

# Integrated Resistive Heating Systems in a Microfluidic Platform for Biological Applications

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## Summary:

In contrast to traditional heating solutions described in the literature, which often rely on complex and time-consuming lithographic processes or metal thin-film deposition [1], this work utilizes the innovative technology of rapid, direct printing of carbon nanotube (CNT) resistive heaters onto a glass substrate. This method offers the tremendous advantage of unparalleled flexibility in forming heaters of arbitrary shapes. By integrating these heaters into a microfluidic LOC platform, we provide a reliable system that enables precise temperature control for cell studies, allowing for more advanced *in vitro* research.

**Keywords:** heating system, carbon nanotubes, lab-on-chip, microfluidics, hydrogels

## Background, Motivation, and Objective

Rising cancer rates underscore the urgent need for bioengineering innovations that can faithfully replicate the human physiological environment. In this study, we present a lab-on-chip (LOC) platform designed to push the boundaries of cell engineering. Using advanced and biocompatible hydrogel matrices and microfluidic structures, our platform creates a dynamic microenvironment, providing a crucial link between traditional *in vitro* models and the complexities of living systems. A key aspect and innovation of the presented solution is the adaptation of resistive heater technology for precise biological applications. While previous work by the team focused on thermoresponsive phenomena induced by carbon nanotubes (CNTs) for the rapid micropatterning of hydrogel systems [2], the current approach presents a fully functional, modular research workstation. Its fundamental component is a precise heating system (HS), in which the resistive layer consists of CNTs 3D printed directly onto a glass substrate. This bio-platform is complemented by an external peristaltic pump, which continuously and controllably pumps liquid (culture medium) into the system, accurately simulating the circulation of fluids.

## Description of the New Method or System

Figure 1 shows the main components of the developed and advanced LOC platform. As mentioned, the HS of a special design incorporated into the bio-platform was fabricated utilizing the additive manufacturing (AM) technique (Fig. 2).

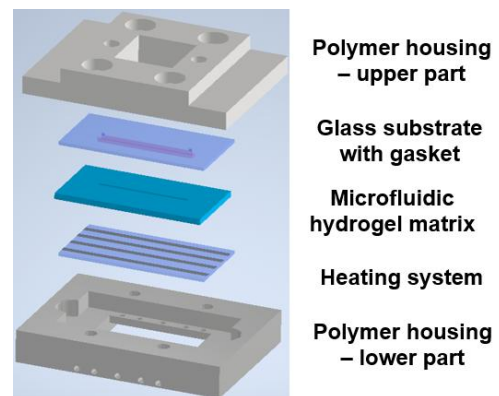


Fig. 1. Microfluidic LOC device scheme.

Conductive layers (5 layers per HS) of single-walled carbon nanotubes SWCNTs (OCSiAl's Tuball Batt with 0.4% SWCNT and 0.8% poly(vinylpyrrolidone) (PVP) in H<sub>2</sub>O) of various geometries were extruded on the borosilicate glass substrate (Borofloat 3.3 glass), being a part of the sandwiched type platform with hydrogel matrix. The extrusion parameters were as follows: printing speed 5 mm/s, nozzle temperature 28 °C, print bed temperature 30 °C, printing pressure 25 – 30 kPa, and nozzle size 0.25 mm.

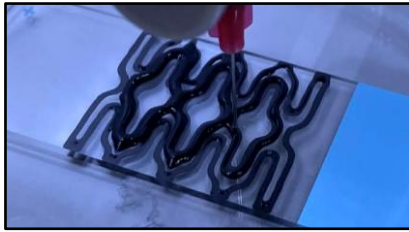


Fig. 2. Extrusion of the SWCNT.

To validate the platform's capabilities, diverse flow tests were conducted using water and a cultivation medium by the standard gravimetric method. The flow speed was set to 50  $\mu\text{L}/\text{min}$ .

## Results

Using AM technology, three types of such heaters were manufactured and tested, as shown in Fig. 3.

