# Micropumping by Directional Growth and Hydrophobic Venting of Bubbles

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## ABSTRACT

This paper reports a new micropumping mechanism that combines directional bubble growth and symmetric bubble removal for a net liquid flow. By employing the recent hydrophobic venting technique, the problem of slow bubble collapse is solved and the removal of insoluble gas bubble is enabled. An electrochemical (i.e., electrolysis) bubble pump is built and tested to prove the concept. An open-loop pump produces the maximum flow rate of 65nL/s and the maximum static pumping pressure of 195 Pa, using 14 mW of input power, about an order lower than most reported micro pumps using thermal bubbles. A closed-loop pump circulates at the flow rate of 4.5-13.5 nL/s with input power of 2-85 mW. Variable flow rate is demonstrated by adjusting the input power.

## 1. INTRODUCTION

Bubble-driven valve-less micropumps [1, 2] are attractive for microfluidics. Compared to micromechanical pumps with moving valves [3], their fabrication is simpler and reliability is generally higher, due to the absence of wear and tear. However, thermal generation of bubbles (boiling), the most common bubble-actuation method, is "energy hungry" [4] due to the dramatic heat loss in microscale. On the other hand, condensation of vapor bubbles, , a far slower process than boiling, dominates the maximum achievable actuation frequency [5]. Prompt energy dissipation is actually desired in this step. Therefore, thermal insulation to save energy is not acceptable. As for other bubble generation approaches, removal of insoluble gas bubble from a sealed device is even harder, if possible at all [6, 7]. This difficulty prohibits the bubble-driven pumps from using other bubble generation methods than boiling, e.g., injection [8] that is cleaner or electrolysis that is energetically more efficient than heating. As a result, most bubble-driven pumps are made open (i.e., more like dispensers), so that the bubbles are expelled with liquid [5, 8]. There is no bubble-driven pump suitable for a closed fluidic device on a portable (i.e., energy efficient) system like a micro Direct Methanol Fuel Cell (μDMFC). In order to explore more gas generation methods for micro bubble-driven pumps, an omnivorous bubble removal method is desired. In this paper, a new pumping mechanism is introduced by using a hydrophobic nano-porous venting membrane [9] to breathe out virtually any kind of gas bubble. The concept is implemented by an electrochemical bubble-driven micropump; both open-loop liquid delivery and close-loop liquid circulation are demonstrated. A Similar pump configuration can be easily applied to enable bubble driven micro pumps with other gas sources, such as heating, electrolysis, injection, chemical reaction and ultrasonic cavitation. Therefore, the concerns of specific applications (e.g. energy efficiency, thermal sensitivity, bio-compatibility, adjustable flow rate), can be addressed by the flexibility of available gas sources.

## 2. PUMPING PRINCIPLE

The general concept is schematically described in Figure 1. To simplify the analysis, a pumping cycle with a single bubble is divided into three steps:

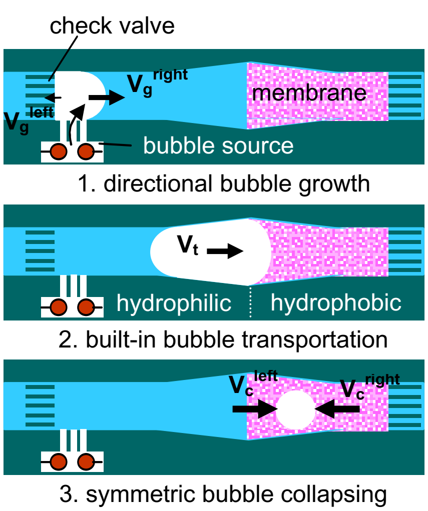


***Figure 1.*** *The concept of pumping*

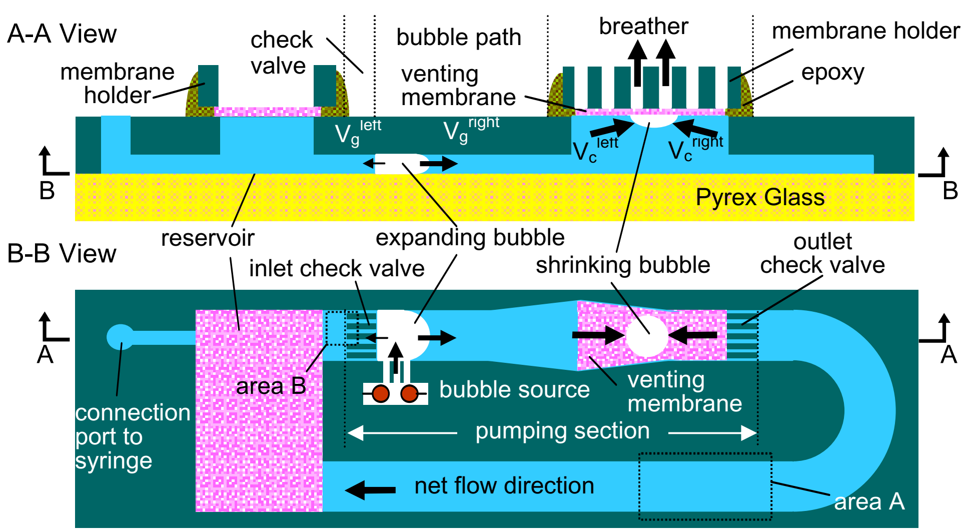


***Figure 2.*** *Pump loop configuration*

(1) When a bubble grows in a channel (e.g., by electrolysis) adjacent to a screen of relatively narrower channels (check valve), expansion of the meniscus is hindered by the check valve on the left so that the bubble only grows to the right and pushes the liquid rightward. (2) The bubble in the diverging hydrophilic channel tends to move to the right (the wider side) by Laplace pressure. Once the bubble reaches the hydrophobic nanoporous membrane, the bubble is drawn into the region. (3) The bubble is vented out through the membrane and the liquid fills into the section symmetrically. A pump cycle is thus completed and a net pumping to the right is achieved.

Although this concept is illustrated with a single bubble, coexistence of multiple bubbles is acceptable for pumping, as long as the venting rate of the membrane is sufficient to remove all the bubbles promptly. Therefore, continuous bubble generation can be used for the bubble-driven micropumps reported here. This is different from traditional thermal-bubble-driven pumps, which use pulse power input to generate a vapor bubble and then turn off the heater to wait for bubble collapse. Tolerance of constant bubble generation without precise modulation can significantly simplify the driving circuit (i.e. reduce power consumption) and enable the pump's applications where precise regulation of bubble generation is difficult (e.g. chemical reaction).

This pumping concept is implemented in a closed pump loop (figure 2) in order to demonstrate continuous liquid movement and eliminate uncertainties the open ends of microchannels may pose, such as evaporation and effect of menisci. The pumping concept is also implemented in open microchannels for pumping characterization, which is difficult to be performed accurately in a closed loop.

## 3. ELECTROCHEMICAL BUBBLE PUMP

An electrochemical bubble pump, using electrolysis as the bubble source, is designed to prove the concept. The finished device is schematically illustrated in Figure 2. The pump chip and membrane holders are both fabricated from the same 400 μm-thick (100) silicon wafer by DRIE etching. In the pump chip, the microchannels of the breather, the reservoir and the connection port are etched through, while other parts of the pump loop are protected by polyimide tape once the DRIE etching has reached the desired depth. After DRIE and subsequent Piranha cleaning, the pump chip is anodically bonded to a piece of Pyrex® glass. Then the venting membranes are sandwiched between the pump chip and membrane holders, with the aid of epoxy adhesive, to form channels. During the epoxy adhesive bonding, through-holes on both chips are used as alignment marks. The alignment is assisted by strong illumination from below. Details of this alignment and bonding technique are described in [9]. Two platinum wires are inserted into the "bubble source" position as the electrodes for electrolysis. The finished pump loop is subsequently connected to a syringe via a set of UpChurch® tubing/fitting/adapter apparatus.

Before being tested, the pump loop is carefully pre-filled with $Na_2SO_4$ water solution as the working fluid. The presence of ions can lower the voltage drop between the anode and cathode and therefore facilitate the electrochemical reaction. Since the reservoir is covered by the venting membrane, the gas bubbles accidentally introduced during the filling can be breathed out. The pump loop can thus be kept bubble-free to avoid bubble-clogging problems. DC voltage is applied on the two platinum electrodes after the pump loop is ready. Substantial electrolysis is observed when the voltage is higher than 10 V, although the theoretical minimum voltage for electrolysis of water is 1.23V. The main reason for this relatively high operation voltage is attributed to the distance between the two electrodes (~2 mm). Much lower operation voltage can be expected if the electrodes are lithographically integrated in the future. Bubble motion and pumping process in the real device is demonstrated in Figure 3, with an operation voltage of 20 V. Unlike the boiling/condensation cycle for thermal bubbles, electrochemical bubble generation doesn't have to be halted during the bubble collapse. Accordingly, DC voltage instead of pulse is used for continuous generation of gas bubbles. In this way, pumping efficiency can be improved and the driven circuit can be simplified.

