FLUID METERING FOR PERISTALTIC PUMPING

Y. Feng, C.M. Jiang and W.H. Deng
Siargo (Shanghai), Ltd.
Building 4, No. 1 the Second South Science Park Road, Chengdu 610041 China

Y.H. Yao, C.C. Chen and L.J. Huang
Siargo Ltd.
2041 Mission College Boulevard, Suite 250, Santa Clara, California 95054 USA
Liji@Siargo.com

Abstract

Peristaltic pumping is a common process in chemical, biomedical and pharmaceutical applications. However, the actual measured flow is frequently found to be erroneous with an accuracy no better than 10%. In this paper we present a design of the precise fluid metering sensing technology using MEMS thermal time-of-flight principle in a close loop with the peristaltic pumping for the bio-fluidic analyser. The data indicate that the MEMS fluidic meter could significantly improve the accuracy and control of the fluid delivery within 5% which not only substantially reduces the cost but boosts the performance of the instrument by better controlling the sample to carrier liquid injections.

Introduction

Peristaltic pumps have been widely used in biomedical, physiological, chemical and pharmaceutical applications. [1, 2] During the operation of a peristaltic pump, protuberances are driven into the tube wall to create waves of fixed wall displacement. Regardless of the fluid characteristics, the instability with the pulses in fluids usually could not ensure a high precision for the delivery. One particular example of the interests in this study is the urine sediment analyser. The fluidic system of the analyser utilizes a fluidic system controlled by peristaltic pump that delivers the urine samples after being diluted and carried with special water based medical fluid into the analysing chamber. As the uncertainties for the delivery by peristaltic pump are high, and the reproducibility is poor, the carrier fluid is often prepared in the carrier bath with 25% additional of the theoretic volume required for the completion sample analysis. This not only increases the cost for each sample analysis but adding the undesired system management uncertainties. It is therefore highly desirable to have a higher precision control system for the analyser such that the accurate amount of carrier fluid could be controlled.

In this paper, we discuss a time-of-flight (TOF) flow metering technology based on the MEMS (micro electro mechanical system) sensing technology in which an integrated TOF flow sensor is used to measure the fluid flow rate and provide control of the carrier fluid delivery by the peristaltic pumps.

Meter Design and Experiment

MEMS TOF sensor design and fabrication

The MEMS TOF sensors were made on a silicon substrate where a 1.5μm thick low stressed silicon nitride prepared by low pressure chemical vapour deposition was used as the membrane support under which the thermal isolation cavity was realized by etching away the bulk silicon materials using deep reactive ion etch process. Three thermistors disposed on the silicon nitride membrane were made of platinum via electronic beam evaporation. Each of the thermistors had a resistance about 500 Ω and been separated with a distance of 300 μm. The thermistor at the middle was used as the heat wave transmitter while the other two thermistors placed symmetrically to the middle thermistor were designated as the receivers. In this configuration, the sensor could be employed to measure the bi-directional flow. The surface of the sensor was passivated with a 350 nm low stress silicon nitride prepared by plasma enhanced chemical vapour deposition. Additional thermistor deposited on the silicon chip substrate can be used to monitor the environment temperature for controlling the temperature of the heat pulse generation.

MEMS TOF meter design

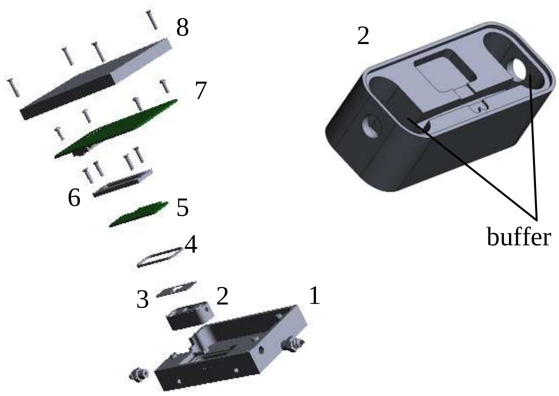

Figure 1.Explosive view of the meter

The TOF meter for the liquid fluids was driven by an alternative current circuitry in which a square wave function was designed for the transmission of the heat waves and the phase shifts were detected at the receiver thermistors. The mechanical structure of the meter can be found in Figure 1.

