM. Study shows that, for the adsorption of SDS onto a negatively charged silica surface at high pH, it is very small at low SDS concentration up to HMC due to electrostatic repulsion; with the SDS concentration increasing beyond HMC, it grows sharply mainly because of hydrophobic attractive force between alkyl chains of SDS; and finally it reaches a plateau after CMC point. Meanwhile, for the corresponding zeta potential, it almost remains unchanged for SDS concentration lower than HMC and then is reduced sharply in magnitude when concentration growing beyond HMC; but it is greatly enhanced in magnitude after CMC and finally reaches an even higher absolute value [15-17]. Another commonly applied surface treatment approach is ultrasonic which is conducted by exposing samples to ultrasonic energy transmitted through an aqueous bath. The ultrasonic treatment can effectively clean and degas the PG and, essentially, make it being fully wetted, which greatly benefits to the stability and efficiency of the power generation process.

This work mainly focuses on experimental study of effects of surface treatment on EK power generation. Two surface treatment approaches, ultrasonic treatment and SDS treatment, will be separately and cooperatively investigated.

2. Materials and methods

2.1. Experimental setup and instrumentation

A kind of PG disk (Schott Duran®) is used in experimental study due to its excellent chemical and physical properties, compositions of which are: SiO$_2$ ~ 80%, B$_2$O$_3$ ~ 13%, Na$_2$O/K$_2$O ~ 4%, Al$_2$O$_3$ ~ 2% (by weight). This PG is sealed in an EK holder. Closely contacted with PG at each end, two Silver/Silver-Chloride (Ag/AgCl) mesh electrodes protrude from the EK holder to connect with Keithley Source Meter for measuring/sourcing a voltage from/into the PG. The measured results are logged into a computer for subsequent processing and analysis. Since this work mainly focuses on surface treatment on the PG, the testing system is simplified by replacing the FO sub-module mentioned in introduction part with a peristaltic pump (Masterflex®), which is shown as Fig. 1. A flow damper is placed between the pump and the EK holder to regulate the pulse flow supplied by the pump. Since the flow rate shown on the pump is not exactly accurate, especially for high flow rate, an analytical balance is used to calibrate the actual flow rate. The measured liquid decrement within reservoir-I was logged into the computer, which will be post-processing to actual flow rate.

In this work, experimental study mainly focuses on effects of surface treatment, including ultrasonic treatment and surfactant treatment, on the PG. The machine, ultrasonic cleaner (Branson 8510MT), is applied to provide ultrasonic treatment on the PG. Meanwhile, SDS (Sigma-Aldrich) is employed as anionic surfactant. Deionized (DI) water was used to prepare SDS solution and generate EK power all through the experiments. The conductivity of the DI water is strictly kept to within 0.9 ~ 1.1 µS/cm.
2.2. Experimental procedure

SDS solution concentration is one of the variables to be tested. In this work, a total of 5 different SDS solution concentrations were used to treat the PG, namely 0 mM, 3 mM, 6 mM, 8.2 mM and 12 mM. Generally, two sets of experiments were conducted, one is EK power measurement based on PG only treated with SDS; the other one is EK power measurement based on PG treated with ultrasonic and SDS.

The procedure of surface treatment on a PG with SDS solution is as follow: (1) pump the prepared SDS solution (0 mM, 3 mM, 6 mM, 8.2 mM or 12 mM) through the PG at 5 ml/min for 1 hour; (2) stop pumping and incubate the PG for another 30 minutes; (3) pump DI water through the PG to flush away the SDS solution and stop pumping when the measured potential difference is stabilized. For the combined surface treatment with ultrasonic and SDS, prior to being treated by SDS as mentioned up, the PG should be immersed in ultrasonic water both for 30 minutes. For each surface treated PG, potential difference and streaming current at 5 different volume flow rates, 5 ml/min, 10 ml/min, 15 ml/min, 20 ml/min and 25 ml/min, are measured based on experimental setup shown in Fig. 1.

