MASSIVE ENHANCEMENT OF STREAMING POTENTIAL POWER BY APPLICATION OF TWO-PHASE FLOW

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Abstract: We report that the performance of microfluidic energy conversion can be enhanced by using two phase flow technique. Recently we discovered that the addition of bubbles inside liquid channel increases the maximum output power. In single phase system conduction current originates from the generated streaming potential limits the output power. In the two-phase system the bubbles reduce this current and increase the power. From our experiment results, output power could be enhanced by over 100 times lager compared with single phase flow due to the addition of bubbles.
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Keywords: streaming current, resistance, power, two-phase flow

INTRODUCTION

Energy has become one of the most important topics for modern scientific research. Especially we need novel energy conversion systems, which are not harmful to people's living environment. The developing "lab on chip" technology provides unique opportunities to convert fluidic mechanical energy to electrical energy.

The electro-kinetic phenomena, such as electro-osmotic flow and streaming current, can convert electrical energy to mechanical energy (or inverse).[1] Here, we just discussed the energy conversion from the mechanical to the electrical domain by the streaming potential. Any charged surface accumulates net charges near the surface to form an Electrical Double Layer (EDL). If we apply an external pressure difference over a liquid-filled channel, the net charges will move with the water flow, creating an electrical current. By placing two electrodes at the endings of channel, we can pick up the electrical energy. As a result, kinetic energy can be converted into electrical energy in a quite simple manner.

Traditionally, investigators studied the performance of such a fluidic energy conversion system using single phase flow. Yang pointed[2] out that the convection current in fluidic channels could be a simple and effective energy conversion system. However, because of the defects of the materials and for other reasons, the energy conversion efficiency was much less than 0.01%. Subsequently many researchers have tried to enhance the energy conversion efficiency, which has reached about 3~5% in a single nano-channel[3] and nanopore[4] respectively. Recently, Andrew M. Duffin and their colleagues[5] using microjets greatly enhanced the energy conversion efficiency to exceed 10%.

However, recently we discovered that the addition of bubbles inside liquid channel increases the maximum output power and also has potential to increase the efficiency. A recent theoretical report also points in this direction [6]. In short, in a single phase system a back-current ("conduction current") inside the channel which originates from the generated streaming potential limits the output power. In the two-phase system the bubbles increase the channel resistance, reducing this current and increasing the power.
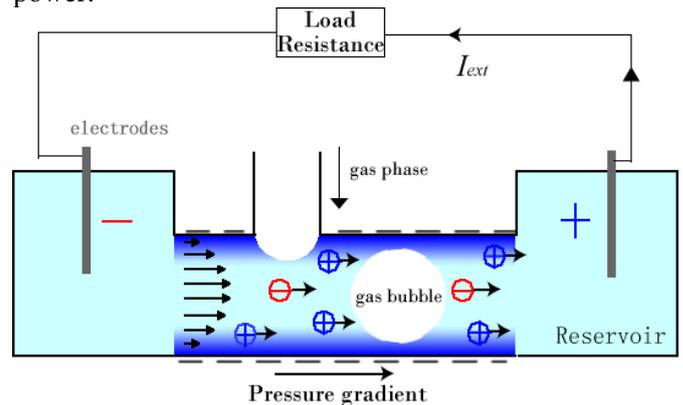

Figure 1 shows the scheme of our experimental principle. With injecting gas bubbles into the solution, conduction current could be decreased.
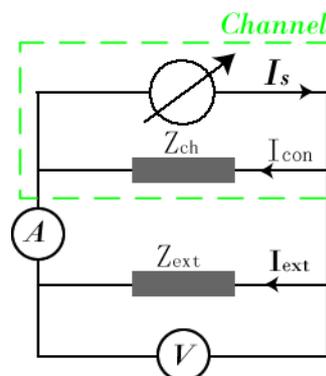

Figure 2 shows the equivalent circuit

THEORY

If there is no external load resistance connected, current flow through the external circuit reaches a maximum value, which is called the streaming current (I_s). With increasing external resistance, an electrical potential difference will be generated. This potential difference will induce a conduction current with opposite direction of the streaming current. When the external resistance is large enough (much larger than the channel resistance), there is almost no current

flow through the external resistance, and the potential drop over the external resistance is called the streaming potential.