The explosive view of the structure of the designed meter is shown in Figure 1(a) where the flow sensing assembly (2) is embedded in the base (1) of the meter. The sealing plates (3) and gasket (4) provide the necessary leakage proof. The signal conditioning circuitry (5) is connected to the MEMS sensing chip via the 6 wires that are further sealed with epoxy. The isolation gasket (6) provides additional leakage proof and the electronic control board (7) is connected to the signal conditioning board through a pin connector. And finally the top cover (8) also can have the display window. The measurement flow range can be easily adjusted via the modification of the flow channel of the flow sensing assembly for which a close look is shown in Figure 1(b). For applications relevant to this study, the full scale flow rate of the meter is designed to be 0~70 mL/min that corresponds to a flow channel in a rectangular shape with cross-section area of 1.0x1.3 mm. The TOF sensor chip was packaged at the sidewall of the flow channel where the thermistor elongation direction was perpendicular to the flow direction with the edge as in the form of a plate emerged in the fluid such that a stable boundary layer can be well established. The two pools symmetrically placed at the two ends of the flow channel in the flow sensing assembly are made as a buffer to attenuate the pulse flows that are generated by the peristaltic pumping process.

The electronic interface of the meter includes standard RS485 Modbus digital data communication and analogy port. A display is readily showing the instant and totalized flow rate.

Test setup

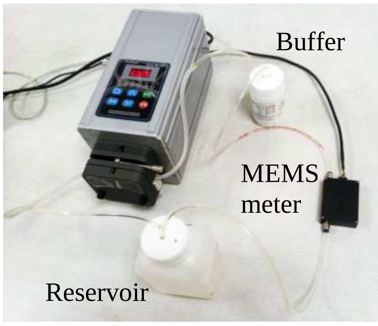

Figure 2. Peristaltic pumping test setup

The measurements comparison among the set values and the measured data from the TOF meter were conducted in a configuration as shown in Figure 2. The peristaltic pump BL100-KZ15 was made by Prefluid, Inc. with a pump rotary rate adjustable from 0.1~100 rpm and a resolution of 0.1 rpm. The reservoir was used for the close loop measurement while the buffer was designed for a smooth flow comparison. During the measurement, the flow was pulled by the peristaltic pump from the reservoir through the plastic soft pipe entering into the flow meter with or without buffered and then returned to the reservoir. The pipe inner diameter was 2.4 mm and the fluid media was de-ionized water.

Results and Discussions

Meter calibration

In theory, if a pure time-of-flight principle can be achieved, then the measurement data of the time span that the thermal pulses travel can be used to calculate the flow speed of the fluid and the flow rate subsequently. However, due to many restrictions, a true time-of-flight signal may not be easily obtained directly [3]. Not only the thermal boundary layer effects but the actual thermistor responses to the fluid media would play a significant role in the performance [4], even though the MEMS process already allows the reduction of the wire dimensions that yields a high speed response [5]. Therefore, before the true thermal time-of-flight data can be decomposed from the measurement, the meter shall still require a calibration such that the true performance can be recovered.

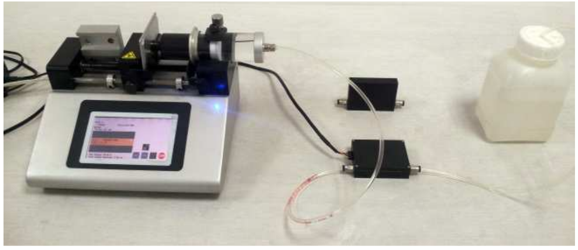

Figure 3. Calibration setup

Figure 3 shows the flow meter calibration setup. The calibration was done with a syringe pump KD Scientific Legato 110 with an accuracy of ±0.5% and a flow range up to 88mL/min. The data were collected from the direct set points on the syringe pump and those read from the digital interface of the meter.

