

Simulation of Thermal Transport Based Flow Meter for Microfluidics Applications

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Abstract: In our study, COMSOL Multiphysics® is used to simulate a thermal transport based flow sensor, which will be embedded in a micro-channel of a Poly-methyl methacrylate (PMMA) based microfluidic device. The channel height is 400µm and for simulation purposes the lengths has been set to 1.2mm. The heater element and the two sensors are made of platinum and were modeled using Heat Transfer in Fluids, Laminar flow and Joule heating interfaces. The three elements have a thickness of 300nm, which can be sputtered and patterned in the real device.

Keywords: flow meter, microfluidics, sensor, thermal sensing.

1. Introduction

A miniaturized and non-invasive methodology for ascertaining the velocity and/or direction of different flowing media is imperative in microfluidic devices. The amount of heat removed or redistributed from a heated temperature sensor by a surrounding flow can be used to determine the flow velocity. The sensors that use the heat dissipation principle are called thermal transport flow meters [1]. The absence of moving parts in these flow meters makes them suitable for applications where small diameter tubing is required. The advantages of thermal transport sensors also include high sensitivity and broad dynamic range, compared to other types. They can be sub-classified in hot-wire based or calorimetric sensors.

In calorimetric-type thermal transport sensors (Figure 1), the device measures variations on the temperature profile around a heater, which is affected by the fluid flow. The central resistor (R_2) acts as the heater, while the others are used to monitor the temperature profile around it. In presence of flow, the temperature of R_1 will decrease along with its corresponding resistance value, while the temperature and resistance of R_3 will increase. This calorimetric technique is widely used in

micro-machined or MEMS-based flow sensors, obtaining highly compact and non-invasive flow meters [2, 3]. Also, their simplicity in structure and electrical response, as well as their well-known operation principle make them suitable for microfluidics applications.

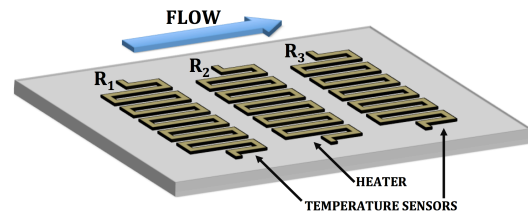


Figure 1. Calorimetric flow sensor.

2. Background Theory

Anemometry is defined as the process of ascertaining the force, speed and/or direction of wind or an airflow. This process and gas flow measurements in general find many applications in meteorology, manufacturing processes, automotive, air-conditioning industry and many others where the flow rate measurement and/or control of air or other gases are necessary. Anemometers or gas flow sensors with limited moving parts, which introduce little restriction to the flow, will be addressed in this report. Going through the literature and in compliance with the systematic reviews presented by Nguyen (1997) [2] and Wang (2009) [3], flow sensors can be broadly classified as thermal or non-thermal types.

2.1 Basics of Fluid Dynamics

In general terms, the moving media whose flow is measured in mechanical engineering are liquids, air or other gases. Streamlines can be drawn through every single point of any moving medium, as shown in Figure 2(a). Any sample of the flow enveloping a bundle of streamlines is called a tube of flow. Since the boundaries of such a tube consist of streamlines, no fluid can cross the boundary of a tube of flow and it can be treated as a pipe of some sort. Inside the pipe,

