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# Bubble time-of-flight: A simple method for measuring microliter per minute flows without calibration

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ABSTRACT

Monitoring liquid flow at microliter per minute (μL/min) rates is important for many lab-on-a-chip applications. Several technologies have been investigated to achieve this resolution, most of which require expensive detection systems and extensive calibration. Those technologies also rely on phenomena impacted by diffusion (e.g., heat pulses) that quickly lose accuracy as flow rates decrease. An alternative method, bubble time-of-flight, surmounts the limitations of diffusion by tracking the flow with bubbles. This method also has the advantage of not requiring calibration or complex sensing circuitry to accurately measure flow rates. We demonstrate this method with a device that uses thermoresisitive sensors to detect the passage of bubbles between two points. This device is able to measure flows from 100 to 1 μL/min. The accuracy of the system increases as flow rates decrease such that the low end uncertainty is 1% (±0.01 μL/min). We also demonstrate the feasibility of measurements in the sub 100 nL/min range by using a single sensor.



## 1. Introduction

The measurement of microliter per minute (μL/min) liquid flows is important to many lab-on-a-chip and low-dose drug delivery systems. Consequently, the development of an accurate, inexpensive flow sensor has been an active area of research for over four decades [1]. During this time, several sensing modalities have been tested on the microscale. Table 1 summarizes the lower limit and range of devices created to measure these small flows. Clearly, several technologies meet the accuracy requirements of many microfluidic applications. However, with the exception of thermal time-of-flight, these technologies all rely on an analog measurement of a fluid property (e.g., heat conductivity, inductance). This necessitates a calibration step for every fluid under test as well as a high-sensitivity sensing circuitry.

Thermal time-of-flight (TOF) avoids the need for calibration by measuring the time required for a heat pulse to travel a fixed distance down a microchannel. As long as the pulse is detectable, the properties of the fluid are irrelevant. However, thermal diffusion on the microscale rapidly dissipates pulses, resulting in a trade-off between the amount of heat injected into each pulse and the lower limit of detectable flows. For practical purposes, this limits these devices to flow rates above 1 μL/min and to fluids that are insensitive to heating.

We propose an alternative method for flow detection called bubble time-of-flight (BTOF) where thermal pulses are replaced with bubbles [9]. As shown schematically in Fig. 1, bubbles are introduced into a channel to track the flow of fluid. By measuring the time taken to travel from one point to the other, a TOF can be calculated. Dividing the cross-sectional area of the channel by the TOF gives the flow rate. Because bubbles maintain coherence due to surface tension, the range of detectable fluid flow is not limited by diffusion. Heating of the flow is not inherent to the process, making BTOF ideal for temperature-sensitive fluids. As with thermal time-of-flight, the BTOF method does not rely on an analog measurement of any fluid property. Thus, this method does not require calibration or complex sensing circuitry.

## 2. Theory

For a BTOF device to work properly, bubbles must travel at the same rate as the bulk fluid, and the device must be able to detect those bubbles reliably. We address both issues in turn.

### 2.1. Bubbles as flow markers

Experiments in capillaries have shown that bubbles do not necessarily travel at the same rate as the bulk fluid [10]. Fluid can flow past a bubble instead of pushing it forward—causing the bubble

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**Table 1**
Comparison of fluid flow sensing modalities used in MEMS-scale fluid flow sensors.

| Method | Lower limit [μL/min] | Range [Db] | Reference |
|---|---|---|---|
| Anemometry | 0.07 | 13.1 | [2] |
| Calorimetry | 1.0 | 10.0 | [3] |
| Coriolis | 0.02 | 27.0 | [4] |
| Doppler | N/A | N/A | [5] |
| Electromagnetic | 0.1 | 14.8 | [6] |
| Momentum | 5.0 | 13.0 | [7] |
| Pressure | 0.5 | 10.0 | [8] |
| Thermal time-of-flight | 1.0 | 14.8 | [3] |

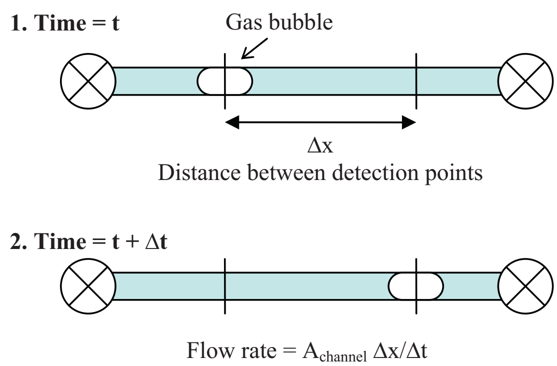


**Fig. 1.** Bubble time-of-flight concept. By measuring the time, $\Delta t$, required for a bubble to travel between two points separated by a known distance, $\Delta x$, a bubble velocity is obtained. If the bubble is sufficiently large that it moves at the same rate as the flow, the flow rate can be calculated by multiplying the bubbles velocity by the cross-sectional area of the channel $A_{\text{channel}}$.

velocity to be less than the bulk fluid velocity. In square channels, this problem is exacerbated by the fluidic path created in the corners of the channel (Fig. 2).

