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A printed circuit board capacitive sensor for air bubble inside fluidic flow detection

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Abstract This paper presents a three-electrode capacitive fluidic sensor for detecting an air bubble inside a fluidic channel such as blood vessels, oil or medical liquid channels. The capacitor is designed and fabricated based on a printed circuit board (PCB). The electrodes are fabricated by using copper via structure through top to bottom surface of the PCB. A plastic pipe is layout through the capacitive sensor and perpendicular to the PCB surface. Capacitance of sensor changes when an air bubble inside fluidic flow cross the sensor. The capacitance change can be monitored by using a differential capacitive amplifier, a lock-in amplifier, filter and an NI acquisition card. Signal is processed and calculated on a computer. Air bubble inside the liquid flow are detected by monitor the unbalance signal between the three electrode potential voltages. Output voltage depends on the volume of the air bubble due to dielectric change between capacitor's electrodes. Output voltage is up to 53 mV when an 2.28 mm^3 air bubble crosses the sensing channel. Air bubble velocity can be estimated based on the output pulse signal. This proposed fluidic sensor can be used for void fraction detection in medical devices and systems; fluidic characterization; and water–gas, oil–water and oil–water–gas multiphase flows in petroleum technology. That structure also can apply to the micro-size for detecting in microfluidic to monitor and control changes in microfluidic channels.

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1 Introduction

Detection of air bubbles is important in microfluidic, biology, and special in medical. Appearance of air bubble in the patient's blood vessels is dangerous in case of the unpredictable of cerebral embolism can lead to instant death (Muth and Shank 2000). Bubbles may appear in the blood of the body tube when dialysis or air bubbles can be created when intravenous infusion of the patient's body, so the detection of air bubbles in the blood or in the pipe conduit body fluids is essential (Correa et al. 2004). Different physical principles have been employed in air bubbles detection. The earliest air bubbles detectors consisted of a light source which triggered a photocell situated on the opposite side of the bubble trap; the cell did not react if blood obstructed the light path (Vivian et al. 1980). These devices were insensitive to foam and could not react if fibrin deposits on the inner wall of the bubble trap obstructed the light path. In addition, ambient light could reach the photocell and cause false alarms. Infrared light photocell devices have increased the sensitivity to air bubbles detection but are still not foolproof against obstruction to the passage of the infrared waves, or sensitive enough to be reliable against foam without causing multiple false alarms. Other methods to detect gas bubbles in the fluid tube is under using the microscope and by using ultrasonic method, this method is complicated (Barak and Katz 2005; Jonsson et al. 2007; Markus 1993). Capacitive sensor is convenient to fabricate and setup measurement, capacitive sensor is applied

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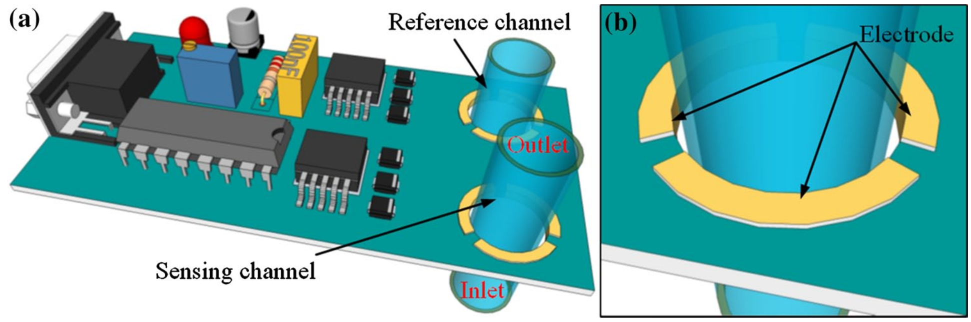


Fig. 1 **a** Design of micro-fluidic sensor, there are two micro-fluidic channels for sensing and reference; **b** the capacitive sensors are directly fabrication on the printed circuit board

in many field of research such as in general applications (Meng Sun et al. 2008; Caniere et al. 2007), in pharmacy (Ernst et al. 2009), in microfluidic channel apply to biochemical screening, particle synthesis and chemical analysis (Elbuken et al. 2011), in void fraction liquid flow (Ko et al. 2012; Vahey and Voldman 2008), petroleum industry (Thorn et al. 2013), inkjet technology (Wei 2010).

