Two-terminal longitudinal hotwire sensor for monitoring the position and speed of advancing liquid fronts in microfluidic channels

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(Received 23 June 2005; accepted 2 February 2006; published online 9 March 2006)

We report a simple and practical sensor for monitoring both the absolute position and advancing speed of liquid front in a microfluidic channel. The sensor consists of a longitudinal hot wire element—a two-terminal electrical device, with its length spanning the entire channel. The design, materials, fabrication method, and use of this sensor are extremely simple. Characterization results are presented. © 2006 American Institute of Physics. [DOI: 10.1063/1.2180447]

Today, microfluidic laboratory-on-a-chip (LOC) devices are being investigated for realizing biochemical detection protocols on chip. Microfluidic chips offer many potential advantages, including automation, reduction of reagent volume, acceleration of reaction processes, and miniaturization/portability. To confidently operate a microfluidic system and carry out complex biochemical protocols, it is imperative to incorporate sensors for feedback control and process monitoring/verification.

In this work, we focus on the task of identifying the position and speed of advancing liquid fronts in a plug flow situation, which is often encountered in lab chip applications. In macroscopic and manual bench-top assay protocols, the volume of liquid reagents is often large enough for direct visual observation. However, as the size of microchannels and volumes of reagents shrink, it becomes increasingly more difficult to measure the position of advancing liquid fronts and the speed of its movement. Such measurements are vital information to verify the functioning of a system. Simple tasks such as introducing liquid into an empty channel (priming) or knowing if the channel is emptied are not straightforward for microfluid channels. For example, channels may be blocked due to bubbles, particles, or hydrophobic wall conditions.

Flow measurement can be achieved by using optical detectors such as microscopes, optical fibers, and CCD chips. However, these solutions are not amenable to miniaturization, system simplification, and cost reduction. Additionally, the field-of-view of optical measurement systems is often too small to observe the process in a long microfluidic channel (e.g., often more than 1 mm long).

In order to continuously and accurately monitor the position of fluid fronts in a microchannel, conventional practice requires embedding a series of sensors with electrical output along the entire length of the channel with given intervals. For example, an array of micromachined pressure sensors has been integrated along a microchannel to monitor pressure distribution. (Note that the purpose of this sensor is not for measurement of velocity and position of liquid front.) However, the accuracy for position measurement using an array of sensors is limited and the complexity is high. For example, the use of many sensors increases the number of electrical terminals and wiring complexity.

We have designed a sensor that measures the absolute position and advancing speed of the liquid front movement. The operation principle, fabrication and packaging method, as well as testing results are discussed in the following.

The schematic diagram of the sensor is illustrated in Fig. 1. A resistive element made of a thin metal film traverses the length of the channel section of interest. We select a metal that offers finite temperature resistive sensitivity, i.e., its resistance is a function of the temperature. Many metal thin films satisfy this requirement, including gold, which is used in this case.

For small temperature fluctuations, the resistance of the resistive element, $R$, is related to its temperature $T$ according to

$$R = R_0 [1 + \alpha (T - T_0)],$$

where $R_0$ is the nominal resistance under a reference ambient temperature $T_0$ (e.g., room temperature), and $\alpha$ is the temperature coefficient of resistance (TCR) of the thermal element.

When a channel is in its initial unfilled state, the resistive element is surrounded on three sides by air and on one side by the substrate. The wire is slightly heated by passing a dc electric current. The temperature of the resistive element reaches an equilibrium point above the ambient ($T_0 + \delta T$). If

![FIG. 1. Longitudinal hot-wire sensor in a fluid channel. As the liquid fills along the channel, the resistance of the hotwire decreases linearly. The resistance value is proportional to the value of $x$, the length of the liquid filling.](image-url)
the media in the channel is homogenous (i.e., completely filled with air), the temperature of the wire is assumed to be uniform along the length of the channel ($L$).

As a liquid enters the channel from one end, air is displaced by liquid (Fig. 1). Consequently, a portion of the resistive element is surrounded by liquid instead of air. The liquid provides an increased rate of heat transfer (conduction as well as convection) compared to the ambient air, therefore changing the temperature of the resistive element locally. Specifically, the segment of the resistor overlapped with liquid will be cooler than the segment surrounded with air (assuming the liquid is at the room temperature). In fact, we assume that the liquid, with its high thermal conductivity and large thermal mass, forces the temperature of the section of the sensor to $T_0$.

