POLYMER-ENHANCED ENERGY HARVESTING FROM STREAMING POTENTIAL

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ABSTRACT

In this contribution, we present the experimental results of energy conversion from the streaming potential when a polymer, polyacrylic acid (PAA) with concentration from 200 ppm to 4000 ppm in background electrolyte KCl solution was used as the working fluid. The results show that when PAA was added in KCl 0.01 mM solution, the energy conversion efficiency of the system was enhanced a factor of 447 as compared to the case without polymer. An enhancement factor of 257 was also observed when PAA was in the higher ionic strength background solution, KCl 1 mM. These are the first experimental demonstrations of this effect.

KEYWORDS

Energy conversion, efficiency, streaming potential, polymer.

INTRODUCTION

Energy harvesting from the streaming potential is based on the electrokinetic phenomena which are associated with interfacial charges. In general, every surface obtains a surface electrical charge when brought into contact with a polar medium. These interfacial charges, in turn, influence the ion distribution in the polar medium and lead to the formation of the electrical double layer (EDL). The streaming potential is generated by pressure-driven transport of the net charged liquid in the EDL. The main goal of researchers in the field is to increase the energy conversion efficiency (Eff) of the systems.

The Eff equals the ratio of (electrical) output power (P_{out}) and (hydrodynamic) input power (P_{in}):

$$\mathrm{Eff} = \frac{P_{out}(\text{electrical})}{P_{in}(\text{hydrodynamic})} \tag{1}$$

Recently, Berli et al. [1] predicted theoretically that addition of polymer to the working fluid in a microfluidic channel can enhance the Eff. However, this prediction has not yet been investigated experimentally.

When non-adsorption polymers are introduced into a microchannel, depletion layers near the channel walls are formed due to the repulsive force between polymer chains and the walls, which is of entropic origin (Fig. 1a). The thickness of these layers (δ) will be approximately equal to the radius of gyration of the polymers (R_g). This results in two different viscosity zones in the channel, one of low viscosity (η_s) within and the other of high viscosity (η_p) outside the polymer depletion layers. [2] Figure 1b shows the approximate predicted velocity profile of the fluid flow for polymer solutions (red curve) and for normal viscosity electrolyte solutions (black curve). The decrease of the bulk velocity on polymer addition will decrease the hydrodynamic input power P_{in}. Because the thickness of the depletion layers can be varied from a few tens to hundreds of nanometers depending on the polymers of choice, it can be made larger than the thickness of the EDL, so that the transport of charge and hence P_{out} remain unaffected. Thus, one can gain Eff by reducing the volumetric flow rate in the bulk liquid without affecting the electrokinetic phenomenon which happens only inside the EDL (Fig1. b).

In this paper, we present for the first time the results from experiments of energy conversion from streaming potential when polymer solutions were used as working fluids, and show that the energy conversion efficiency can be strongly enhanced.

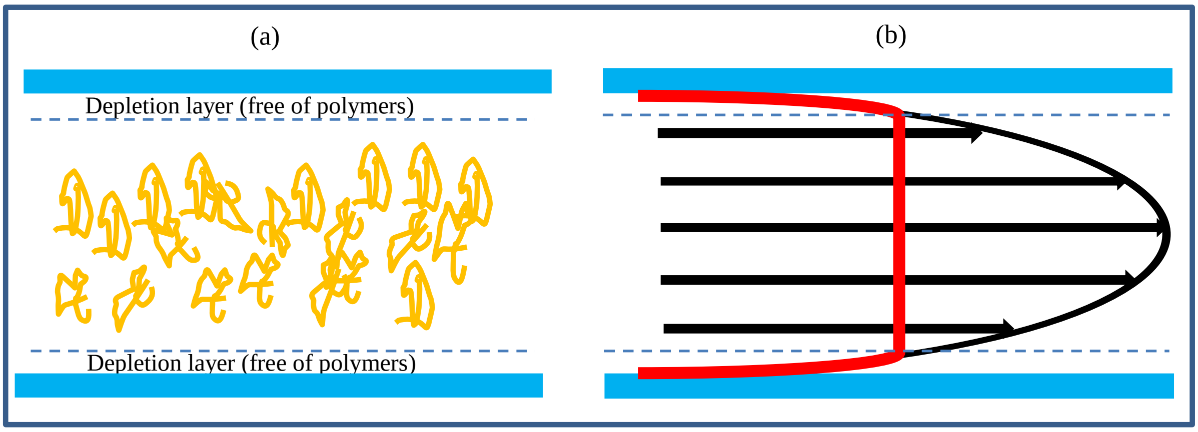

Figure 1: (a) a scheme of depletion layers when polymer is added to the working fluid. (b) predicted velocity profile of the fluid flow for polymer solutions, (red curve) and for normal electrolyte solutions, (black curve)

EXPERIMENT

In this work we focus on the effect of polymers on Eff in a long, straight and smooth microchannel. Microfluidic devices were fabricated in the clean room of MESA$^+$. The Pyrex glass chip has a microchannel with dimensions of width (w) 40 µm, height (h) 10 µm and length (L) 3.8 mm. The scheme of the experimental set up is shown in Fig. 2. A 99% purity nitrogen gas source was employed to drive the liquid flow from the reservoir via fused silica capillary tubing through the microfluidic chip to the downstream collector by a high accuracy gas pressure pump (Fluigent MFCS). A flow meter from Fluigent Maesflo was used to measure the liquid flow rate Q. Two Ag/AgCl electrodes were placed into the reservoirs for electrical measurements. Voltages were applied by a Keithley 2410 voltage source, and current measurement was performed by a Keithley 6485 pico-ammeter.