In this paper, a three electrode capacitive sensor structure, which was fabricated by PCB technology, can be used in monitoring an air bubble in a fluidic channels with output capacitance of about few fF to a some tens fF depend on the dielectric parameter of the investigated liquid and occurring inside of the capacitive sensor. Similar structure of this proposed capacitive sensor can be reduced to a micrometer size for using in microfluidic channels. In this study, fluidic channels can be real-time monitored to detect air bubble and control the fluidic channel flow. The velocity and volume of an air bubble in fluidic channel is estimated by analyzing the received signal. This system therefore can be applied in detecting unwanted air bubble which is occurred in a medical fluidic channel, petroleum industry, pharmacy, chemical analysis and synthesis, and so on.

2 Fluidic capacitive sensor and electronic circuit design

A capacitive sensor based on a change of capacitance corresponds to permittivity and conductivity of liquid inside can detect a change in fluidic channel. The dielectric is different for each material or different liquids, so it can be changed the value of capacitance when the something changes inside the capacitive sensor by a change of permittivity and conductivity. In this paper, a three-electrode capacitive sensor is used to detect objects inside the fluidic channel such as air bubbles.

Figure 1a shows a design of the proposed fluidic capacitive sensor system. Two fluidic channel are perpendicular to a PCB board as sensing and reference channels. Figure 1b shows a three-electrode capacitor on PCB which is surrounded the fluidic tube. The two capacitive sensors are fabricated on the same PCB board with the electronic circuits. This design allows to reduce the parasitic capacitance and noise by ignoring connected wires.

This PCB fluidic capacitive sensor is suitable for submillimeter, millimeter and centimeter diameter tube. Therefore, this low-cost design can be applied in petroleum fraction detection, air-bubble in dialysis treatment machine, and so on.

Figure 1b shows a structure of the system design with a three-electrode capacitor layout. Capacitance change is evaluated by using a charge amplifier circuit. This fluidic sensor system consists of two three-electrode capacitors as a sensing capacitor and reference one. This two capacitors are fabricated by using traditional PCB technology. The PCB's copper material via structure is employed to make capacitor's electrodes (see Fig. 1b).

Plastic pipes, which is layout through the capacitor, are fluidic channels (see Fig. 1a). The reference channel is not change during measurement by applying a referenced tube with the investigated fluidic inside. An unbalance capacitance will be occurred when there is an air bubble or particle inside the sensing channel sensor. The value of unbalance capacitance is depended on the volume and ratio of air or particle material dielectric and fluidic one.

Figure 2 shows a configuration of capacitive sensor with fluidic flow and a sphere particle inside. The dielectric of fluidic and particle materials are ε_1 and ε_2, respectively. In general, capacitance between the electrode V_1 and electrode V_1 can be calculated by using traditional capacitive theory (Baxter et al. 1996; Toth 1997; Watzenig and Fox 2009).

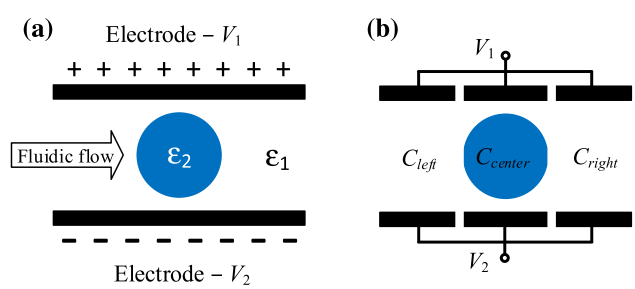
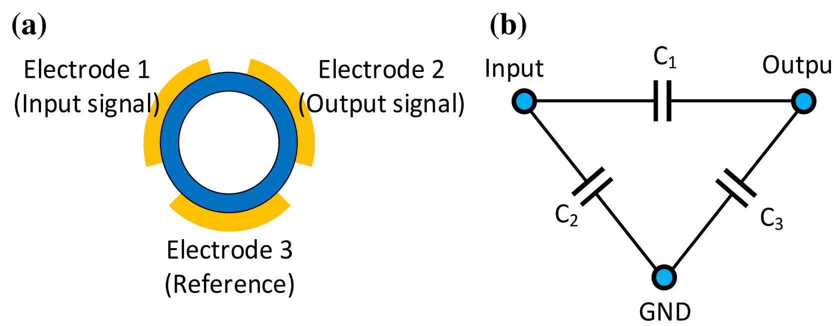