The power conversion system could be described by the equivalent circuit shown in figure 3. The streaming current could be considered as a constant current source and the resistance of the channel as an internal resistance which is connected in parallel with external resistance. Then from network theory, the output power could be expressed as:

$$W_{ext} = I_{ext}^2 Z_{ext} = \frac{Z_{ch}^2 I_s^2 Z_{ext}}{(Z_{ext} + Z_{ch})^2} \qquad (1)$$

where the I_{ext} and I_s are streaming current and external current; Z_{ch} and Z_{ext} are resistance of channel and external circuit.

Assuming the internal and external resistances are ohmic, the maximum output power could be obtained if Z_{ext} equals to Z_{ch}. Then the output power could be described as:

$$W_{ext} = I_s^2 Z_{ch} / 4 \qquad (2)$$
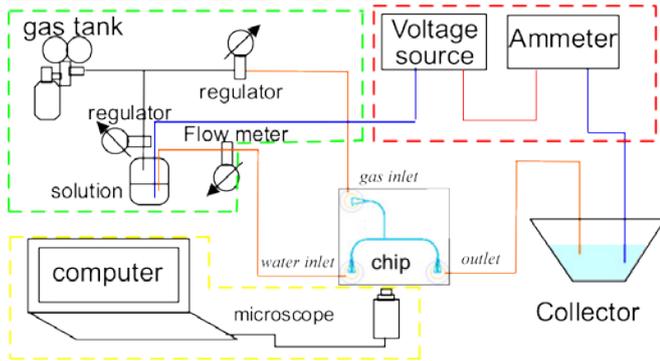
EXPERIMENTAL SETUP

Figure 3 illustrates the scheme of experimental setup.

The experimental setup is shown in figure 2. In general, our experimental setup could be divided into three parts: gas pressure source part (green outline): nitrogen gas was separated into two paths – one path is connected with gas tight bottles, which are filled with 1mM KCl solution (pH 9.2). When gas pressure was applied, solution was driven into the channel; another path is directly connected with the chip by fused silica tubing, which is used for generation of gas bubbles. The second (red outline) part is the electrical measurement system: voltage source and pico-ammeter were used for measurement of the electrical properties of the system. The last part (yellow outline) consisted of an inverted microscope, used to monitor the generation of gas bubbles.
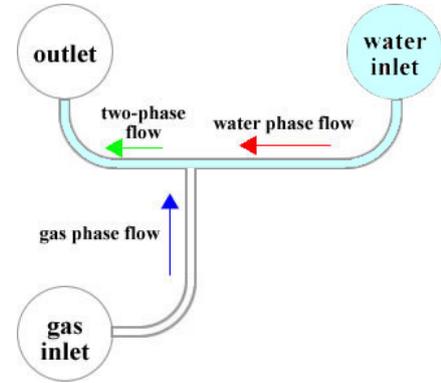

Figure 4 shows the scheme of our chip design.

Our chip design is also quite simple: a T junction was used for gas bubbles generation. T junction connected water phase flow and gas phase flow, and mixture these two phase flow. The dimension of the channels was: 40 μm wide and 10 μm height. Chips were prepared from Pyrex glass in the cleanroom by photolithography and wet etching, followed by thermal bonding. Access holes were provided by powder blasting.

EXPERIMENTAL MEASUREMENT

Ag/AgCl electrodes were inserted in the fluidic reservoirs at inlet and outlet and connected to the electrical equipment to measure the electrical properties of the channel. (figure 3)

The chip was connected with fused silica tubing (inner diameter 100μm). The length of tubing has been listed below:

position	length
Water inlet tubing	75mm
outlet tubing	15mm
gas inlet tubing	36mm

We measured the electrical properties of the whole system, including chip and tubing.

