Measurement of Temperature in Parallel Channel of Microfluidic Reactors

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***Abstract*— Measurement of temperature in microfluidic devices during their operation is a common and important task. Knowledge of the temperature value, steepness of the temperature gradient, or temperature evolution over time is crucial for subsequent modelling or control of chemical processes taking place inside the device. However, due to spatial limitations, the integration of sensors can be very challenging. Herein, the development of a temperature monitoring system integrated into a flexible polydimethylsiloxane (PDMS) based microfluidic reactor is presented for use in electrochemical flow cells. The system is based on a set of thermistors mounted in one of the parallel channels of the multichannel microfluidic reactor. Sacrificing one of the channels allows the integration of inexpensive and relatively large sensors into the device and the measurement of the temperature directly inside the electrochemical system even under harsh conditions. The static and dynamic properties of the system are evaluated. Furthermore, the fabricated system can be easily integrated into the standard manufacturing process of any microfluidic device.**

Keywords—Temperature sensor; Microfluidic channel; Sensor Integration; Microreactor

I. INTRODUCTION

Numerous types of microfluidic devices have been developed as a result of advances in microfabrication techniques [1,2]. However, due to constraints of the manufacturing process and size sensor and geometry, it is still challenging to obtain accurate fluid temperature data [3,4]. Conventional high-precision equipment and temperature sensors have weak interference immunity, high costs, and require professional operators. Although many studies have been carried out on the measurement and calibration of temperature in microfluidic devices [5,6], a unified and systematic theory is still lacking. As a result, research on temperature calibration and the properties of microfluidic heat transfer is becoming increasingly important in a microfluidic chip system [7-9].

The two main methods for measuring temperature in microfluidics are contact methods based on thermocouples and thermistors. Modern non-contact measurement in microfluidics is usually carried out by infrared thermometers [10,11].

Numerous contact temperature sensors, for instance thermocouples [12,13] of micro- or even nano-size, can be applied directly to the fluid of the microchannel. However, using a contact thermocouple probe exposes it to potential chemical damage (e.g corrosion) and falls short of the desired high reliability. Another important type of thermometer is a platinum thin film resistance temperature detector (RTD) [14] but is limited to temperature measurements in small volumes because it must be connected to a substrate.

Herein we designed and fabricated a model of multichannel microreactor that could easily be adopted for electrochemical processes. The developed system is equipped with a set of integrated thermistors to measure the temperature during electrolysis, which is generally a difficult task because of the unfavorable conditions within the system. For that purpose, we selected through-the-wall contact measurement by conventional thermistors in a sacrificed channel. We also addressed the static and dynamic properties of this method.

II. MATERIAL AND METHODS

A. Microchannel structure and design

The inspiration for these experiments is the channel design of the electrochemical flow reactor described in the work of Laudadio et al. [15]. This reactor is special due to its flexible reactor volume, which can be used in parallel mode (i.e. numbering-up) or serial mode (volume ranging from 88 µL/channel up to 704 µL). The microreactor is made mainly of polytetrafluoroethylene (PTFE).

Herein described experiments use simplified two channel model of microreactor made of PDMS. PDMS has excellent thermal stability, optical transparency, isotropy, homogeneity, and resistance to swelling with humidity. However, PDMS still requires a solid support to completely enclose the channels. For this reason, we selected polymethylmethacrylate (PMMA), a relatively inexpensive material, with exceptional optical quality, perfect stability, gloss and transparency finish, hardness, and scratch resistance. Pressure-sensitive adhesive (PSA), also known as self-adhesive, self-stick, or pressure-sensitive adhesive, is a kind of nonreactive adhesive that adheres to a surface when pressure is applied. To activate the adhesive, no solvent, water, or heat source is required, however we use oxygen plasma bonding [16]. As temperature sensor, we selected a commercial high precision Negative Temperature Coefficient (NTC) thermistor MF52. Its characteristics include a large resistance range (0.1 ~ 500 kΩ), compact size, quick response, good consistency, long-term stability, and an exceptional temperature range (-40 ~ +125°C). The schematic of the device is seen from Fig. 1.