a. 0s

b. 2.5s

c. 3.3s

d. 3.4s

e. 4.5s

f. 8.1s

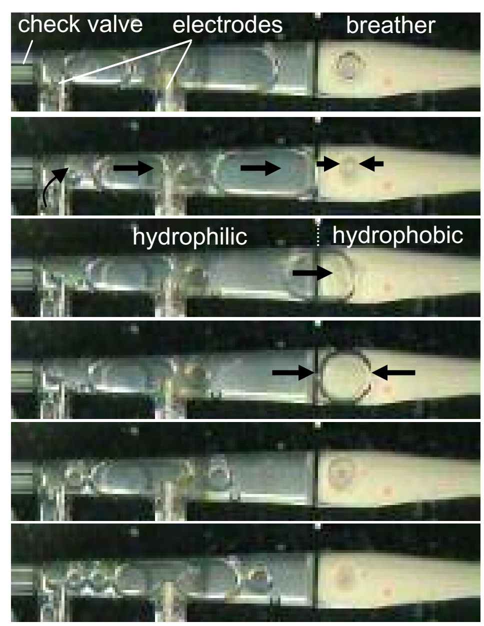


***Figure 3.*** *Bubble motion in pumping section*

Fluorescent particles (4 μm in diameter) are mixed into the working fluid to visualize the flow. The particle motion can be observed clearly as Figure 4 demonstrates, with voltage input under 20 V. The flow is pulsatile in nature as expected, but definite net flow is observed to the designed direction. Particle clusters can be distinguished easily and used to measure the flow velocity at different operation voltages. Since the cross-sectional area of the microchannel is 600 μm × 300 μm, the volumetric flow rate can be calculated.

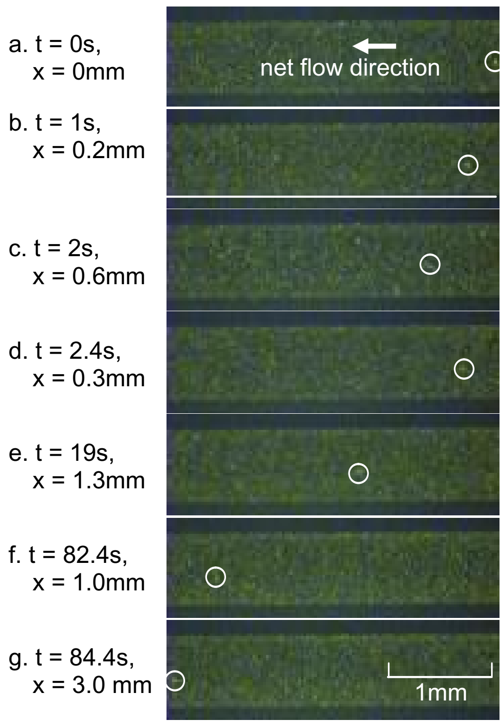


***Figure 4.*** *Florescent particle velometry (area A in Figure 2)*

The characterization results of the pump loop are summarized in Table 1. This result indicates that the flow rate is well controllled by power input and suggests a flow rate adjustable micro bubble pump in a broad flow range. The reason behind this feature is that the bubble generation rate is theoretically proportional to the current. In comparison, generation of thermal bubbles is affected by complicated heat transfer paths and difficult to control with power input.

***Table 1.*** *Power input vs. volume flow rate in pump loop*

| Voltage (V) | 10 | 20 | 30 | 40 |
|---|---|---|---|---|
| Average Current (mA) | 0.20 | 0.69 | 1.32 | 2.13 |
| Average Power (mW) | 2.0 | 13.8 | 39.6 | 85.2 |
| Particle Velocity (μm/s) | 25 | 33 | 50 | 75 |
| Volume flow rate* (nL/s) | 4.5 | 5.9 | 9.0 | 13.5 |

In order to verify the fluid circulation more concretely, the fluid uptake from the reservoir was observed through a fluorescent microscope, as Figure 5 shows. The flow close to the inlet of the check valve was found to be much steadier (unidirectional with occasional stops) than the flow in the downstream microchannel of the bubble pump (figure 4). This different flow pattern in the same fluidic loop is reasonable because the check valve effectively blocked the leftward bubble growth, and the flexible venting membrane buffered the interaction of the two isolated segments of liquid. Unidirectional fluid uptake implies that the fresh liquid (reactant from the reservoir) can be supplied to the microreactor promptly.