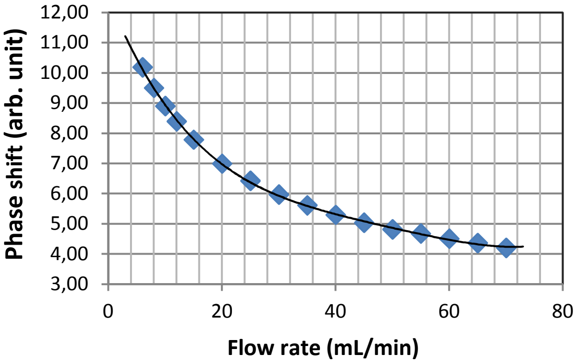

Figure 4. The typical calibration for the TOF meter

The typical TOF meter output versus the calibration can be fitted with a 3rd order polynomial as shown in Figure 4. The meter after calibration can retain an accuracy of ±1.5%. During the calibration, the syringe pump delivery shall also produce the small wavelet flow depending on the quality of the motor used in the system. The data readout from the meter then was processed using software filter to eliminate such effects. The dynamic range is over 50:1 that well outperforms most of the flow meters for liquid applications. The dynamic range of the meter is also dependent on the sensor design on the distance between the thermal pulse generator thermistor and the receiver thermistor. The closer the distance is better for the sensitivity in low flow rate range while the longer distance shall benefit the measurement in higher flow rate range. In order to expand the dynamic range, multiple receiver thermistors can be integrated on the same chip such that the sensitivity can be maximized and a high-accuracy performance can be achieved in the full dynamic range for the desired applications.

Performance for peristaltic delivery

The feature of the flow delivered by a peristaltic pump is a pulsed one. Therefore it is usually difficult to design a precise control for the desired delivery in the system. In particular, the available and commonly used liquid flow meters in the applications of interest are the plastic turbine meters that cannot alter the delivery of the pulses but to reproduce the flow pattern while suffering from the small measurement dynamic range. The MEMS flow sensing, on the other hand, is based on an all-electronic metering architecture, and the data could be easily processed for enhanced precision.

The most commonly used thermal MEMS flow meters are based on measurement of the calorimetric data of the fluid. The calorimetric measurement in principle does not dependent on pressure and temperature of the fluid but it utilizes the amplitudes of the thermal responses that are proneto the interference externally. The TOF measurement processes the frequency signals that are in particular more stable for the low flow rate where many disturbances may exit. For the liquid flow measurement, the pressure and temperature effects are in many cases less important as compared to that for gases.