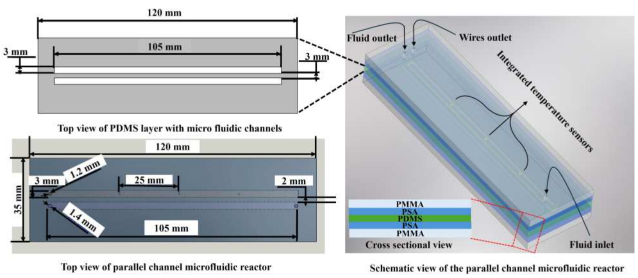
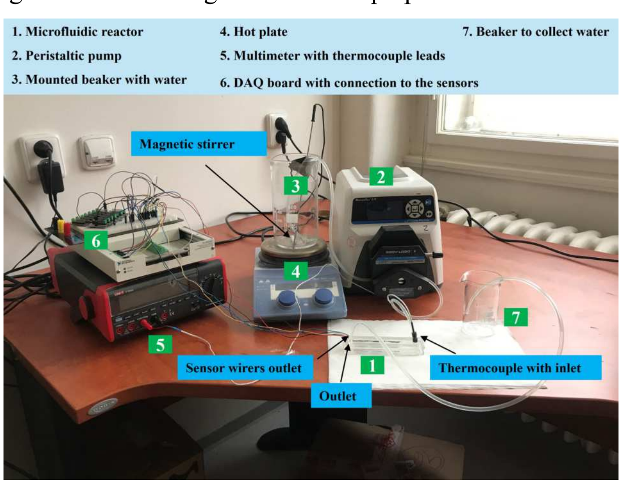


Fig. 1. Schematic representation of the microfludic reactor.

B. Concept and working mechanism of the device

The conceptual framework, experimental representation, and working mechanism of the proposed parallel microfluidic reactor with integrated temperature sensors are schematically illustrated in Fig. 2. It depicts the experimental setup, designed for temperature measurements, where hot water is used as a testing fluid. This setup comprises a stirring and heating plate, peristaltic pump, bread board, DAQ board, and laptop with LabVIEW development environment. A mounted beaker with water on a heating plate setting a temperature between 23°C and 50°C is used to accurately regulate the temperature by supplying water through the inlet. A peristaltic pump is used to accurately inject the water with a flow rate of 15 $mL.min^{-1}$ to the microfluidic reactor with integrated temperature sensors. The integrated sensors are connected to the power supply from the DAQ board to the breadboard. To visualize temperature fluctuations during hot water flowing from one sensor to the other all the way through the channel, the process is observed using the LabVIEW algorithm from laptop.



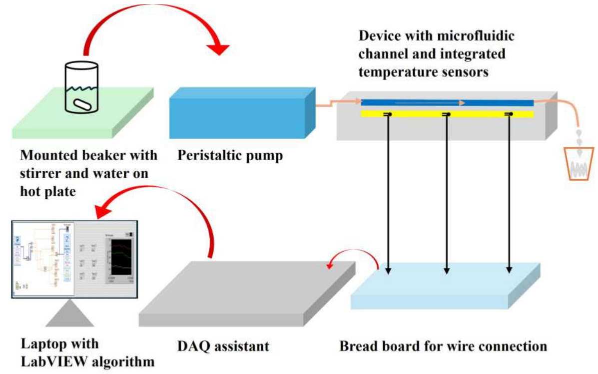


Fig.2. Working mechanism, experimental, and schematic representation of the fabricated prototype.

C. Fabrication of reusable 3D printed mould

Using the Autodesk Inventor Professional 2024 CAD software, models are created before being manufactured using PETG (polyethylene terephthalate glycol) and the Original Prusa i3 MK3S+ 3D printer. The CAD and 3D printed versions are displayed in Fig. 3.