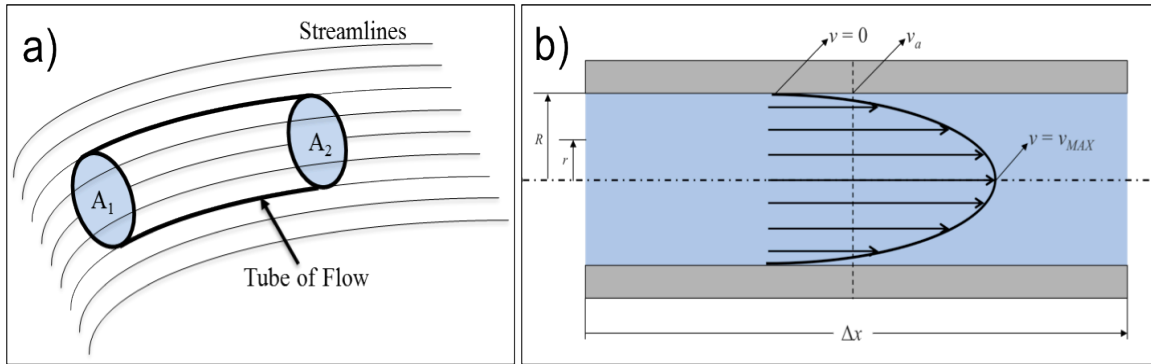


Figure 2. a) Tube of flow [1]. b) Flow velocity profile within a pipe.

the velocity profile of the moving material have a parabolic shape with different magnitudes at different points along the tube, see Figure 2 (b) above. If we cut a plane of the pipe, the volume of moving material passing it in a specific time interval is as follows [1]:

$$\Lambda = \frac{V}{\Delta t} = \int \frac{\Delta x}{\Delta t} dA = \int v dA \quad (1)$$

Where Δt is the time interval, Δx is the displacement of volume V , and v is the velocity of the moving material that must be integrated over the area A . Since the velocity of a fluid in a pipe varies over the cross-section, an average velocity is defined as:

$$v_a = \frac{\int v dA}{A} \quad (2)$$

Then, a product of the average velocity and the cross-sectional area is what we called flux or flow rate:

$$Av_a = \int v dA \quad (3)$$

Flow sensors usually measure the average velocity, v_a . Therefore, to determine the flow rate, the cross-sectional area of the tube of flow is always required. There are many types of sensors that can measure the flow velocity by determining the rate of displacement of either mass or volume. But, regardless of the type of sensor, it is necessary to take into account other parameters that also affect the measurement besides the cross-sectional area of the pipe, such as temperature and pressure.

2.2 Thermal Flow Sensors

The amount of heat removed or redistributed from a heated temperature sensor by a surrounding flow can be used to determine the flow velocity. The sensors that use the heat dissipation principle are called thermal transport flow meters or thermo-anemometers [1]. The absence of moving parts in this kind of flow meters makes them suitable for applications where small diameter tubing is required.

The advantages of thermal transport sensors also include high sensitivity and broad dynamic range, compared to other types. Thermal flow sensors can be classified into two sub-types [2]:

1. Hot-wire or Hot-film sensors: The sensor measures the cooling effect of the flow on a hot body. This effect can be detected by either the increase of heating power to maintain a constant temperature, or the decrease of the temperature when a constant heating power is applied.
2. Calorimetric sensors: The sensor measures variations on the temperature profile around a heater, which is affected by the fluid flow. This technique is almost exclusively used in micro-machined or MEMS-based flow sensors.

2.3 Micro-machined Thermal Sensors

Micro-fabrication techniques have been implemented to develop many new sensors and improve existing ones since the formal introduction of micro-electro-mechanical systems (MEMS). Highly compact and non-invasive flow meters have been developed using this technology. Other advantages typically shown by miniaturized flow sensors include greater precision, lower power consumption,

more rapid response and low-cost batch production [3]. They have also been important during the development of microfluidic devices, as they often require the integration of flow sensors capable of measuring very small flow rates.

In general terms, thermal sensors have been preferred to implement MEMS-based flow meters due to their simplicity in structure and electrical response and their well-known operation principles. In fact, the first flow sensor based on silicon technology, introduced by Van Putten in 1974 [5], was developed upon hot-wire anemometry.

3. Geometry design and model setup

For the present project we have used the CFD and Heat Transfer modules of COSMOL Multiphysics 4.3b. The simulations were modeled in a two-dimensional environment, as a cross-section of a micro-channel with an embedded flow meter. The dimensions of the micro-channel are: 1.2mm in length and a height of 400 μm .