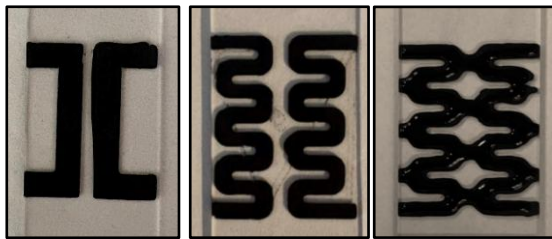


Fig. 3. Conductive layers of the HS with varying geometries: simple, meander, and connected.

Representative dimensions of a simple heater are shown in Fig. 4. Furthermore, the 3D printing fidelity of the heaters was evaluated by comparing the fabricated geometric dimensions with their nominal values specified in the design files. For simple heaters, the dimensional deviation was merely about 3%. However, for arbitrary, more complex patterns, which represent a core advantage of this technique, the deviation reached over 14% due to material spreading on rounded edges during the 3D printing process.

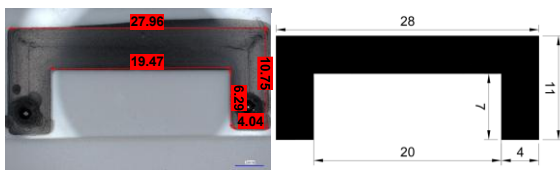


Fig. 4. Representative dimensions of a resistive heater [mm].

Electrical connections were implemented using two distinct methods: a standard mechanical connection utilizing alligator clips and a customized, low-resistance soldered connection. Notably, the measured resistance of the heaters was, on average,  $\approx 27\%$  higher with alligator-clip connections than with non-standard soldered joints. The soldered joint ( $\approx 1$  mm in height) significantly facilitates the soldering of a lead wire and ensures a highly reliable ohmic contact, a notable

achievement when working with carbon-based materials.

The heaters were driven by a DC voltage of up to 20 V, and the power dissipated within them results from the flow of electric current according to the Joule-Lenz law. The electrical power consumption and all relevant heater parameters are summarized in Tab. 1. By optimizing the power supply parameters, a target surface temperature of  $\approx 30^\circ\text{C}$  was successfully attained on the glass substrate for all heater configurations, confirming the high efficacy of this direct-write approach.

Tab. 1: Resistive heater parameters

| Parameter                                  | Simple Soldered joint | Simple Alligator clip | Meander Soldered joint | Meander Alligator clip | Connected Alligator clip |
|--------------------------------------------|-----------------------|-----------------------|------------------------|------------------------|--------------------------|
| Average absolute dimensional deviation [%] | -2.84                 | -1.36                 | 10.68                  | 7.94                   | 14.45                    |
| Resistance value [ $\Omega$ ]              | 138.5                 | 207.5                 | 501.5                  | 661.0                  | 255.0                    |
| Electric power [mW]                        | 12.44                 | 13.32                 | 25.14                  | 31.45                  | 17.53                    |
| Temperature [ $^\circ\text{C}$ ]           | 30.2                  | 29.8                  | 30.9                   | 30.1                   | 30.3                     |

The flow characteristics of the tested liquids are shown in Fig. 5, exhibiting a positive correlation between the mass increase over time. The highest flow rate was observed for the culture medium. In turn, water flow exhibits the best consistency between the pumped mass and the set flow rate (50  $\mu\text{L}/\text{min}$ ).

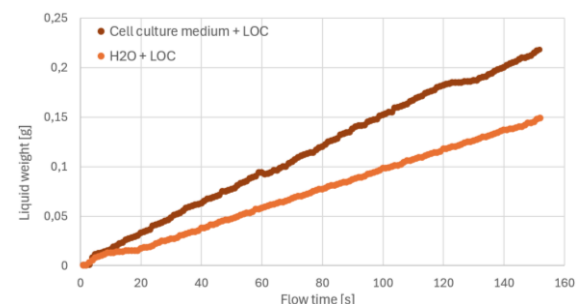


Fig. 5. Positive results of microflows for water and cultivating medium.

## References

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