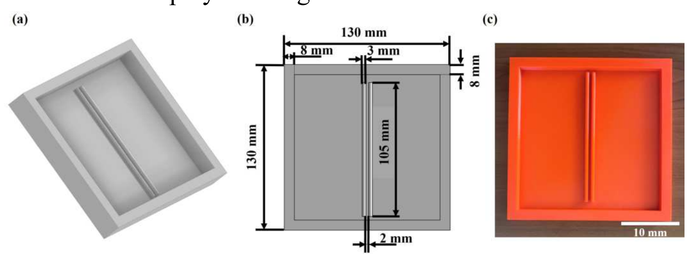


Fig. 3. 3D printed versions of the microchannel replica. (a) 3D model, (b) front view, (c) printed mould with visible channels

D. Fabrication of PDMS microchannel

The PDMS mixture was prepared by mixing a 10:1 ratio of base polymer to curing agent and was then placed in a vacuum oven for 30 min to remove air bubbles. The PDMS mixture was subsequently poured onto the 3D printed replica and again degassed in a vacuum oven for 10 min (Fig. 4. a) and followed by curing at 80 °C for 90 min using a preheated oven. After curing, the PDMS layer with well-defined parallel channels was gently removed/peeled off from the 3D printed mold (Fig. 4. b-f).

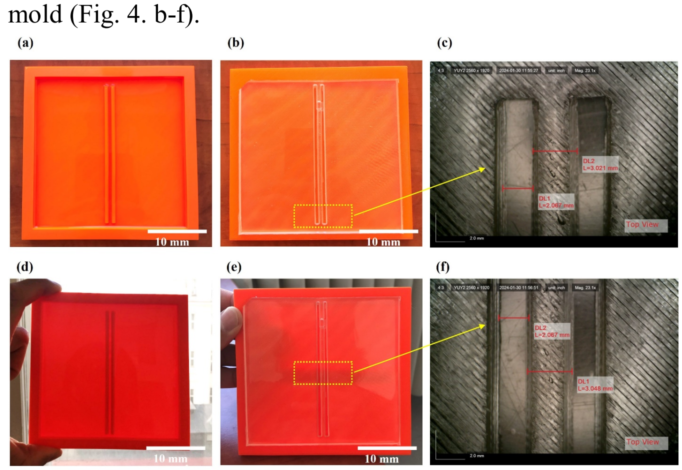


Fig. 4. Fabrication of PDMS based microchannels. (a) Fully cured PDMS inside the 3D printed mould, (b) Peel off the PDMS from the mould, (c) microscopic images of the well-defined PDMS based channels, (d) (e) front view from different angles of the fabricated PDMS layer with parallel channel, (f) microscopic image from the middle section of the channel to confirm the uniformity.

E. *Fabrication of multichannel microfluidic reactor with integrated sensor*

After the successful fabrication of the PDMS based microfluidic reactor, we need two critical components. First, the well-balanced support by using a 30 mm thick (PMMA) plate and Pressure Sensitive Adhesive (PSA) a double-sided tape with the thickness of 3 mm to match the compatibility of PDMS. Once, the PMMA substrate was gently cleaned with isopropyl alcohol solvent and wipes, the PSA was laminated onto the PMMA substrate. To aid in bonding, the PMMA-PSA assemblage was compressed for two minutes using a hydraulic press (Trystom OLOMOUC). For the bonding of these two materials, the PSA laminated on the PMMA and PDMS surfaces were then exposed to oxygen plasma treatment for 1 minute while operating at 100 W, 25 mL_min^{-1} oxygen flow, and 600 mTorr chamber pressure. The treated PDMS layer was then placed above the PSA. Gentle pressing using a hydraulic press for 10-15 seconds at room temperature (23 °C) was followed by curing in the oven at 80 °C for 20 min. Additionally, a high thermal conductivity adhesive resin was used to firmly integrate the temperature sensors to the channel.