The two-dimensional geometry of the sensor is shown in Figure 3. The sensor is mounted on a platform or a step height difference in the micro-channel. The sensor base (platform) has the following dimensions: height of 10 μm and a length of 120 μm . The sensor comprises three different metallic features: left sensor, heater and right sensor. The heater is located between the two sensors, such that the flow in the channel will displace a temperature gradient to the immediate sensor (in the flow direction).

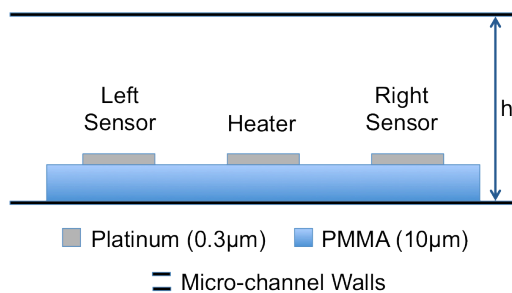


Figure 3. Two-dimensional micro-channel model, height (h) is 400 μm . (Cross-section not in scale)

The platform of the flow sensor contributes to the overall working principle of the device. Because the substrate positions the sensor in a

higher flow velocity of the fluid (towards the center of the channel, where maximum flow velocity is reached), the temperature distribution in the fluid along the channel is transferred in a better manner. This can be seen in Figure 4, where two simulations were performed: one with the PMMA platform and one without it (leaving the flow sensor directly in contact with the channel bottom wall (where the flow velocity is close 0 m/s, which restrict the temperature distribution to the immediate sensor).

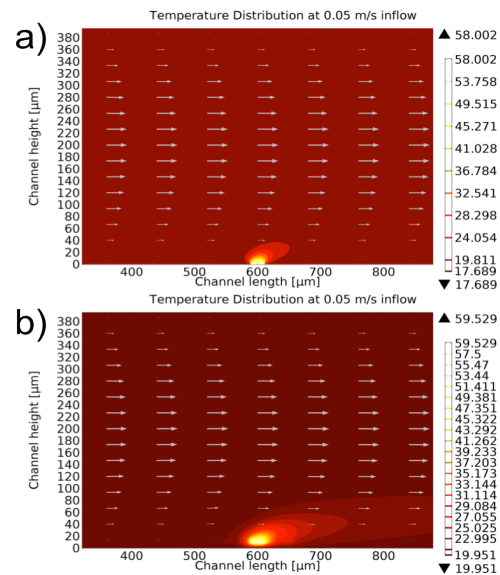


Figure 4. No PMMA platform vs. PMMA platform simulations: a) No PMMA platform b) PMMA platform. (Inflow for both: 0.05m/s).

2.3 Materials and boundary conditions

The materials chosen for our simulations were: water (for the main fluid in the micro-channel), platinum for the heater and sensors and PMMA for the platform (base) of the flow sensor. To have an accurate simulation of the device physical boundary conditions need to be set up correctly.

For the Laminar Flow physics of the CFD module the boundary conditions were as follows: wall of the channel (to constrain the fluid), an inlet and an outlet. For the Heat Transfer in Fluids physics the boundary conditions were: heat transfer in solids (for the PMMA and metal layers used for the flow sensor), temperature 1 (external environment temperature of 20 $^{\circ}\text{C}$) and temperature 2 (constant temperature emitted by the heater at 60 $^{\circ}\text{C}$).

