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MONOLITHIC INTEGRATION OF A CALORIMETRIC MICROFLUIDIC FLOW SENSOR USING FLAT PANEL DISPLAY TECHNOLOGY

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ABSTRACT

This abstract describes the design, simulation and experimental characterization of a thin film thermal flow sensor fabricated using flat panel display technology. Patterned microelectrodes were successfully applied as a thermal flow sensor, showing good correlation between experimental and simulated data. The use of flat panel display technology could provide an interesting option for cost-effective integration of flow sensing in Organ-on-Chip technologies.

KEYWORDS

Organ-on-Chip, microfluidics, thermal flow sensor, monolithic integration, flat panel display technology.

INTRODUCTION

Over the last decennium, Organ-on-chip (OoC) has shown to be a rapidly expanding field [1]. Although OoC technology holds great promise, the lack of standardization in, among other aspects, fabrication methodologies, chosen fabrication materials, device footprints, required peripheral systems, and operational protocols has hampered its widespread adoption.

Design and use of open technology platforms can provide a solution to improve on standardization. An example is the Smart Multi-Well Plate (SMWP) [2]. This platform combines modularity and configurability by choice of functional components such as OoC devices, sensors and pumps in a well-plate format with embedded functionality including in-line perfusion, electrode stimulation, sensor read-out and wireless communication.

An attractive feature of the SMWP is the in-line perfusion by integrated micropumps, which obviates the need for external pneumatics and tubing. To accurately control the micropumps (sensor-pump feedback loop) and monitor their performance over time, in-line flow sensing is required. Although flow sensor technology is well-known and available, it is challenging to upscale and multiplex this technology in a cost-effective manner. Flat panel display (FPD) technology provides a solution to this challenge [3]. Microelectrodes and microfluidic channels - either on thin flexible films or glass - can be cost-effectively fabricated in high resolution.

In this proof-of-concept study, patterned Au microelectrodes in a microfluidic channel make up a flow sensor based on a thermo-resistive, calorimetric principle. In this approach, a set of sensing microelectrodes are situated up- and downstream with respect to a central heater electrode (Fig. 1). The flow of liquid over this heater results in transport of heat towards the downstream electrode, causing an increase in its electrical resistance, which provides an indirect measure of the fluid flow rate.

MATERIALS AND METHODS

COMSOL Multiphysics simulations

To study and optimize the flow sensor performance, a COMSOL Multiphysics (5.2) 3D model was constructed (Fig. 2). This model, shown in figure 1b, is based on the geometry of the physical sensor and includes and combines all relevant physics: electric current, heat dissipation and fluid flow. A biasing electric current is applied to the microelectrodes (10 mA to the heater, 1 mA to the sensors), in which the middle electrode acts as a heater. By means of conduction and convection, heat is dissipated to the liquid. The flow of liquid inside the microchannel is defined to be laminar. These physics were coupled together (multiphysics) by the electromagnetic heating and non-isothermal flow modules. To minimize the complexity of the model and to optimize simulation time, the thin electrodes (100 nm) were represented as a 1 layer conductive shell. The temperature of the liquid at the inlet was set to room temperature (20 °C), the outlet was defined as a fluidic and thermal outflow. The fluid flow rate was determined by a parametric sweep, varying the flow rate between 1 and 100 µL/min.

Prototype design

The design of the prototype is shown in figure 1. The fluidic parts is fabricated by TNO Holst Centre (figure 2), consisting of three layers of dry foil resist (TOK, 45 µm). The first layer contains embedded microelectrodes (Au 75 nm) for flow sensing, the second layer contains the microfluidic channel features (width 300 µm, height 45 µm) and the third seals the fluidic circuit and provides access to the microfluidic channel.