Polyacrylic acid (PAA, M_w 1250000 g/mol, gyration radius shown in table 1) was obtained from Sigma-Aldrich (USA). In order to have a full insight into the effect, the experiments were conducted in two different batches. In the first batch, potassium chloride KCl 1 mM (approximate EDL thickness 9.5 nm), pH 9.5 was used as the background electrolyte solution. This background solution was then employed as solvent for preparation of PAA solutions with varying concentrations of 200 ppm, 500 ppm, 1000 ppm, 2000 ppm, 4000 ppm. In the second batch of experiments, KCl 0.01 mM (approximate EDL thickness 100 nm) pH 9.5 was used to prepare PAA solutions with the same set of concentrations as the batch number one. All the PAA solutions were adjusted to pH 9.5.

Prior to the introduction of the different solutions into the apparatus, the microchannel and the entire tubing system were bidirectionally rinsed with KOH 100 mM for 15 mins. Following that, a second 15-min rinsing cycle was initiated using MiliQ water and the third cycle was 15 mins of the desired solution before performing measurement. The transparent nature of the microchannel surfaces allowed visual inspection of the channel (via a microscope) to ensure that all bubbles had been removed. The working solution was allowed to flow into the system until the equilibrium was reached which was manifested by the stability of the flow rate and the streaming current. Once the equilibrium was established, the measurement was conducted. All the measurements were repeated in triplicate and carried out at ambient temperature.

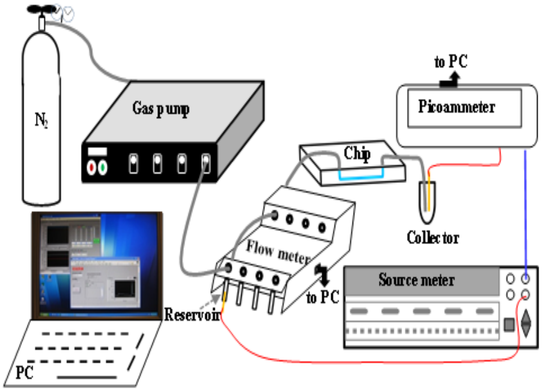

Figure 2: Scheme of experimental set up

Table 1: gyration radius of PAA
in different ionic strength background solutions

KCl concentration	$R_g = 1.57 \times n^v$ (nm); n is the number of monomer in polymer chains [3, 4]	
1 mM	$v = 0.5$	$R_g = 207$
0.01 mM	$v = 0.6$	$R_g = 549$

RESULTS AND DISCUSSION

Fig. 3a compares the reduction of volumetric flow rate in both experimental batches. The reduction of flow rate in case of KCl 0.01 mM at small added PAA is larger than in KCl 1 mM. This can be explained by the changes of polymer conformation according to the ionic strength of the solvents (background electrolyte solution). In the case of high ionic strength solution, counter ions, in our case K^+ will strongly screen the negative charges on polymer chains. This results in polymers having random coil conformation. If one now reduces the ionic strength of the solvent, the polymer conformation will be changed from random coil to expanded stage due to lesser screening and hence repulsive force of negative charges along the polymer chains. At expanded stage, the random coils take more space; increasing the viscosity of the solution.[5] This explains why the volumetric flow rate was reduced more rapidly by PAA addition to the low ionic strength background solution.

The I-V characterization of the system is shown in figs. 3b and 3c. In both experimental batches, the streaming current increased and the streaming potential decreased with increasing polymer concentration. The reduction of streaming potential can be explained by the increase of bulk conduction when acidic polyanion PAA was added to the working solutions. The underlying mechanism for the increase of streaming current is under discussion. It must be so that the amount of positive charge that is transported increased when the polymer was added. On this account, it is reasonable to hypothesize the following: (i) possibly there was a faster speed of solution inside the depletion layer since the streaming current is proportional to the velocity in the electrical double layer inside the depletion layer or (ii) possibly a movement of the solution occurred in between the polymer with respect to the polymer. The first hypothesis is probable. Furthermore, figs. 3b and 3c show that there was a sharp increase of the streaming current when PAA was used with low ionic strength background solution (KCl 0.01 mM) as compared to the higher ionic strength one (KCl 1 mM).

Due to the strong reduction of volumetric flow rate and the significant increase of streaming current, the Eff of the entire system was increased enormously. In particular, compared to the Eff of the normal viscosity electrolyte solution, the enhancement of the Eff for PAA added into KCl 0.01 mM solution was a factor of 447 and for the case of PAA in KCl 1 mM it was a factor 0f of 257, as shown in fig. 3d. The maximal energy conversion efficiency we obtained for the entire system is 0.038 % and it was 0.34% for the chip.