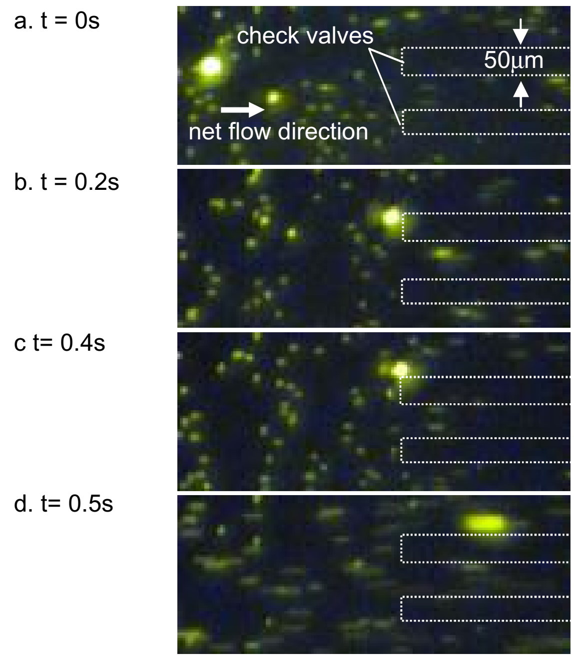


***Figure 5.*** *Fluid uptake from reservoir (area B in Figure 2)*

An open loop pump is fabricated with a similar procedure, whereby the loop is substituted with a straight channel with a pumping section, as Figure 6 illustrates. Through-holes are etched at the two ends of this straight channel, with two glass tubes attached to them by epoxy. Working fluid (water with $Na_2SO_4$) is introduced slowly from the top of the inlet tube by syringe. After the meniscus of the outlet tube rises to the same height as the inlet meniscus and stabilizes, DC voltage is applied and pumping starts. The movement of the outlet meniscus during the whole process is recorded by a digital video system.

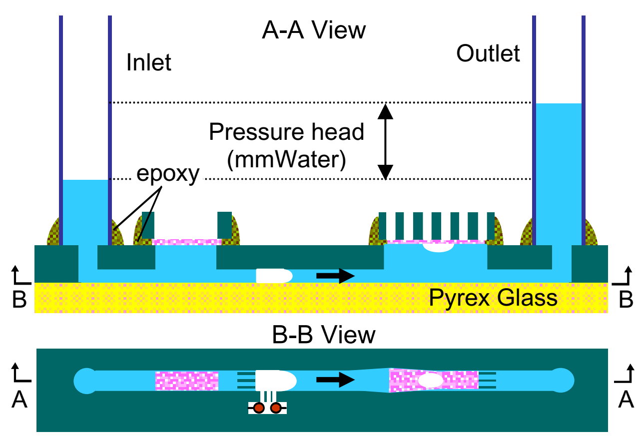


***Figure 6.*** *Open loop test*

From the video clips, pumping rate can be calculated by multiplying the meniscus velocity by cross-sectional area of the tube. The pressure head at any given time can be determined from the height difference of the two meniscuses. The measured relationship between the flow rate and the pressure head is shown in Figure 7. When the pump just starts to work, the two meniscuses are at the same height. Since the pressure head is close to zero, the maximum flow rate is achieved at this point. However, the first data point of every experiment is discarded because the pumping is not yet stabilized and the flow rate before the first bubble is breathed out only reflects the bubble growth rate. The pump rate against ~30 psi of back pressure was measured to range between 20-65 nl/s. The static pumping pressure, obtained when the outlet meniscus stays at the same level for more than 5 min, which means the flow rate is about zero, was measured to range between 120-195 Pa.

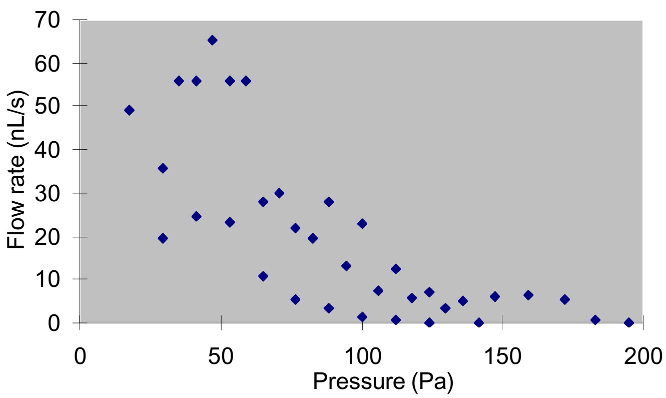


***Figure 7.*** *Flow rate vs. pressure head in open loop test*

## 4. CONCLUSIONS AND FUTURE WORK

The electrochemical bubble pump introduced in this paper is demonstrated to circulate liquid in a closed pump loop as well as deliver liquid against back pressures. The operation power is substantially lower than the reported power input of thermally actuated micro bubble pumps. The fast venting rate allows the usage of DC voltage instead of pulse, which can simplify the driven circuit. Volumetric flow rate can be adjusted by power input in a broad range. However, special caution should be made to make sure that the reactant will not be affected by the electrochemical reaction of bubble generation before this pump is adopted for specific applications, for example, bioMEMS.

The operation power can be decreased further by decreasing the distance between the two electrodes. Other bubble generation methods for this pumping principle will be investigated to provide suitable micro pumps for different applications.

## 5. ACKNOWLEDGEMENT

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