Fig. 2 **a** Capacitive sensor with fluidic flow and particle inside, **b** Equivalent circuit. Capacitance value is depended on the volume, shape and dielectric value of the particle

Fig. 3 **a** Front view of capacitive sensor and **b** a simple equivalent circuit



However, the output capacitance is depended on the volume, shape and dielectric value of the particle.

When there is only fluidic in between the two electrodes without any particle. The dielectric is constant. The capacitance can be calculated by (Toth 1997)

$$C = \frac{Q}{V_1 - V_2} \tag{1}$$

where Q is charge of electrodes, V_1 and V_2 is potential of the top and bottom electrode, respectively. Output voltage can be then calculated by

$$Q = \int_s \rho_s dS \tag{2}$$

$$V = \int_s \frac{\rho_s dS}{4\pi\varepsilon_0\varepsilon_1 d} \tag{3}$$

where ρ_s is surface charge density, $\varepsilon_r$is dielectric of liquid between electrodes. Eqs. 2 and 3 show that the output capacitance depends on both fluidic dielectric $\varepsilon_r$inside the channel and shape of electrodes.

The configuration of capacitor is changed when an air bubble in between the two electrodes (see Fig. 2a). This capacitor is then simplify considered as an equivalent circuit of several component capacitors when the edge effect is ignored. The two component capacitors C_{left} and C_{right} can be calculated by using Eq. 1. The center capacitor C_{center} is effected by the air bubble due to dielectric change (see Fig. 2b). It is quite complicated to estimate the value of this configuration. Readers are referred to the reference (Toth 1997) for this capacitance calculation.

Figure 3 shows a front view of a three electrodes capacitor and its equivalent circuit. Figure 3b is a simple equivalent circuit of this proposed capacitive sensor. This circuit consists of three node and three capacitor C_1, C_2, and C_3. It is assumed that the equivalent capacitance between two adjacent electrodes is $C_1 = C_2 = C_3 = C$. In this paper, the capacitance edge effect is ignored, C can be therefore calculated by (Wei 2010).

$$C = \frac{\varepsilon_0\varepsilon_r wh}{4.d} \tag{4}$$

where ε_0 is the dielectric constant of fluidic material, ε_r is the relative permittivity of the dielectric layer on the electrodes, w is the width of the each electrode, d is diameter of the pipe, and h is the vertical length of the electrode.

Table 1 shows the dimension parameters of capacitive sensor which is demonstrated in Figs. 1 and 4. Figure 4 shows cross-side and front-side view of this capacitor. The electrode high h is equal to the PCB thickness (see Fig. 4a). The copper pad is divided to three equal parts. Each part is corresponded to a capacitor electrode (see Fig. 4b). Capacitance value is vary from about few fF to some tens fF corresponding to dielectric of typically oil ($\varepsilon_r = 3$) or water ($\varepsilon_r = 80$).

By using Eqs. 4 and 5, the output capacitance C can be calculated equal to 2.71 and 8.13 fF for air channel and oil channel, respectively. The capacitance change when replacing air channel by oil channel is up to 5.42 fF.