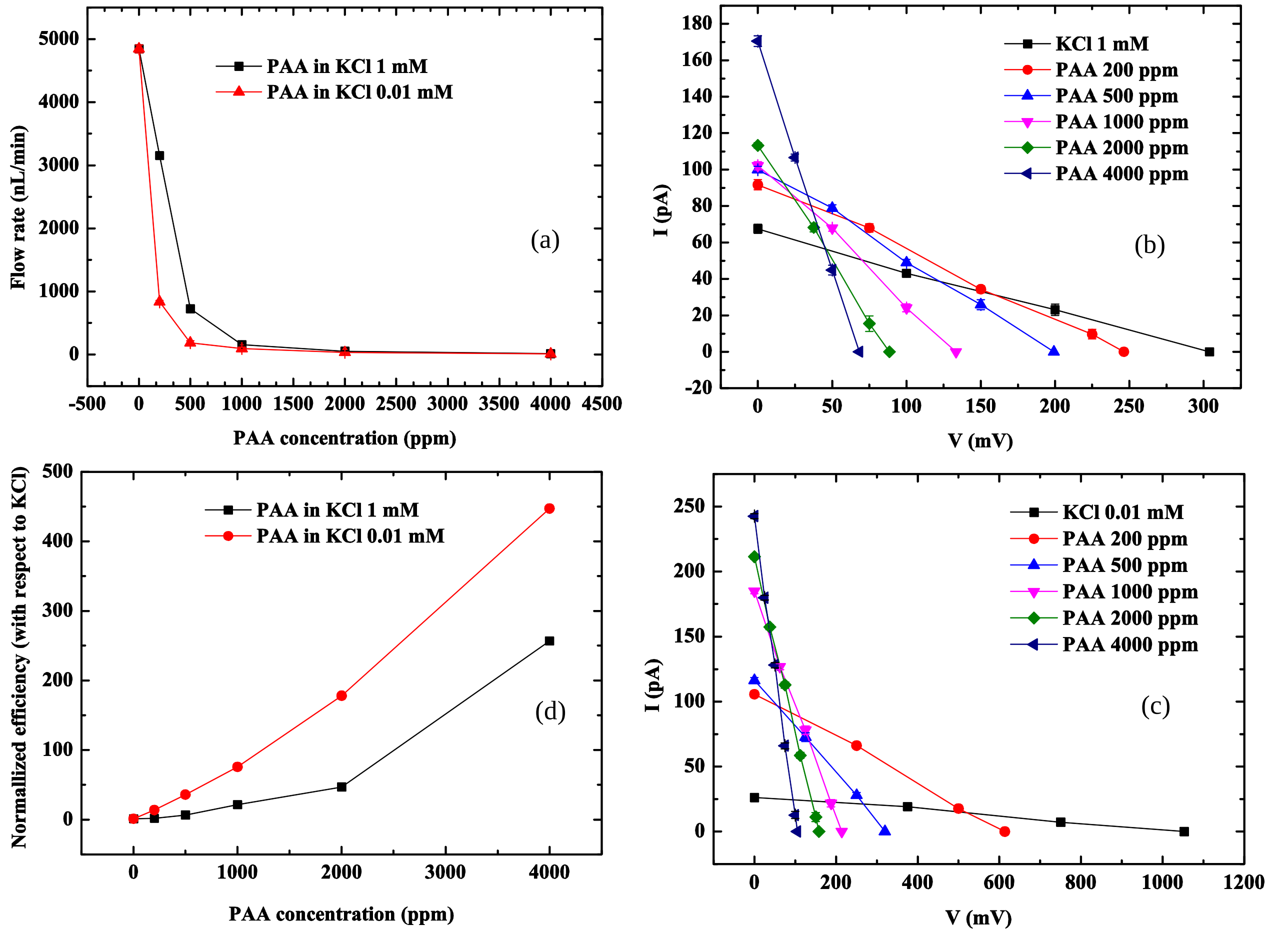

Figure 3: (a) The reduction of volumetric flow rate on PAA addition; (b) I-V characterization in case of PAA in KCl 1 mM; (c) I-V characterization in case of PAA in KCl 0.01 mM; (d) Normalized energy conversion efficiency of PAA containing solutions with respect to normal viscosity KCl 0.01 mM and 1 mM solutions.

CONCLUSION

The energy conversion efficiency from the streaming potential in microchannel with polyacrylic acid (PAA) added to background electrolyte KCl solution was investigated experimentally. The results showed that the presence of this charged polymer caused a reduction of input power, an increase of streaming current and a decrease of streaming potential simultaneously. Furthermore, PAA in low ionic strength solution (KCl 0.01 mM) caused a large reduction of input power and increase of streaming current than at the higher ionic strength (KCl 1 mM). These combined factors resulted in an enhancement of the energy conversion efficiency of the system with a factor of 447 in case of PAA in KCl 0.01 mM and a factor of 257 for PAA in KCl 1 mM.

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