A COMPARATIVE STUDY OF ELECTROLYSIS AND BOILING FOR BUBBLE-DRIVEN MICROACTUATIONS

De-Sheng Meng*, Yongho "Sungtaek" Ju and Chang-Jin “CJ” Kim
Mechanical and Aerospace Engineering Department
University of California, Los Angeles (UCLA), U.S.A.
*Email: desheng@seas.ucla.edu

ABSTRACT

Thermal generation (i.e., boiling) has been the most common bubble-generation method for bubble-driven microactuation, followed by the recent interests in electrochemical generation (i.e., electrolysis). This paper studies energy consumption of the two approaches through systematic experiments and simple thermal models. The objective is to start building a design guideline for the bubble-driven micro actuators in microfluidic systems. The results indicate the power consumption of electrolysis microactuation is several orders of magnitude lower than that of boiling. Analysis of controllability, bio-compatibility and scaling effect also shows the advantages of electrolysis. However, removal of bubbles is more problematic for electrolysis than that for thermal bubbles.

Keywords: bubble microactuation, boiling, electrolysis.

INTRODUCTION

Actuation by mechanical solid moving parts has its own challenges in the microscale, such as long-term reliability, stiction problems, elaborate fabrication processes, and large-scale integration. Accordingly, actuation without mechanical moving parts has attracted significant interests in MEMS. The interest has further been amplified by the demands to handle biomedical liquid samples in micro total analysis systems (µTAS). Gas bubbles have been considered as promising micro actuators without solid moving parts [1, 2]. Bubble actuators use surface tension, the dominant force in the microscale [3], to drive micro devices. Compared with electroosmotic or electrohydrodynamic actuations, gas bubble actuation is less demanding on the properties of liquid.

Thermal generation (i.e., boiling) of vapor bubbles has been the most common due to its simple structure (electrical heater) and convenient bubble reduction (natural condensation). However, several drawbacks limit the application of thermal bubble actuation in microfluidic devices, such as µTAS and µDMFC (micro Direct Methanol Fuel Cell). Firstly, thermal generation of a microscopic gas bubble is an “energy hungry” process [4]. Secondly, it is difficult to precisely predict or control the bubble growth rate (actuation rate). Thirdly, overheating for boiling denatures most biological large molecules (e.g. DNA and protein). Fourthly, the collapsing (condensation) of thermal bubbles desires a quick heat dissipation, which in turn increases energy consumption. Heat dissipation tends to take the priority, because condensation, being far slower than boiling, is usually the bottle-neck of actuation speed or pumping rate.

Another option of bubble-driven actuation is electrolysis of water (electrochemical actuation). Four orders-of-magnitude higher power efficiency has been achieved by replacing boiling with electrolysis in similar devices [5]. Electrolytic bubble actuation has also been reported to manipulate living cells [6], which is difficult for thermal bubble actuations. The main problem of electrolytic bubble actuation is the removal of essentially insoluble gas (H$_2$ and O$_2$). The slow removal of the electrolytic bubble has recently been addressed by catalyzed reaction [7] and hydrophobic venting [8]. The latter can remove the gas bubbles even faster than the collapsing of vapor bubbles. With the electrochemically-generated bubbles finally becoming viable for microactuation, the time is ripe to compare electrochemical bubbles and thermal bubbles for the development of bubble-driven micro devices.

This paper, through simple modeling and controlled experiments, intends to address the following three aspects of the two bubble actuation approaches: 1. minimum power consumption; 2. relationship between power input and actuation speed; 3. scaling effect of power consumption. The result can therefore provide a guideline for the design of future micro bubble actuators.

DEFINITIONS AND ASSUMPTIONS

Considering the diverse applications of bubble actuators, it is imperative to focus on the most important factors in a simplified scenario. It is decided that bubble generation in a bulk liquid environment (DI water) by electrolysis/boiling will be analyzed first. In spite of the
simplifications, the results will provide information for the study of more complex configurations, e.g. bubble actuators in a microchannel. Bubble collapsing will not be discussed here because it depends on the specific gas removal techniques and shows little difference if a universal bubble removal approach (i.e. hydrophobic venting [8]) is applied.