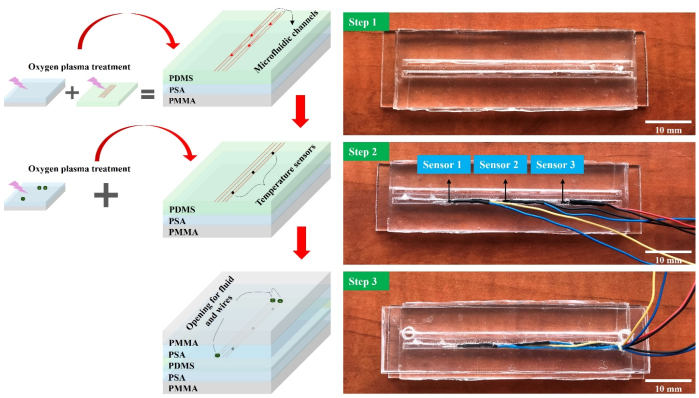


Fig. 5. Sensor integration into channel representation both schematically and fabrication of the real device.

Moreover, we created a second PMMA layer with the same geometry, but this time it was intended for the channels top cover with integrated sensors. An inlet and outlet for fluid and tiny hole for wires were neatly drilled to connect the layer to the circuit for additional analysis. Ultimately, the height of the constructed platform with integrated temperature sensors was measured to be 70 mm, including the wires for the power supply as seen from Fig. 5.

III. Results and Discussion

A. *Characteristics of the multichannel microfluidic device with integrated sensors*

The optimal design strategy for the platform was essential to achieve the desired temperature change. The results are shown in Fig. 6. that the fabricated microfluidic based microreactor has a potential for further investigation.
Fig. 6 (a,b) represents the dynamic characteristics of the sensors when the fluid temperature was 34.4 °C, and 28.6 °C respectively. The gradual decline from Sensor 1 to Sensor 3 reflects the fluid cooling over the distance between sensors which is 25mm. Fig. 6 (c) depicts Sensor 1 which is close to the inlet, that's why it shows a better outcome for all temperatures (37.7°C ~ 26.2°C). The final Fig. 6(d) indicates the final measured temperature with respect to the input temperature of the fluid. That's why the static characteristics was led by Sensor 1 by margins from Sensor 2 and vice versa.

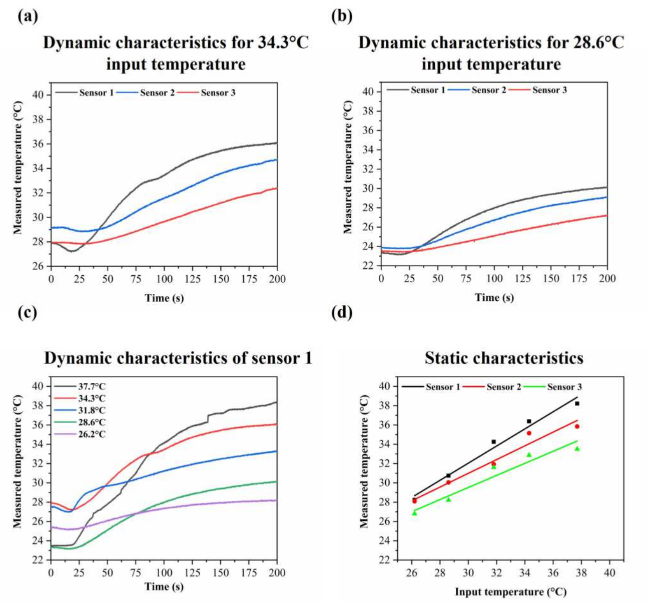


Fig. 6. Temperature profile of the integrated sensor into microfluidic reactor. (a-b) sensors dynamic characteristics with two different temperatures of the fluid, (c) sensor 1 temperature changes with different temperature of fluids (37.7°C~26.2°C), (d) Linear plots of the sensor's static characteristics.

IV. Conclusion

We successfully fabricated a model of the microfluidic reactor from PDMS that can be applied to electrochemical processes. Subsequently we achieved the integration of thermistors as conventional temperature sensors and measure their static and dynamic properties which proved to be promising and should be further investigated in an electrochemical reactor in use for temperature control/measurement.

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