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Flow Rate Measurement in Microfluidics Using Optical Sensors

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Abstract

A system using low-cost and off-the-shelf electronic components for measuring very low flow rates of liquids is reported. The system records the time duration a liquid column needs to travel, in a transparent capillary, between two optical sensors. The average flow rate is then calculated from the time duration, the distance of the two sensors, and the diameter of the capillary. Our first prototype was capable of measuring flow rates as low as 280 nl/s with an average error of 1.37 %. However, with small modifications, the system could achieve a volumetric resolution <0.1 nl. The system could be an ideal tool to characterize microfluidic devices or calibrate liquid micro flow sensors.

Keywords: microfluidics, flow sensor, nanoliter

1 Introduction

The exponential growth of microfluidics in the last decade has been demanding accurate flow measurement. A variety of liquid flow sensors have been developed. They utilize a variety of sensing principles: thermal, mechanical, electrical and optical [1].

Thermal flow sensors are the most popular sensor types and can measure liquid resolution on the order of nl/min [2,3]. Commercial thermal flow sensors are available with resolution of 0.5 nl/min (SLG1430, Sensirion Company). Thermal flow sensors can be integrated in fluidic system to form a control loop. However, their accuracy can be affected by changes in ambient temperatures.

Besides thermal concept, other flow sensing techniques have recently achieved very high resolution. A recent paper reported a flow sensing based on the measurement of electrical admittance of conducting liquid [4]. This method can measure flow rates less than 1 nl/s. Mechanical flow sensors used to be viewed as not capable of measuring flow rates in the order of nl/s. However, a flow sensor based on periodic flapping is reported to achieve a resolution of 2 nl/s [5]. Micro Particle Image Velocimetry (microPIV) is a powerful optical method for studying micro flows because it can provide other useful information such as the velocity flow field. The disadvantage of microPIV is the high equipment cost [1]. Video microscopy is another popular optical flow measurement method. In this method, the displacement of a liquid column in a microchannel is observed through a microscope and recorded. The flow rate is calculated from the time in which the liquid column travels over a fixed distance [6].

An optical flow measurement system using similar principle as the video microscopy but simpler has been reported [7]. Two optical sensors of a modified computer mouse detected the passing of a liquid column, travelling in a transparent capillary, and transmitted the data to a software processing program. The software calculated the time duration the liquid travelled between the two optical sensors and the flow rates. The detection of liquid column is based on the difference of the refractive indexes of liquid and air. The system can measure flow rate of liquid up to 115 µl/min with an error of ±2 %. However, its resolution depends on the sampling rate of the computer (0.05 s). Furthermore, this system is difficult to adjust because of the use of photo diodes in the optical sensors.

We report here a stand-alone flow measurement system, called Optical Flow Measurement System (OFMS). It shares the optical detection concept with [7]. However, it uses a dedicated hardware. Having its own control circuit, it works independent of computers and does not have problem with sampling resolution. The system can measure flow of any liquid over a wide range. Potentially, the system can achieve a volumetric resolution less than 0.1 nl. Therefore, it could be an ideal tool for characterizing microfluidic devices as well as calibrating micro flow sensors.

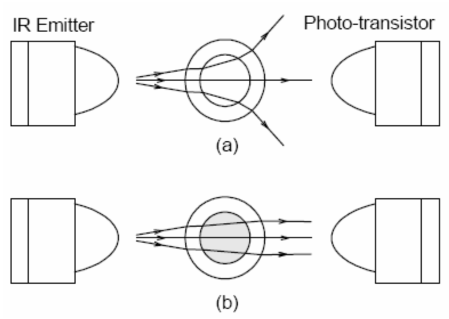

Figure 1: The principle of detecting liquid in a glass capillary using the difference of refractive indexes. (a) Air-filled capillary disperses light. (b) Liquid-filled capillary focuses light. (Adapted from [7])

2 Design

2.1 Detection principle

The detection of air or liquid in a glass capillary is based on their difference in refractive indexes. An air-filled capillary disperses light while a liquid-filled capillary focuses light, Fig 1. The reason is that the refractive indexes of liquid and glass are from 1.3 to 1.5 while that of air is only 1.0 [7].

2.2 Choice of Optical Sensors

Each optical sensor consists of a matched pair of an IR emitter (SEP8736, 880 nm, Honeywell) and a phototransistor (SDP8436, 880 nm, Honeywell). IR is chosen over visible light for it is less susceptible to interfering light.