The size of bubble-driven microactuators typically varies from tens of micrometers to several millimeters. Circular actuators with a radius of 120µm are used for the first batch of actuators in this comparative study, schematically shown in figure 1. Two kinds of substrate are tested: glass and SiO₂/Si (insulator thickness is 0.13µm).

The experiments always start with increasing voltage/power input from zero until bubble generation is observed. The power is hence recorded as the minimum power requirement for bubble generation. After that, several data points are acquired to know the voltage, current and corresponding bubble growth rate in volume per second. The measured bubble growth rate (actuation rate) will be put into the models to calculate the theoretical power requirements, which can then be compared with the experimental data to validate the theoretical models.

The average gas (H₂ and O₂) bubble growth rate \( \Delta V/\Delta t \) is determined by the current consumed by electrochemical bubble generation

\[
\frac{\Delta V_{\text{bubble}}}{\Delta t} = \frac{I}{C_e}
\]

where \( C_e = 5.2 \times 10^6 \text{ A s/m}^2 \) is a constant under the controlled experimental conditions (1atm, 300K).

The minimum voltage input can be determined by the Nernst equation as 1.23V for DI water. The actual voltage is higher than this value, depending on both ion concentration and electrode distance. The voltage of electrolysis is also experimentally measured. Table 1 summarizes the experimental results and power consumption calculated from the model.

**Table 1. Measured data for electrochemical actuation**

<table>
<thead>
<tr>
<th>voltage (volt)</th>
<th>3.2</th>
<th>4.0</th>
<th>5.0</th>
<th>6.0</th>
<th>8.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>current (µA)</td>
<td>4.9</td>
<td>16</td>
<td>43</td>
<td>70</td>
<td>140</td>
</tr>
<tr>
<td>power (µW)</td>
<td>16</td>
<td>64</td>
<td>220</td>
<td>420</td>
<td>1100</td>
</tr>
<tr>
<td>bubble growth rate ( \left(10^{-13} \text{ m}^3/\text{s}\right) )</td>
<td>2.0</td>
<td>5.2</td>
<td>18</td>
<td>26</td>
<td>49</td>
</tr>
<tr>
<td>theoretical power (µW)</td>
<td>3.3</td>
<td>11</td>
<td>48</td>
<td>84</td>
<td>210</td>
</tr>
</tbody>
</table>

* measured in glass substrate, Si substrate shows similar data

The measured power consumptions are always higher (~5 times) than the theoretical predictions. This is because an even larger part of power (~80%) is consumed in the liquid circuit between the two electrodes. This power loss can be reduced by decreasing the electrode distance or increasing the ion concentration. However, a linear relationship between the current and actuation speed is observed, as figure 2 shows. This implies that the actuation speed can be both measured from and controlled by the current input. This unique feature of electrochemical bubble actuation can be employed to get a stable actuation speed by using a constant-current power source or feedback control circuit.
into substrate ($P_{sb}$) and heat loss into water ($P_{wt}$). $P_{evp}$ can be estimated from the average bubble growth rate:

$$P_{evp} = C_{evp} \frac{\Delta V}{\Delta t}$$

(2)

where $C_{evp} = 1.34 \times 10^6 J/m^3$ under the normal atmospheric condition.

Heat conduction into the substrate ($P_{sb}$) and water ($P_{wt}$) are considered separately. $P_{sb}$ can be estimated as:

$$P_{sb} = \alpha K_{sb} \cdot R_0 \cdot (T_h - T_o)$$

(3)

from two-dimensional steady state heat conduction analysis [9]. Here $P_{sb}$ is the thermal conductivity of the substrate and $R_0$ is the heater radius. The proportionality factor $\alpha$ is 4 if the substrate thickness is much greater than $R_0$.

For a homogeneous substrate (e.g., glass), $P_{sb}$ can be calculated from equation (3) directly. If there is an isolation layer on the substrate (e.g., $SiO_2$ film on a Si substrate), the two-layer substrate can be modeled using two thermal resistances connected in series. Heat loss on this substrate can be calculated as:

$$P_{sb} = K'_{sb} \cdot R_0 \cdot (T_h - T_o)$$

(4)

where

$$1/K'_{sb} = \frac{h}{\pi R_0 K_{in}} + \frac{1}{\alpha K_{sb}}$$

is the equivalent thermal resistance. Heat loss into the water ($P_{wt}$) can be calculated by using an equation similar to equation (3):

$$P_{wt} = 4K_{wt} \cdot R_0 \cdot (T_h - T_o)$$

(5)