EXPERIMENTAL RESULTS

First, the streaming current was investigated in *single phase flow*, with results shown in figure 4. Pressure was applied on the water phase for 60 seconds. The data points were obtained by averaging the streaming current for each measurement and the error bar was calculated statistically from averaging of streaming current.
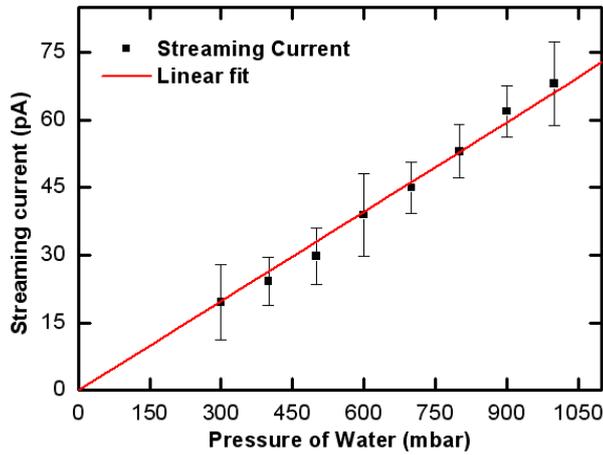
Figure 5 The streaming current linearly increases with water pressure drop in single phase flow.

The red line in figure 5 is a linear fit of the streaming current, indicating that the streaming current linearly increases with pressure drop of water phase increasing as theoretically expected. To study the influence of gas bubbles, we kept the water pressure constant at 300 mbar and measured the streaming current at increasing gas pressure (see Figure 6).
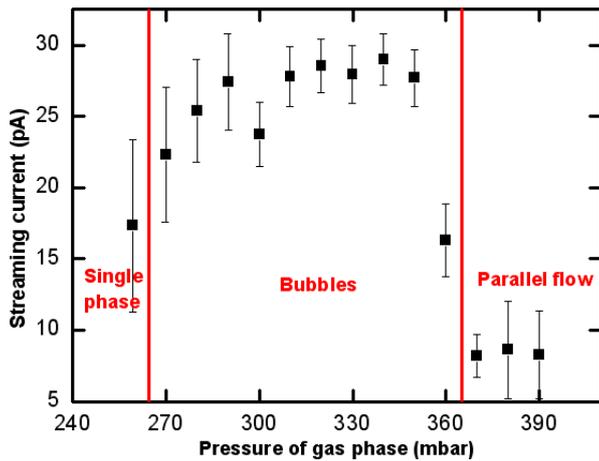

Figure 6 The streaming current was enhanced by injecting bubbles; it decreases when parallel flow occurs.

The streaming current is 17 picoamperes under 300mbar in single phase flow. With increasing gas pressure, gas bubbles are injected into the liquid channel. The streaming current then increases to a value 1.6 times larger than in single phase flow. This enhancement of streaming current in bubble flow is mainly due to the water velocity increasing near the channel wall due to the addition of the gas bubbles, which contributes to generation of streaming current.

If we increase the gas pressure above 360 mbar, the streaming current drops down again to become even smaller than in single phase flow and subsequently almost remains constant when the gas pressure is increased further. In this case water and liquid flowed in parallel so that a part of the inner wall was occupied by gas phase and did not contribute to generation of streaming current. Further increasing the

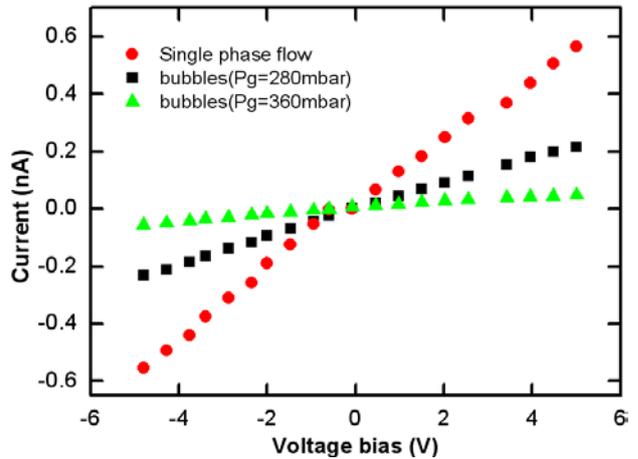gas pressure will therefore not help to enhance the streaming current.

Figure 7 An I-V characterization of the fluidic system with (black, green) and without (red) bubbles. The system behaves as an Ohmic resistance.