The phototransistors are used in common-collector amplifier circuits Fig.2. In order to detect two levels of inputs for comparison, the transistors must work in the active mode. That is the light current IL is proportional to the IR intensity. The condition for

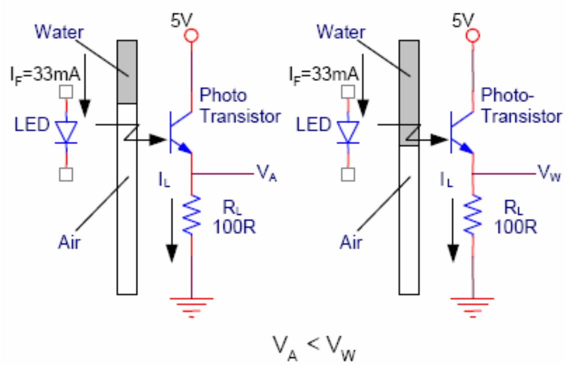

Figure 2: The phototransistor works in active mode, common-collector configuration. Water-filled capillary transmits infrared (880 nm) better than air-filled capillary. Therefore, the output voltage of water is higher $V_w > V_a$.

Table 1: Output voltages of two phototransistors at two conditions: air-filled capillary and water-filled capillary. V_{s1} and V_{s2} are voltages at the emitter terminals of the two phototransistors, respectively.

	V_{s1} (V)	V_{s2} (V)
Air-filled capillary	1.00	1.10
Water-filled capillary	1.60	1.75
$V_{ref} = 0.5(V_a + V_w)$	1.30	1.42

active mode is governed by:

$$R_L = \frac{V_{CC}}{I_L} \quad (1)$$

Where V_{CC} is the supply voltage, R_L is the load resistance, and I_L is the nominal light current. With V_{CC}=5V and I_L=10 mA (from data sheet of SDP8436), R_L must be smaller than 500 Ω. We chose R_L = 100 Ω, Fig.2. We carried out experiments to determine the output signal $V_s = I_L\ R_L$ when the infrared passed water-filled capillary and air-filled capillary, Fig.2. A capillary tube (silicone EW-95720-00, Cole Parmer, ID=0.8 mm, OD=2.4 mm) was filled partly with water. The supply current for IR emitters is 33 mA. The output voltages are listed in Table 1. These results confirm that because the air-filled capillary disperses light, the corresponding output voltage is lower. The liquid-filled capillary focuses light so the output voltage is higher. The reference voltage $V_{ref} = 0.5(V_a + V_w)$.

2.3 Description

The OFMS consists of a main box (MB), a measurement platform (MP), and a solenoid valve, Fig.3. The MB is an acrylic box, which contains major components of the system including the power supplies, the electronic control circuit and the time counter.

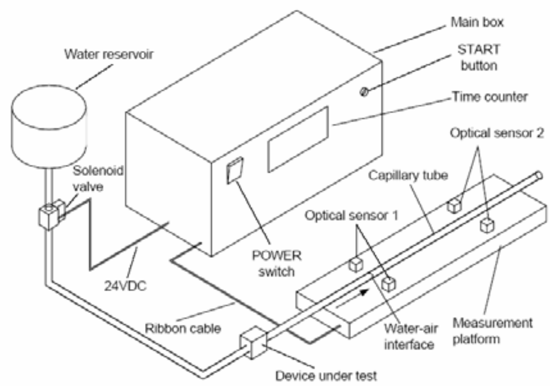

Figure 3: Perspective view of the OFMS. The two optical sensors detect the water-air interface to start/stop the time counter.

The MP contains two OSs and a capillary tube. Each OS consists of an infrared (IR) emitter and a phototransistor, placed face-to-face and 12 mm apart. The position of OS1 is fixed; while the position of OS2 can be changed in order to adjust their distance (from 10 mm to 200 mm in step of 10 mm). A ribbon cable electrically connects the OSs to the electronic control circuit in MB. The solenoid valve (2/2, NC, 1/8 in, Type 6031, Burkert) is optional. The solenoid valve is useful for testing of passive devices such as check valves. The MB opens the valve when the test starts and closes it when the test completes. The working principle of the OFMS is as follows. When the liquid-air interface passes OS1, OS1 transmits changes in IR intensity back to the MB in term of voltage. The control circuit in MB sends a signal to start the time counter. When the liquid-air interfaces passes OS2, MB sends another signal to stop the time counter. The time displayed on the time counter is the time the liquid column needs to travel from OS1 to OS2. The flow rates then can be calculated by:

$$q = \frac{\pi r^2 l}{\Delta t} \tag{1}$$

2.4 Block Diagram and Operation

The operation of the OFMS is described by the block diagram Fig.4 and the timing diagram, Fig.5. The DC power supplies which convert 220VAC mains down to 5 VDC and 24 VDC are not shown for the sake of simplicity. The operation begins when the START button is pressed. V start goes low (LO), Fig. 4. Upon receiving V start LO the time counter is reset. The solenoid valve is turned on, Fig.4.