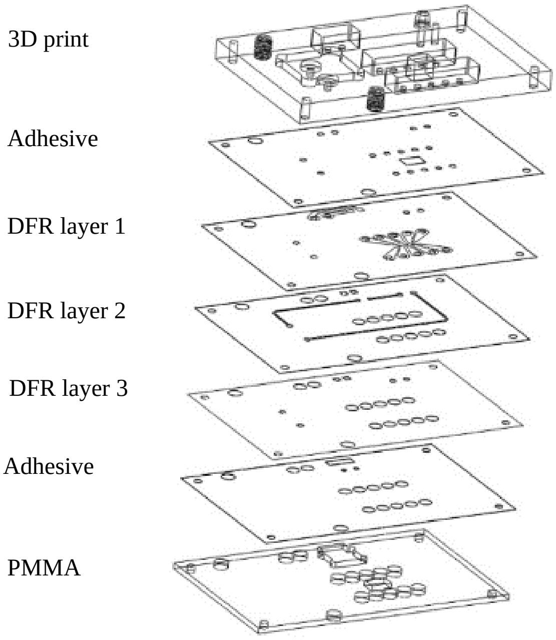

Figure 1: Exploded view of the flow sensor design. The fluidic layer consists of 3 layers of dry foil resist, which is bonded in between a 3D printed and a bottom PMMA layer using laser-cut pressure sensitive adhesive.

The fluidic stack is sandwiched in between a 3D print (Asiga Max X27, Moiin Tech Clear) and a lasercut PMMA layer (thickness 1 mm) to allow integration of the flow sensor and connection to an external pump. Effective bonding between the different layers is accomplished using laser-cut pressure sensitive adhesive (PSA). A conductive silver paste was used to electrically connect the gold electrodes to the pin headers, which were glued in place using epoxy glue. The Sensirion flow sensor will be used to benchmark the embedded thermal flow sensor and to optimize its performance.

Experimental setup

A piezoelectric micropump assembly (µP030, EMFT Fraunhofer) was fluidically connected to the inlet of the prototype (figure 3) to supply a fluid flow of DI water at ± 21°C (Extech SDL200). The flow rate was varied by adapting the actuation signal (waveform, amplitude and frequency) provided by a custom piezo-actuator and software. A flow sensor (Sensirion LPG10-1000) and head stage were mounted on the 3D print. A current source (BK precision 9130) was connected to the heater electrode, providing a constant current condition. A digital multimeter (HP3478A) was used to measure the resistance of the down-stream sensor electrode. As a control, a Fluke 115 multimeter was used to monitor the resistance of the upstream electrode. Presented results indicate the increase of downstream sensor resistance after drift compensation.

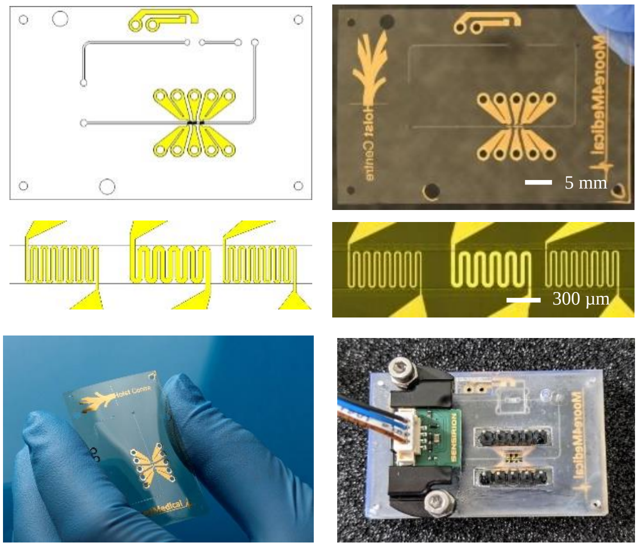

Figure 2: Design (top left) and fabrication (top right) of the fluidic layer (DFR) containing microelectrodes. Bottom: assembled prototype including the Sensirion flow sensor with head-stage.