To know the output power W_{ext} (equation 2), we still need to know the resistance of the channel Z_{ch}. Figure 6 shows the I-V characterization of the fluidic system, made by applying a ± 5 Voltage sweep between the two endings of the fluidic system and recording the current. For clarity we chose the three curves displayed. The red one is the I-V curve in single phase flow and the others are measure in bubble flow. All of them are linear so that we could consider the fluidic resistance in all cases as a normal (Ohmic) resistance.
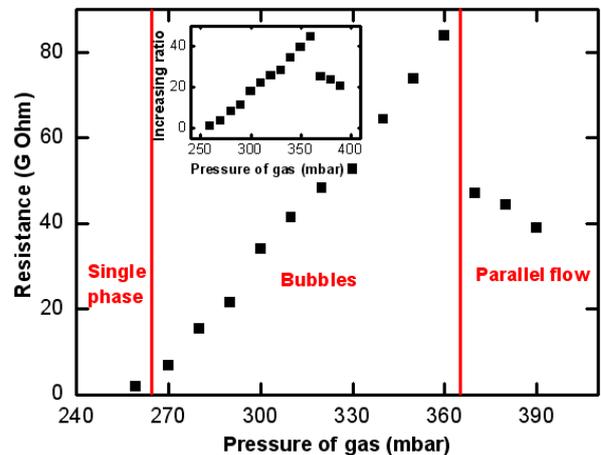

Figure 8 The fluidic resistance could be enhanced more than 40 times larger by injecting gas bubbles.

By linear-fit of the I-V curves, we obtain the fluidic resistance. Since the tubing could be made to be as short as technically possible, we could just focus on the resistance of device (including chip and outlet tubing). By injecting bubbles, the resistance is seen to increase strongly. With increasing gas pressure, more and more bubbles were injected into the liquid channel, causing a gradual resistance increase. The maximum enhancement ratio reached a value 45 times larger than in single phase flow. If we increased the

gas pressure further, parallel flow occurred, causing a continuous water column and decreasing the resistance again.
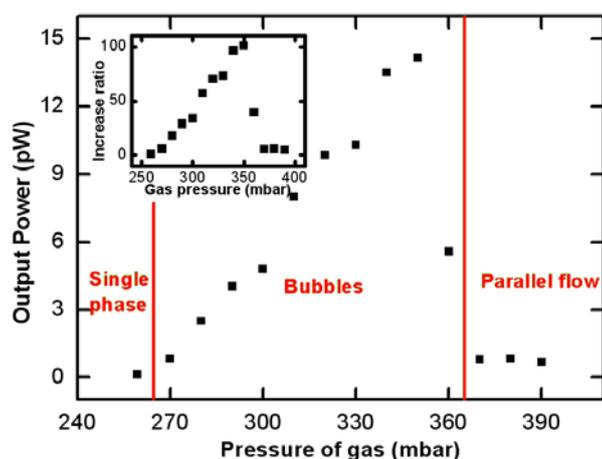

Figure 9 The output power could be enhanced more than 100 times by two phase flow compared to single phase flow.

After measurement both the streaming current and fluidic resistance, we could calculate the output power by equation (2). The increase in the ratio of two-phase and single phase power is shown in the inset. By creating bubble flow, the output power could be enhanced over 100 times compared to single phase flow. The output power for a single channel could almost reach 15 pW. In parallel flow, the output power dropped down obviously.

DISCUSSION

The energy conversion efficiency is defined by ratio of output power and input power. The conversion efficiency is another important performance characteristic for an energy conversion system. In order to know the input power, we need to know both the liquid and gas pressure drop and volume flow. At present we are working at establishing both.

In our experiment, when the gas pressure was close to the transition point from bubble to parallel flow (gas pressure = 360), the streaming current dropped down strongly while the resistance still kept growing. At present we cannot explain this phenomenon, but possibly there is a transition point where both gas bubble flow and parallel flow sequentially occur. Hence, the streaming current decreased due to the introduction of parallel flow, but the amount of gas bubbles was still large enough to dominate the resistance so that the resistance still increased.

CONCLUSION

We successfully showed the generation of streaming current in a two phase flow system; we showed that the output power could be enhanced over 100 times compared to single phase flow at the same water pressure drop; the output power enhancement

thereby depended on the amount of gas bubbles and gas pressure.

OUTLOOK

The enhancement of resistance is quite important for energy conversion. Therefore a square or rectangular channel as we used is not the best solution. The gutter flow in such systems still provides a shortcut for current and decreases the resistance. If we could use a cylindrical channel instead of a rectangular channel, the gutter will disappear and thin water film will be left instead. The total cross-sectional area occupied by solution will therefore decrease quite a lot. As a result, by changing for round channel, we expect to obtain higher enhancement ratio of output power at the same water pressure.

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