The water from the reservoir flows through the device under test (DUT). Until now, IR is transmitted from IR emitter D1 through air-filled capillary to phototransistor Q1. The emitter voltage of Q1, V s1 equals to V a1. When the water-air interface passes OS1, V_{s1} changes to V_{w1}, Fig.4. V_{s1} is now larger than V_{ref1}, so the voltage comparator Comp1 changes its output voltage V_{c1} from high (HI) to LO, Fig. 4. The transition of V_{c1} to LO triggers the one-shot circuit 1 to fire a 183-µs-wide single pulse Vsh1). Vsh1 is connected to the preset port of the D-flip-flop (DFF), therefore it sets the output /Q to LO. The count

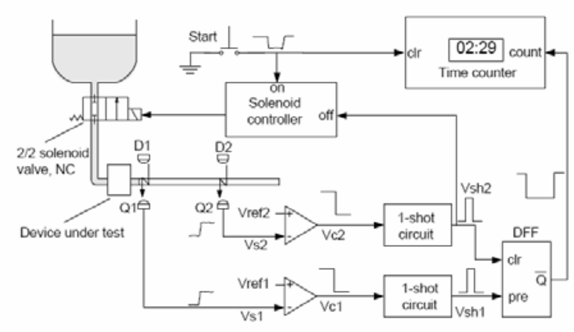

Figure 4: Block diagram of the OFMS.

Figure 5: Calibration setup. The syringe pump drives a syringe to generate various precision flow rates, which are then compared to the measured data.

terminal of the time counter (Elapsed timer Tico 735, Hengstler), tied to /Q, also goes LO, which starts the time counter, Fig.4.

When the interface passes OS2, Vs2 changes from Va2 to Vw2, Fig.5(f). Therefore, Vc2 changes from HI to LO. One-shot circuit 2 fires a pulse to the clear terminal of the DFF, Fig.4). This signal sets the output /Q to HI to stop the time counter. The transition of V sh2 from HI to LO is sent to the solenoid controller to turn off the valve.

3 Calibration and discussion

A highly precision syringe pump (Cole Parmer) and a precision 1ml-syringe (Hamilton) were used to calibrate the OFMS. The setup is depicted in Fig.7. The syringe pump drove the syringe, filled with pure water, at constant flow rates. The syringe was connected to a capillary (fused silicate, Polymicro Technolgies, id=530± 1 µm, od=700 µm). The distance between the two OSs was 200 mm. The flow rates, measured by the OFMS, are plotted against the set flow rates of the syringe pump, Fig.6. The errors versus set flow rates are plotted in Fig.7.

Achieving an average error rate of 1.37% over wide ranges of flow rates, not to mention the lack of any

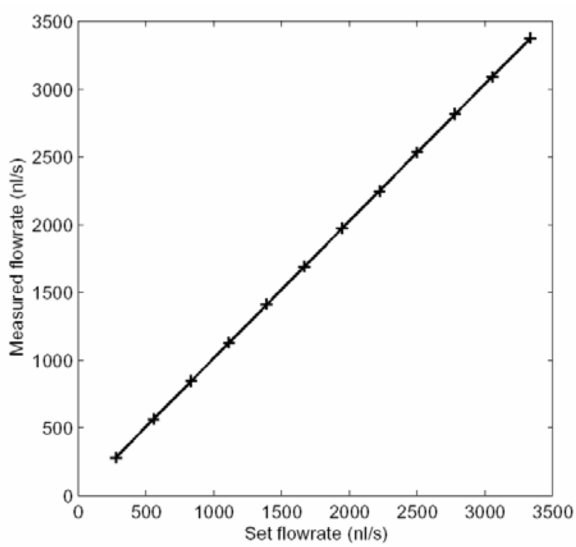

Figure 6: Measured flow rates vs. set flow rates.