The total power consumption can then be estimated as:

$$P_{tot} = P_{evp} + P_{sb} + P_{wt}$$

(6)

$$T_h = 100^oC$$

$$R_0 >> h$$

Our approximate model does not take into account transient heat transfer in the water and cannot capture the actuation speed dependence. More detailed models must take into account transient convective heat transfer in the water and finite superheating in the heater. The amplitude and temporal shape of power input affect the temperature distribution in the water and thus change the actuation speed, as observed in the experiments. But this relationship is far less straightforward than the actuation-speed/current relationship in electrolysis. More importantly, the boiling phenomenon can be affected by both surface condition (prone to fabrication variations) and heat transfer boundary conditions (prone to environmental changes). Precise control of the thermal bubble actuation speed is much more difficult than electrolysis.

**DISCUSSIONS AND CONCLUSIONS**

**Minimum power consumption:** For the specific design of actuators, electrolysis gas bubbles can be generated with tens of $\mu$W, while the thermal vapor bubbles require hundreds of mW (glass substrate) or even several W ($SiO_2$/Si substrate). Even if the substrate is a near-perfect insulator (e.g., device on a membrane), thermal bubble generation still consumes tens of mW to heat the water.

**Actuation speed vs. power consumption:** The experimental data indicate a wider range of actuation speed for electrolysis, with only $10^2$-$10^3$ of the power consumption of boiling, as figure 4 shows. It is also confirmed that the speed of electrochemical bubble

**Table 2. Measured data for thermal actuation**

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Voltage (V)</th>
<th>Power (mW)</th>
<th>Bubble growth rate ($10^{-13} m^3/s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass (1.5mm)</td>
<td>3.9</td>
<td>180</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>240</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>280</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td>366</td>
<td>28</td>
</tr>
<tr>
<td>SiO$_2$(0.13µm)+Si (500µm)</td>
<td>12.8</td>
<td>2500</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>3000</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>3400</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>4300</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>5900</td>
<td>36</td>
</tr>
</tbody>
</table>

**Figure 3. Model for thermal bubble actuation**

Our model predicts that $P_{sb} > P_{wt} > P_{evp}$ for both glass and $SiO_2$/Si substrates. $P_{sb}$ is estimated to be of the order of 100 mW for glass substrates and of the order of 1000 mW for $SiO_2$/Si substrates. These values are consistent with the experimental results listed in table 2. $P_{evp}$ is much smaller and is of the order of $\mu$W. This suggests that power consumption in thermal bubble actuation is dominated by heat loss into the substrate and not by phase change.
actuation can be both measured from and controlled by the current input. Conversely, thermal bubble generation lacks this feature.

![Graph showing relation between power and growth rate for different actuation methods]

**Figure 4.** Average actuation speed vs. power consumption

**Scaling effect of power consumption:** The simple models make it easier to predict the scaling effect of power consumption. The existing data can therefore be used to provide information for smaller or larger actuators. The characteristic length ($L$) in scaling analysis can be defined as the radius of actuators or bubble ($R_0$).

Since $V \propto L^1$, equation (1) tells the scaling effect of electrolysis current: $I \propto L^3$. If the same voltage ($v$) is used for different electrode sizes, the power consumption is: $P_{elc} = Iv \propto L^3$. On the other hand, considering that $P_{evp}$ can be neglected, equations (2), (5) and (6) indicate the scaling effect of thermal bubble actuation: $P_{boil} \propto L$. Therefore, electrolysis is expected to become more efficient than boiling for smaller actuation bubbles.

In terms of power efficiency, controllability, bio-compatibility and miniaturization potential, electrolysis actuation is a better approach than thermal bubble actuation. However, a microactuation mechanism using electrolytic bubbles most likely would require a provision to remove the bubbles, increasing the complexity of devices. Such aspects other than power consumption should also be considered to decide an appropriate bubble generation mechanism for a specific application.

**ACKNOWLEDGEMENT**

This work has been supported by DARPA Micro Power Generation Program. Discussions with Professors C.-M. Ho, C. Y. Wang, X. Zhang and X. Zhong as well as Mr. J. Jenkins are greatly appreciated.

**References:**