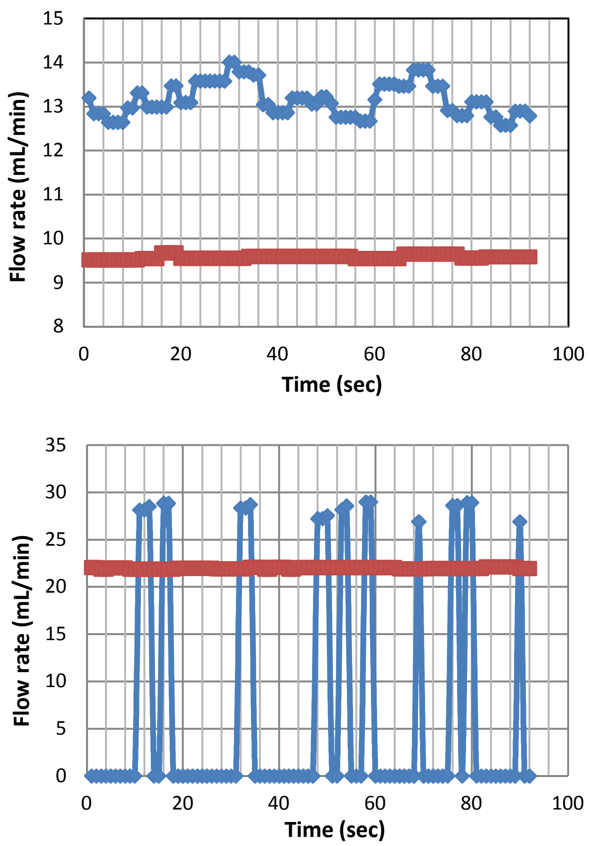

Figure 5. Comparison of the measurement schemes at 10mL/min (above) and 30mL/min (below)

Figure 5 shows the comparison of the flow pattern delivered by the peristaltic pump with and without a buffer. It can be observed that the pulsed flow pattern can be eliminated by the addition of a buffer that is a reservoir to ensure the protuberances can be removed inside the buffer. This enables the system to control the delivery accuracy from over 30% in this particular example down to less that 2%. From the data plots shown in Figure 6, additional evidence can be seen for the significant improvement in the stable delivery after introducing the buffer reservoir into the fluid system lines before the TOF flow meter. The nonlinear correlation between the set flow rates by the peristaltic pump and the ones measured by the TOF meter was changed to a linear correlation with the buffer reservoir. Therefore, although the TOF meter can provide feedback to system with an averaged value for the pulse flow pattern but the small buffer inside the meter is apparently not enough for the delivery of a stable flow. Hence, in order to ensure the system delivery accuracy, a buffer would be necessary for improving the performance.

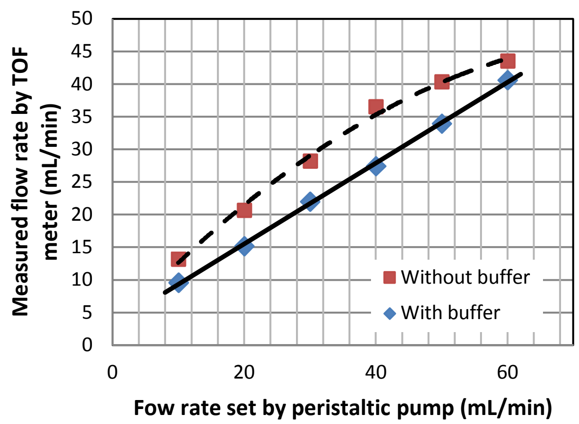

Figure 6. Correlation of the set flow rate by peristaltic pump and the TOF metering with and without a buffer

The above measurement data also indicated that the delivery errors by the peristaltic pump would be very large. It is therefore expected that the reproducibility of a peristaltic pump would not be desirable as well and it will not be sufficiently improved by simply modifying the fluid delivery system with a buffer reservoir to ensure the stable and precise flow delivery of no pulse patterns. Another fact is that the correlations between the peristaltic delivery and the measurement data by the TOF meter shown in Figure 6 indicated a large offset difference would be due to a smaller dynamic range of the peristaltic pump in delivery capability that adds up the uncertainties for the offset. Therefore to ensure the precise delivery of the fluid for the system controlled by the peristaltic pump, an addition of flow meter that has a high precision with a large dynamic range would be a must. From the above example, one could conclude that the TOF meter could very well play such a role for the improvement of a fluid delivery system.

Concluding remarks

The present study indicates that the MEMS TOF meter can significantly increase the accuracy of fluid measurement for a system using peristaltic pump to deliver or control the amount of fluid. A buffer reservoir placed after the peristaltic pump shall substantially alter the flow stability from a pulse pattern into a smooth flow delivery. The MEMS TOF meter features a large dynamic range, high precision and a small form factor that can be particularly applicable for small flow applications. The MEMS technology also enables to significantly reduce the meter manufacturing cost in mass production.

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