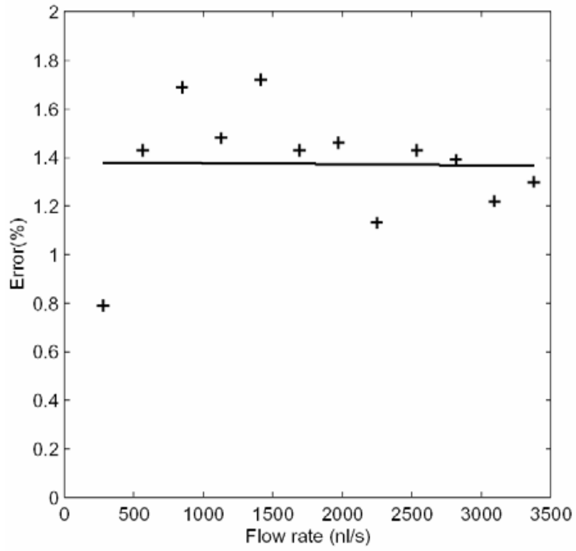

Figure 7: Errors (%) of the OMFS at different flow rates.

pre-calibration, the OFMS shows good potential in measurement of microfluidic flows. However, all the errors are positive which means there are systematic error sources, Fig.7. They could be: the resolution of the time counter, and the beam width of the IR emitter. First, due to the availability, we could only buy the time counter with a resolution of 0.1 second. Therefore, if the total elapsed time is less than 10 seconds, the error caused by the time counter is already 1%. Using a time counter with a higher resolution would definitely solve this error source. Second, in the discussion so far, we assume that in a pair of OS, the IR emitter and the phototransistor are perfectly aligned. And that, when the liquid-air interface passes the line connecting the centers of the IE emitter and the phototransistor the output voltage changes from V_a to V_w. In reality, however, the IR emitter has a beam width of 20^o, so the position of the interface when the transition happens is not known.

As the gap between Measured flowrate (nl/s) the IR emitter and the transistor is 12 mm, the transition position can happen anywhere within the $\Delta l = 1.71$ mm area shown in Fig.8(a). With the capillary diameter $d_c = 530$ µm, the volumetric resolution is $\Delta V = 375$nl. The resolution can be improved by using smaller capillary and replacing IR emitter-phototransistor by fiber optic as depicted in Fig.8(b). For a capillary with diameter $d_c = 100$ µm and fiber optic with diameter $d_f = 10$ µm, the resolution is now $\Delta V = 0.08$ nl. With this accurate resolution, the system can be used to calibrate micro flow sensors. Even though accurate and simple, the system is far from perfect. Its working principle results in two fundamental limitations. First, the detection based on difference of refractive indexes of air and liquid makes it not possible to measure gas. Second, it can only measure average flow so not suitable for online monitoring.

4 Conclusion

A system for measuring liquid micro flow has been designed and implemented. Its advantages are simple design, potentially accurate to 0.08 nl, being able to measure most liquids with minimum calibration. Therefore, it is ideal for characterizing microfluidic devices and calibrating liquid micro flow sensors. However, it is not suitable for measuring gas flow and online monitoring.

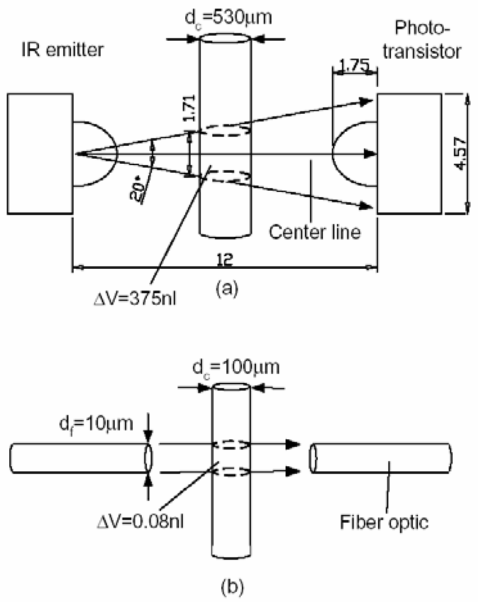

Figure 8: Volumetric resolution of the system. (a) Current configuration has volumetric resolution of 375 nl (b) Using finer capillary and replacing IR emitter-phototransistor by fiber optic improves the volumetric resolution to 0.08 nl.

5 References

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