Table 1 Fluidic capacitive sensor parameters

Symbol	Quantity	Unit (mm)
d	Pipe outside diameter	1.6
W	Electrode with	1.4
h	Electrode height	1.4

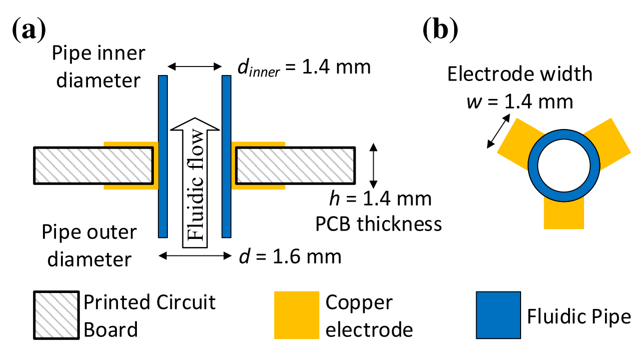


Fig. 4 Description structure of the capacitive sensor and fabrication on PCB

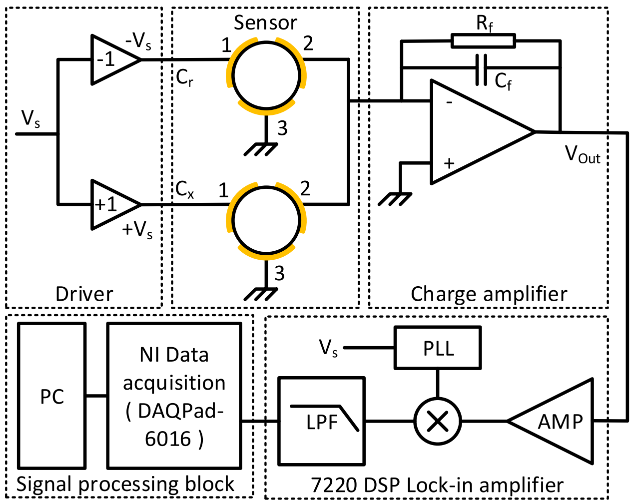


Fig. 5 Differential capacitive amplifier circuit schematic design

To detect void fraction, an electronic circuit is used to convert capacitance change to voltage (Chr 1975; Marioli et al. 1991; Heidary and Meijer 2009). Charge in the electrodes of sensor is converted to voltage by using a single power operational amplified. Figure 5 shows a schematic design, sine signal with phase of 0° and 180° is applied to the first electrode of sensing and reference capacitors (see Fig. 5). Therefore, the common noise is compensated by using this summing circuit. The differential signal is then amplified by using a charge amplifier based on an operation amplifier.

The capacitance change can be determined in a direct manner based on output voltage of the sensor block (see Fig. 5). In this work, the differential ΔC value between the sensing capacitor C_x and reference capacitor C_r can be estimated thank to the output voltage. The reference capacitance C_r is not changed during measurement process, therefore, ΔC is capacitance change of the sensing capacitor. It is given by

$$\Delta C = C_x - C_r \tag{5}$$

When a sine signal $V_s = V_{s0}$ cosωt is applied to the input of the sensor block. The output voltage of the charge amplifier is then calculated by

$$\begin{aligned} V_{Out} &= -\left(\frac{C_x}{C_f} V_{S0}\cos\omega t + \frac{C_r}{C_f} V_{S0}\cos(\omega t + \pi)\right) \\ &= -\frac{V_{S0}}{C_f}(C_x\cos\omega t + C_r\cos(\omega t+\pi)) \\ &= -\frac{V_{S0}}{C_f}((C_r + \Delta C)\cos\omega t - C_r\cos\omega t) \\ &= -\frac{V_{S0}}{C_f}\Delta C\cos\omega t = -\frac{\Delta C}{C_f}V_{S0}\cos\omega t = -\frac{\Delta C}{C_f}V_S \end{aligned} \tag{6}$$

In this case, the negative feedback resistor R_f is used for eliminating the dc drift and ignored in Eq. 6. The function of the resistor is to provide feedback to the dc input to operational amplifier dc at input values are kept in non-island. In addition, the resistor can be connected between the negative input and ground. Without the resistor, the voltage at the input node cannot drift off and the output amplifier can be saturated. The value of ΔC can be determined from the amplitude of the sine wave output. When using a high-frequency ac power, therefore velocity dielectric constant change dependent component of the electric current can be ignored. The capacitance change ΔC can be calculated by

$$\Delta C = \frac{V_{Out}}{V_S} C_f \tag{7}$$

The charge amplifier output is then be input of the lock-in amplifier for demodulation and noise elimination. By using this charge amplifier circuit, a module to connect with sensor is made to convert the signal. The module is covered by aluminum-box as an electrical shield. The metal shield cover can reduce noise and bring a stable result due to Faraday Effect. Figure 6 shows a fabricated structure of the microfluidic capacitive sensor.