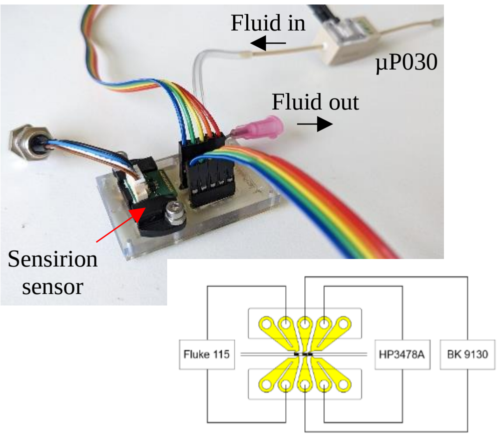

Figure 3: Experimental setup showing the fluidic and electric connections to the flow sensor prototype.

RESULTS & DISCUSSION

The 3D COMSOL model is shown in figure 4. A laminar flow condition is applied at the channel inlet, resulting a simulated fluid flow over the upstream sensor, heater and downstream sensor towards the channel outlet. The selected flow rates for simulation (figure 5) are based on the experimental obtained values (figure 6).

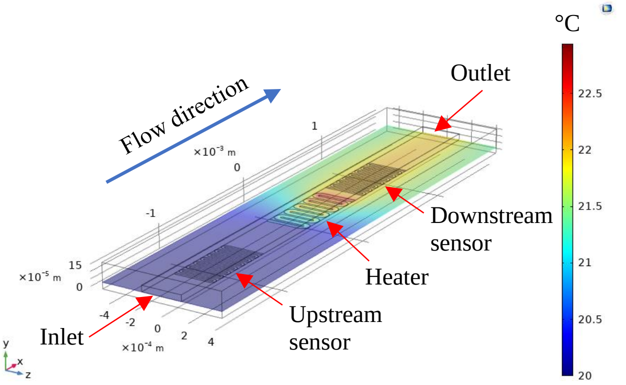

Figure 4: 3D COMSOL Multiphysics model of the thermal flow sensor embedded in a microfluidic channel (channel dimensions h x w x l: 45 x 300 x 3000 µm, flow rate: 24.8 µL/min, electrode current: 8 mA).

Figure 4 shows the concept of thermal flow sensing. Due to a constant current condition at the heater, the liquid heats up, resulting the downstream sensor to heat up as well, resulting in an increase of electrical resistance. Using this model, the temperature development in the channel was investigated at different flow rates (figure 6).

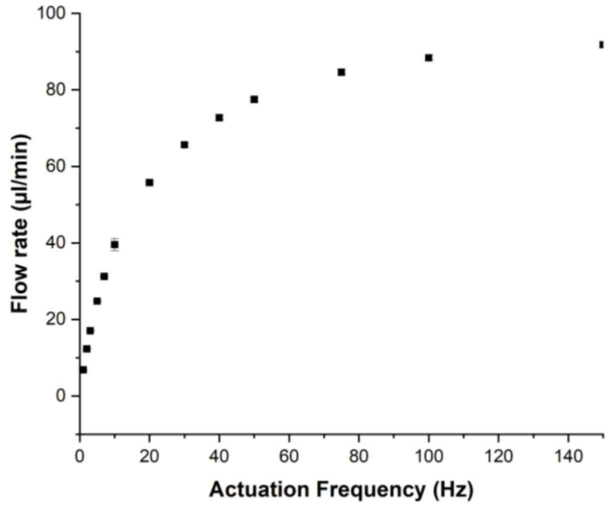

Figure 5: Measured flow rate (Sensirion) versus pump actuation frequency (rectangular waveform, 100/-20V amplitude).

Before simulations were performed, the pump performance was benchmarked using the external flow sensor (Sensirion) using fixed actuation frequencies (figure 4). The resulting flow rates were used in COMSOL simulations (figure 5).