3. Results and discussion

Since the streaming current $I_s$ is a linear decreasing function of the generated potential difference $\Delta \phi$ under open-circuit condition, then the maximum output $P_{\text{max}}$ occurs at the half of the potential difference where the current is just the half of the streaming current $[18, 19]$, i.e.: $P_{\text{max}} = (\Delta \phi \cdot I_s)/4$. If we define the ratio of the generated power to the volume of the PG $V_g$ as the power density $[20, 21]$, $PD$, the maximum power density is expressed as: $PD_{\text{max}} = P_{\text{max}}/V_g$.

3.1. Effect of ultrasonic treatment on PG

![Fig. 2: Effect of ultrasonic treatment on PG.](image)

(a) Potential difference  (b) Streaming current  (c) Power density increment

Figs. 2 (a) and (b) show that the generated potential difference and streaming current almost linearly increase with the increasing flow rate. Moreover, the range of error bars for ultrasonic treated PG is significantly shorter than that for PG not treated by ultrasonic, especially for high flow rate, which means that ultrasonic treated PG produces more consistent potential difference and streaming current. This
phenomenon is mainly due to that the ultrasonic treatment eliminates tiny air bubbles trapped inside the PG and makes the PG being fully wetted, and thus gives rise to much more uniform amount of negatively charged surface through all experiments.

Fig. 2 (c) compares the increment in power density between ultrasonic treated and untreated PGs post-treated with SDS solution. All the positive increments in power density show that PG treated with ultrasonic outperforms the PG not treated with ultrasonic.

3.2. Effect of SDS surface treatment on PG pretreated by ultrasonic

(a) Potential difference increment
(b) Streaming current increment
(c) Power density increment

Fig. 3: Effect of SDS surface treatment on PG pretreated by ultrasonic. ‘Treated’ in the figures above means PG treated by ultrasonic. All the increments are based on PG treated by ultrasonic and SDS 0 mM.

After being treated by ultrasonic, surface charges of PG becomes much more stabilized. Then SDS surface treatment with five different solution concentrations is successively conducted to the ultrasonic treated PG. it is observed from Fig. 3 (a) that, compared with PG treated by ultrasonic and SDS 0 mM, the potential difference performs almost no change for SDS 6 mM but great increased for other SDS concentrations, especially for SDS 12 mM. Different from potential difference, shown in Fig. 3 (b), streaming current is reduced by SDS surface treatment at low flow rate but increases at high flow rate. This is mainly due to that, as the flow rate increases, more and more negatively charged glass surface is involved in power generation process, leading to increasing streaming current. In addition, SDS 12 mM gives rise to the best performance. For the final parameter power density, shown in Fig. 3 (c), it is decreased by surface treatment of SDS 3 mM and SDS 6 mM at low flow rate but increased at high flow rate. For the other two SDS concentrations, the power density is always increased by the SDS surface treatment. Similar with streaming current, SDS 12 mM also gives rise to the best performance in power density. It is also calculated that the PG treated by ultrasonic and SDS 12 mM yields the best power generation performance with power density of 3.08 W/m³, an increment of 27.3 % compared to PG without any surface treatment.

4. Conclusions

In this work, an experimental study is conducted to investigate effects of surface treatments, including ultrasonic treatment and SDS treatment, on EK power generation. Generally, three parameters are considered to assess the performance of EK power generation, which are SDS surfactant, ultrasonic treatment and flow rate. The following conclusions can be drawn:

1) Ultrasonic treatment can effectively wet the PG, giving rise to much more uniform negatively charged surfaces and ultimately producing more consistent and higher potential difference and streaming current;

2) SDS surface treatment on PG pretreated by ultrasonic can further enhance EK power generation. Our experiment shows that the PG treated by ultrasonic and SDS 12 mM yields the best power generation performance with a power density of 3.08 W/m³, an increment of 27.3 % compared to PG without any surface treatment;

3) Both the generated potential difference and the streaming current linearly increase with the increasing flow rate. Also high flow rates are beneficial to EK power generation because with
increasing the flow rate, more and more negatively charged surface is involved in streaming current generation process, giving rise to higher power density increment.

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6. References