3 Measurement setups

To monitor capacitance change a system can be setup based on differential capacitive amplifier, standard pulse generator (HM8030), lock-in amplifier (7220 DSP), filter and NI acquisition card (DAQ Pad-6016) (see Fig. 7). The system is characterized under an inverted microscope (Olympus IX71) with a high speed camera (AOS Technology AG, S-PRI plus).

A lock-in amplifier is used to measure small ac signals up to µV or nV scale. Lock-in amplifiers use a technique called "phase-sensitive detection technique" is used to pick out a mixed signal and determine the frequency, while the noise signal at any other frequency is removed. Figure 5 shows a block diagram of this proposed fluidic sensor.

A sine wave signal from function generator supply to charge amplifier module and also becomes a reference signal into lock-in amplifier. A sine signal with frequency of 100 kHz, amplitude 3.5 V_{pp} from a standard pulse generator (HM8030) is converted to two signal $-V_s$ and $+V_s$ with phase of 0° and 180°, respectively. The lock-in amplifier output is collected through NI data acquisition card and then be processed by using LabVIEW software.

A specific cylinder is designed to create air bubble or inject a particle into fluidic flow through a T-connector (see Fig. 8). A high accurate meter is used to fine control the position of the piston. Therefore, this structure allows

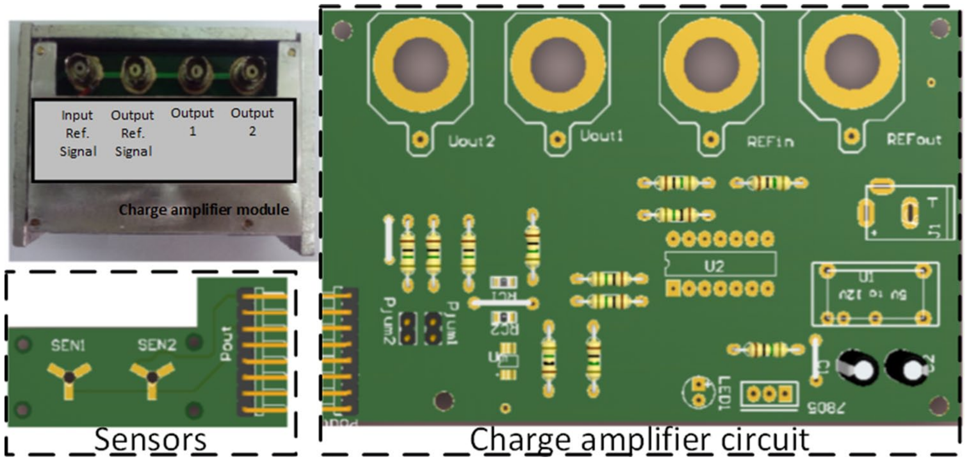


Fig. 6 A different capacitive amplifier module was designed to measure a changing of capacitance

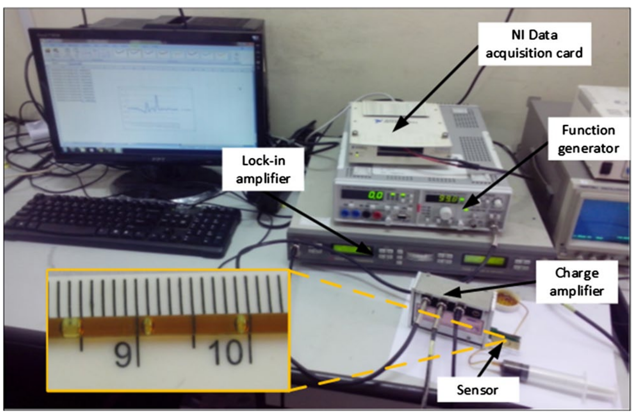


Fig. 7 A measurement system is setup. The capacitive sensor is connected to differential capacitive amplifier module. A sine signal with frequency of 100 kHz is supplied to both differential capacitive module and the lock-in amplifier as a reference signal. An NI data acquisition is used to transfer to a PC

to make a desired volume air bubble and its occurred time. Figure 8b shows several air bubble with variable volume inside an oil channel.