Referring to Fig. 1, the resistance $R$ for the sensor can be modeled as the following:

$$R = R_x + R_{L-x} = \frac{x}{L} R_0 + \frac{L-x}{L} R_0[1 + \alpha(T - T_0)]$$

provided that the liquid being filled is at room temperature $T_0$. From Eq. (2), the resistance $R$ changes linearly from $R_0[1 + \alpha(T - T_0)]$ to $R_0$, as the liquid traverses the entire length of the channel (from $x=0$ to $L$).

By measuring the resistance of the two-terminal device, the length of the liquid body $x$, can be easily found. Further, by monitoring the change of the position $x$ with respect to time, the advancing speed of the liquid front can be accurately determined.

This time-resolved measurement of flow speed indirectly references position-time correspondence. It should be noted that various microfabricated flow rate sensors have been made in the past, based on a variety of principles including lift force,8,9 drag force,10,11 and thermal anemometry.12,13

Typical sensor output is shown in Fig. 3 when the liquid front is moving at a constant speed of 1.4 mm/s with 0.5 psi pressure applied at the inlet. At $t=1.2$ s, the liquid reaches the inlet of the channel segment with sensor. At $t=1.9$ s, the liquid reaches the end of the sensorized section. As expected, the output voltage linearly decreases as the liquid fills the channel with constant speed. The slope of the $V-t$ curve between $t=1.2$ s and $t=1.9$ s is a constant. Before $t=1.2$ s and beyond $t=1.9$ s, the voltage output does not change.

To test the accuracy of the sensor, we conducted the measurement at various flow speeds and compared with optical measurement. As shown in Fig. 4, the flow speeds measured from the sensor are accurate within the range of optical measurement error range of 30 ms. The highest velocity measured, 6500 µm/s, is considered a very high speed for liquid flow in microfluidic channels for many biochemical liquid handling tasks. We were able to obtain a match of the results at this speed.

![Figure 2](image1.png)

**FIG. 2.** (Left) Bridge circuit used to measure the resistance change in the sensor and hence its temperature. (Right) Infrared microscope image of the resistive sensor with bridge voltage of 2 V.

![Figure 3](image2.png)

**FIG. 3.** Voltages output drops linearly as the liquid fills the entire section of the channel. The slope in the graph between $t=1.2$ s and $t=1.9$ s indicates the liquid is moving at a constant speed.
The finite thermal response speed of the resistive element poses an upper limit to the velocity measurement range. If the liquid moves at a speed faster than what it takes for the resistive element to reach a thermal equilibrium, the reading will be inaccurate.

The response time of the sensor immersed in liquid was measured at 4 ms. In theory, this translates into the capability of measuring flow front speed up to 250 mm/s. However, the 30 ms resolution of the optical measurement only enables us to compare the flow rates up to 7 mm/s.

The sensor can successfully measure the position of liquid movement. For example, it has been used to extract rich information about an intermittent filling process (Fig. 5). In this test, the flow front reaches position $x=0.18L$ (position a) with velocity 750 μm/s. It is paused there for 0.5 s before being moved to $x=0.5L$ (position b) with velocity of 560 μm/s. It then moves at a velocity of 710 μm/s until it reaches $x=0.86L$ (position c). The resistive sensor was able to measure the position and speed associated with each stage independently and accurately. If the sensor were to be used to measure multiple sessions of filling and emptying the channel, a finite time interval of 75 ms must be allowed between sessions. In the future, the risetime can be minimized by reducing the thermal time constant associated with a dry resistor.

We have demonstrated a simple two terminal hot wire device for measuring the position and advancement speed of liquid front in microfluidic channels. We have successfully illustrated the ability of the sensor for monitoring the speed of flow movement. The dynamic response has been characterized by flowing liquid to the sensor with the sensor laterally positioned to the direction of the flow (i.e., the entire length of the sensor gets simmered in liquid at the same time). We have proved that the sensor can track flow speed up to 6.5 mm/s under the limit imposed by the optical measurement. Thermal response speed of 4 ms translates into a capability of measuring flow speed up to 250 mm/s.

This work has been financially supported by the DARPA Advanced Lithography program (managed by Dr. David Patterson of DARPA and Dr. Marc Ulrich of ARO). This material is also based upon work supported by the National Science Foundation under Grant No. 9984954.

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