This phenomenon has been examined analytically [11–13], numerically [14], and experimentally [11,15]. Wong and coworkers showed that in a microchannel with polygonal cross-section, the fluid rate of the bulk of the fluid, $Q_{\text{bulk}}$, and the flow of the fluid through the corners, $Q_{\text{corners}}$, can be expressed as [12]:

$$Q_{\text{bulk}} = A_{\text{T}}(ua^2) \tag{1}$$

$$Q_{\text{corner}} = ua^2 \frac{\kappa C_{\text{D}}}{A_{\text{T}} \cdot (L/a)} Ca^{-1/3} \tag{2}$$

where $u$ is the mean velocity of the fluid, $a$ is the radius of the largest inscribed sphere in the capillary (half the width for a square channel), $A_T$ is the non-dimensional frontal area of the bubble (3.76 for square channels), $C_D$ and $\kappa$ are coefficients defined by Wong and coworkers related to the capillary geometry (for square channels, $7.22 \times 10^{-4}$ and 13.35 respectively), $L$ is the length of the bubble, and $Ca$ is the capillary number given by:

$$Ca = \frac{u\mu}{\sigma} \tag{3}$$

where $\sigma$ is the surface tension between the gas and liquid phases, and $\mu$ is the dynamic viscosity of the liquid.

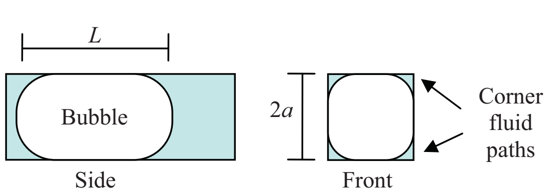


**Fig. 2.** Fluidic path around bubble in square channel. A bubble that spans the channel (i.e., its length, $L$, is greater than the width of the channel, $2a$) will never completely wet the walls creating four fluidic paths in the corners of the channel.

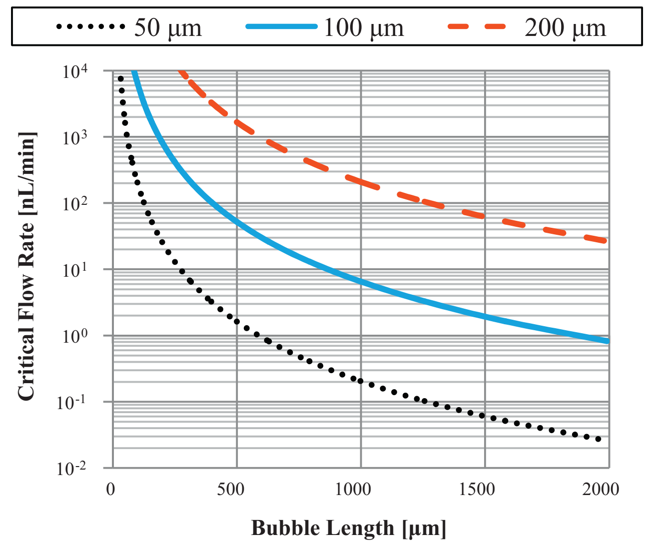


**Fig. 3.** Minimum bubble length to insure that bubble velocity is within 1% for bulk fluid velocity for bubbles moving in square channels filled with water at STP. Each line represent a different channel width.

These terms allow us to define the intrinsic error, $Er_{\text{b}}$, due to flow past the bubble:

$$Er_{\text{b}} = \frac{Q_{\text{corner}}}{Q_{\text{bulk}}} = \frac{\kappa C_D}{A_{\text{T}}^2 \cdot (L/a)} Ca^{-1/3} \tag{4}$$

Combining (1), (3), and (4) and defining a minimum bulk flow rate, $Q_{\text{min}}$, we get:

$$Er_{\text{b}} = \frac{\kappa C_{\text{D}}}{A_{\text{T}}^2 \cdot (L/a)} \left[\frac{Q_{\text{min}}\mu}{A_{\text{T}} a^2 \sigma}\right]^{-1/3} \tag{5}$$

Solving for $Q_{\text{min}}$ gives:

$$Q_{\text{min}} = \frac{1}{Er_{\text{b}}^3} \left[\frac{(\kappa C_{\text{D}})^3}{A_{\text{T}}^5}\right] \left[\frac{\sigma}{\mu}\right] \frac{a^5}{L^3} \tag{6}$$

Thus, we have a term that defines the smallest bulk flow rate for a given acceptable error. The first bracketed term is related solely to geometry and equals $1.20 \times 10^{-9}$ for a square channel. The value of $Q_{\text{min}}$ is relatively insensitive to fluid properties, which are grouped in the second bracketed term. Instead, $Q_{\text{min}}$ scales with $a^5$ and $L^{-3}$, making channel width and bubble length significant. Lastly, $Er_{\text{b}}$ and $L$ affect $Q_{\text{min}}$ equally, meaning an increase in bubble length will result in a corresponding decrease in $Er_{\text{b}}$.

Fig. 3 shows the minimum flow rates required to guarantee a maximum error of 1% for water at standard temperature and pressure conditions (STP) in a square channel of varying width. Water is a limiting case because it has a large ratio of $\sigma$ to $\mu$ compared to other fluids. For a 100 μm × 100 μm channel, a 500 μm long bubble will travel to within 1% of the fluid velocity for flows down to ~50 nL/min.

### 2.2. Thermoresistive bubble detection

Thermoresistive bubble detection is similar to traditional hotwire anemometry in that the change in the temperature of a heated resistor is used to detect changes in the fluid flow over the resistor. However, instead of correlating flow rates to how much heat is dissipated by the fluid, the difference in thermal conductivity between the gas in a bubble and the fluid surrounding it (on the order of 10–50) leads to a change in resistor temperature [16]. This temperature change leads to a change in electrical conductivity