4 Results and discussion

Figure 9 shows the output voltage of the fluidic sensor systems versus time when an air bubble crosses the sensing capacitor (see the subpicture in Fig. 9). The amplitude of output voltage is up to 31 mV when an 1.45 mm^3 air bubble crosses the sensing channel. This output voltage amplitude is depended on the volume of the air bubble due to dielectric change. The width of output signal is respected to the velocity of the flow and also the air bubble inside fluidic channel.

Figure 10 shows six output voltages correspond to the six bubbles with volume varies from 0.1 to 2.28 mm^3. The biggest bubble with volume of 2.28 mm^3 gives largest output voltage up to 53 mV while output voltage is of about 4 mV for the smallest 0.1 mm^3 bubble. Table 2 shows the relation of volume and corresponded maximum output voltage. The maximum output voltage versus air bubble volume is also shown in Fig. 11. This relation is linear with line angle of 23.5 mV/mm^3.

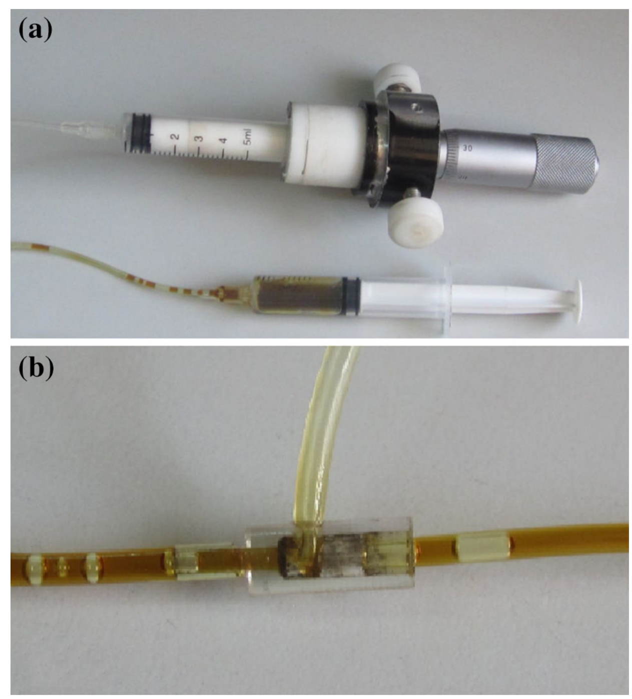


Fig. 8 The pump to create liquid flow inside the pipe using two cylinders to control the liquid channel flow (**a**). The two channels are used to control the size of bubble air (**b**). One channel contains oil, others is full of the air. Both of them is mixed together to make the bubble

Those measurements are not only indicated the bubble volume, but also airbubble velocity. In this work, it is