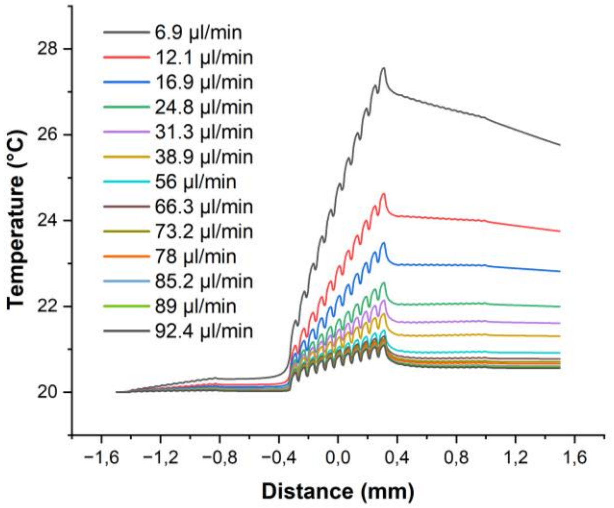

Figure 6: Simulated fluid temperature distribution on the bottom (electrode) plane of the microfluidic channel from channel inlet to outlet at different fluid flow rates (8 mA constant current).

Simulations show that at fluid flow rates above 12 µL/min heat dissipation is dominated by convection, preventing diffusion of heat towards the upstream sensor (anemometric regime). Increasing fluid flow results in more effective “cooling” of the heater, yielding a decrease in fluid temperature at the downstream sensor.

Before experiments were initiated, the resistance of the heater and sensor microelectrode was measured to check the electrical connection to the microelectrodes. Measured resistance was 150 Ω and 50 Ω respectively; simulated resistance values were 72.5 and 25 Ω respectively. Simulated values only account for the resistance of the microelectrode itself rather than the resistance of the electrical leads in total. Furthermore, the width of the sensing microelectrode (±17 µm) was slightly smaller than the design and simulated value (20 µm), further increasing its effective resistance.

The results of the experimental characterization of the flow sensor are shown in figure 7. The experimental data is normalized to an increase of electrical resistance (ΔR) for better comparison with the simulated values.

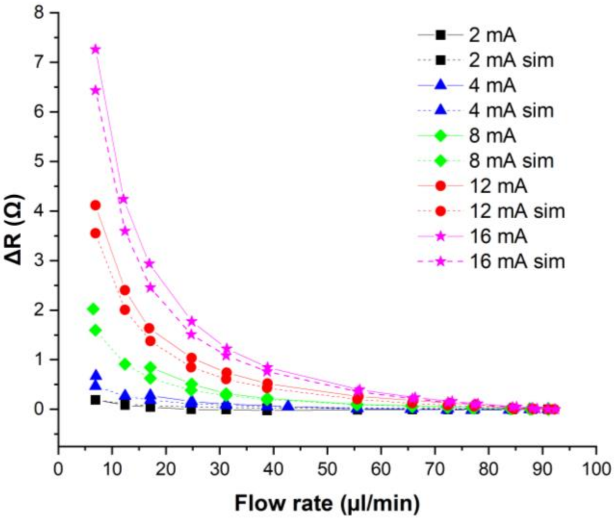

Figure 7. Experimental (straight line) and simulated resistance change (dashed line) of the downstream electrode versus flow rate at 5 different constant current conditions.

At low flow rates, heat transfer from heater to sensor is most efficient resulting in a large increase in resistance. Furthermore, increasing the applied current will result in more heat generation and a larger increase in sensor resistance. A good correlation of simulated and experimental data is observed, proving the functionality of the thin film-based, monolithically-integrated thermal flow sensor and the validity of the COMSOL model.

CONCLUSIONS

This abstract shows the proof-of-concept of a monolithic integration of a thermal flow sensor inside a microfluidic channel using thin film technology. This approach could prove be very interesting for flow sensing in integrated setups including micropumps. Future work will focus on optimizing the design of the flow sensor to achieve proper sensor functionality in the relevant flow rate regime typically used for Organ on Chip applications (1-100 µL/min). Furthermore, the use of different electrode materials will be investigated to make the sensor more robust and to allow more cost-effective integration.

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