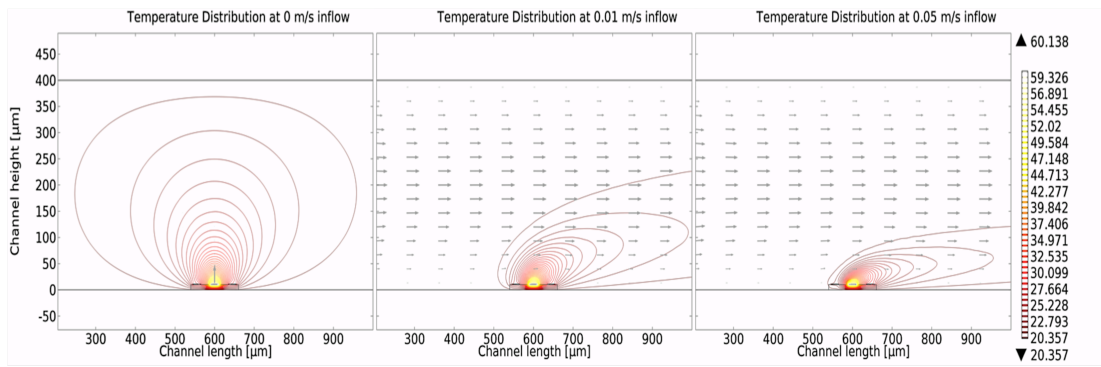


Figure 5. Temperature distribution in a channel with different inflow rates.

4. Results

A parametric study was performed to vary the inlet flow. The “flow” parameter was created to be able to modify the model inflow in the simulations. The temperature distribution at different flow rates was generated in a surface graph, as shown in Figure 5 above.

From this study we were able to plot the temperature seen by both: left and right sensors. Figure 6 shows a graph of the temperature gradient along a 2D cutline of 150 μm in length, positioned just above the metal thickness of the sensors and heater.

The temperature perceived by both sensors is plotted in Figure 7. The read temperature is measured from the top surface of the metal layer in the center of its length.

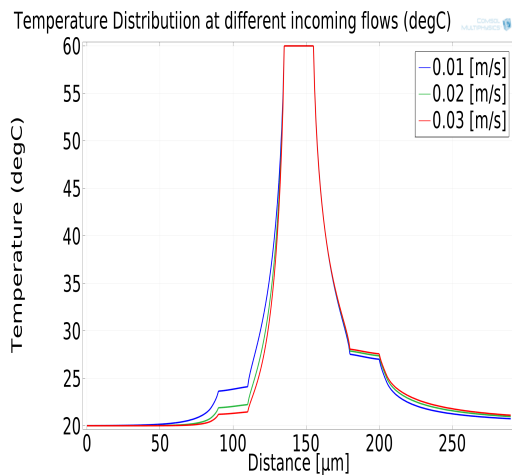


Figure 6. Temperature distribution along the PMMA platform length, above the metal layers.

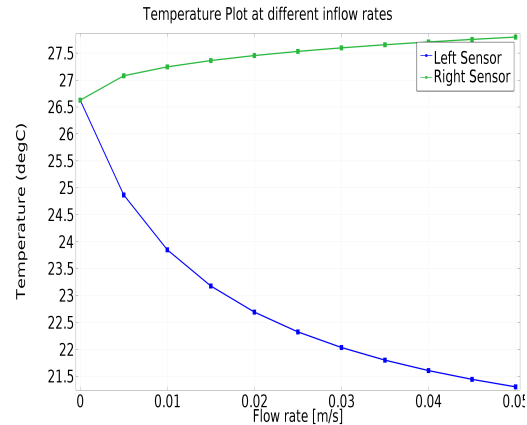


Figure 7. Temperature at top center point of the left and right sensor's surfaces.

5. Conclusions and future work

In this work we presented results of the simulations of one of the possible type of flow sensors described in this report. The largest temperature difference between the two temperature-sensors is approximately at 7 $^{\circ}\text{C}$, these results provide an important characteristic of the working range of the device. Further simulation studies with modified channel height, platform height, sensors to heater gap and metal thickness, will aid in the selection of the optimal parameters for the device fabrication.

Thermal flow sensors have been very popular and widely used for different applications since the early introduction of hot-wire anemometry in 1914. These sensors are preferred for miniaturization, due to their well-known operation principle and easy integration. The implementation of this sensor can be adapted to the current microfluidic projects of our research group, where a flow rate reading within the micro-channels is desired.

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