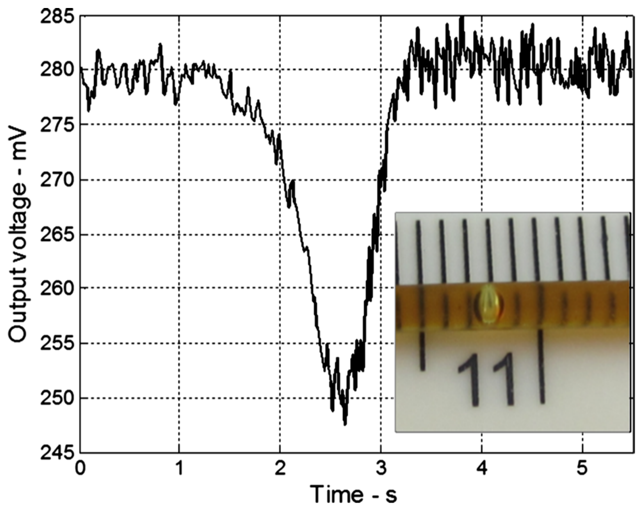


Fig. 9 A signal when the bubble moved through the capacitive sensor

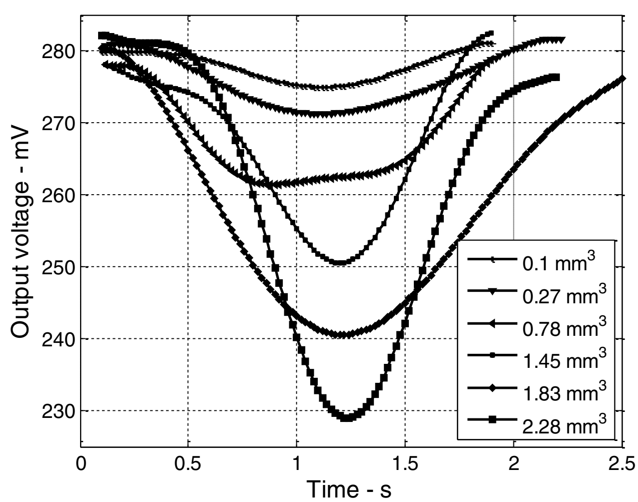


Fig. 10 Output voltage signal of the six air bubbles with different size, the maximum voltages correspond to the size of air bubble

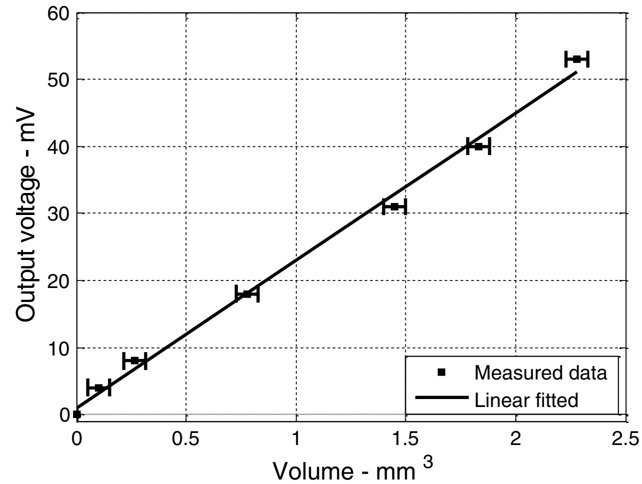


Fig. 11 The chart of different amplitude change corresponds to the volume of air bubbles

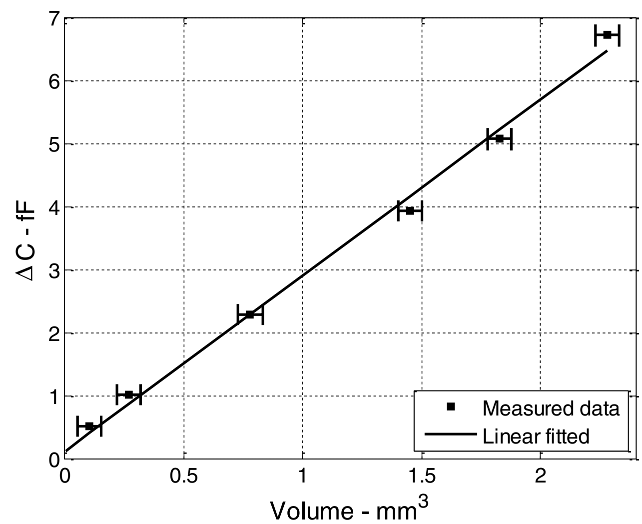


Fig. 12 The chart of different capacitance change corresponds to the volume of air bubbles

Table 2 Sizes of bubbles corresponds to parameters of amplitude and capacitance

Volume (mm^3)	Amplitude (mV)	Capacitance change (fF)
0.1	4	0.51
0.27	8	1.01
0.78	18	2.28
1.45	31	3.92
1.83	40	5.06
2.28	53	6.70

assumed that the velocity of air bubble and fluidic flow are equal. Both air bubble and fluidic material are considered as incompressible material. The boundary condition is also ignored in this consideration. Figure 10 also shows that velocity of the 1.83 mm^3 bubble is slowest thank to the largest width of its output signal.

In this measurement setup, the lock-in amplifier gain is set at 10 dB. The capacitance change can be calculated using Eq. 7 and Fig. 11. Figure 12 shows relation between capacitance change and bubble volume. The capacitance is changed up to 7 fF when an air bubble with volume of 2.28 mm^3 crosses sensing capacitor. The measured values are met the theoretical calculation above which is shown in Eq. 4.

Velocity of an air bubble can be estimated by analyzing the amplitude and also width of output voltage. Figure 13 shows an output response with indicated position of the air

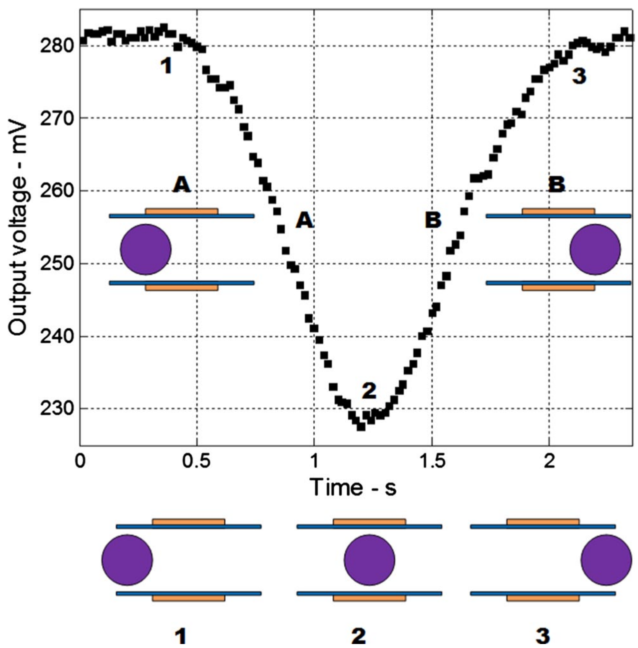


Fig. 13 The measured signal when a bubble though the microfluidic channel

bubble when it crosses the sensing capacitor. In this characterizing, it is assumed that the investigated air bubble is an air sphere (see Fig. 13). The point 1 where the air bubble start going into the sensor, the point 2 shows the position of air bubble is in the center of sensor, and the point 3 where the air bubble is going to move out of sensor. Point A and point B are the time when air bubble is 50 % inside capacitor and 50 % outside. When ignore edge effect, the output signal can be corresponded to 50 % of the maximum value of signal (point A and B). The air bubble velocity can be then estimated by positioning the point A and B (see Fig. 13).

In case of air bubble diameter is smaller than the length of capacitive sensor, velocity of the investigated air bubble can be approximately calculated by

$$Velocity \approx \frac{h}{T_A - T_B} \quad (8)$$

where h is length of capacitor, T_A and T_B is time when air bubble at point A and B. Velocity of the air bubble in Fig. 13 is about 1.84 (mm/s).

5 Conclusions

This paper presents an inexpensive capacitive sensor structure which can apply to many field of detection in fluidic channel base on a printed circuit board technology. This capacitive sensor allows real-time monitor and detect a change in fluidic channels due to the dielectric change. This proposed structure can detect a small bubble volume of 0.1–2.28 mm^3 with output capacitance change of 0.51–6.7 fF and corresponded output voltage of 4–53 mV, respectively. Air bubble velocity is also calculated by analyzing the output signal. This capacitive sensor is fabricated built-in on a printed circuit board which is suited for low cost requirement. This fluidic sensor could be used in void fraction detection in medical devices and systems; fluidic characterization; and water–gas, oil–water and oil–water–gas multiphase flows in petroleum technology. This structure also can apply to the micro-size for detecting in microfluidic to monitor and control changes in microfluidic channels.

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