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Variable Flow Sensing with Thermal Anisotropy

Introduction

Micromachined flow sensors are an increasingly studied area as experimentalists analyze its integration to wireless flow sensing applications that are being utilized in several avenues of research. These flow sensors are typically categorized as either thermal or non-thermal. Thermal flow sensors are notable for their simple design and ease of miniaturization. With thermal flow sensing comes advantages such as low power consumption, higher sensitivity to low flow rates, ability to detect thermal properties like thermal conductivity and thermal diffusivity as well as ease of transition between different modes of operation [1]. Under the subset of thermal flow sensing lies the three forms which are hot-wire and hot film, calorimetric and time-of-flight. The design discussed in this paper closely models the calorimetric sensing. This form utilizes one thermal sensor upstream and another downstream with a thermal actuator in between developing heat that can be later reviewed for its thermal profile during fluid flow experiments. Within this design lies the implementation of thermal anisotropy where thermal profiles are utilized to performed back calculations to track fluid flow based on directional dependency of heat in fluid flow.

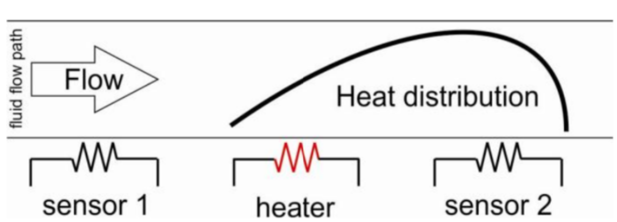

Figure 1. Depiction of Thermal Anisotropy Concept [1]

Within the scope of this research paper, different variables are explored in an effort to collect data that points to the most optimized thermal anisotropy setup. The main objective were to explore capabilities of flow sensing with thermal anisotropy in variable flow regimes (0.01 – 1000 mL/min), to build a phantom skin platform with variable vessel diameters and assemble an array of actuator geometries for testing a wide range of flow rates as well as establish a streamlined data acquisition system to perform multiple tests analyzing the impact of sensor spacing from the end of the thermal actuator. Work is done to identify sensor/actuators architecture and geometry that provides optimal $T_{sensors}/T_{actuator}$ sensitivity for Q_{blood} (~600 mL/min).

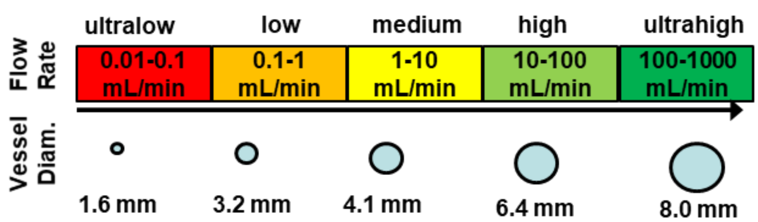

Figure 2. Variable Vessel Diameter and Flow Regimes

Setup

In developing the setup for the study, a couple different factors needed to be accounted for. First it was important to create an adequate replicate of skin conditions so as to obtain translatable data for when the study is transferred on to organic specimen. To do this, a 3D printed mold serving as the base for a phantom skin was designed in SolidWorks. To mimic skin conductivity which typically lies between 0.3-0.5 W/m*K, the mold was filled with Sylgard 170 with a conductivity of 0.42 W/m*K with uniform skin thickness of 1 mm till the tube is reached. Each tube is PTFE tubing with a thermal conductivity of approximately 0.35 W/m*K and uniform tube thickness of 0.8 mm. In an effort to gain some initial confirmation that thermal anisotropy was achievable via this method, preliminary tests were performed with an actuator-only device at high flow (0 and 100 mL/min) with IR camera and a power density of 1 mW/mm^2. These measurements were obtained without insulation of sensor regions and results still demonstrated anisotropy with an observable temperature difference between sensors.

Following up these preliminary studies, an array of NTC sensors were incorporated on different actuator geometries for further flow sensing studies. The NTCs give an advantage to the study as it provides more sensitive data to improve resolution and reduce noise. For now, the actuator widths are held constant at 15 mm with varying lengths of 4, 15, 30, 60 and 130 mm. In Figure 3, a diagram outlining the design is shown.

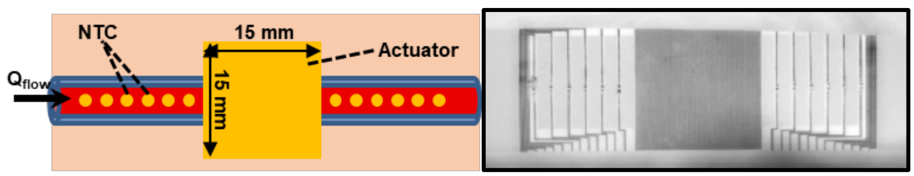

Figure 3. 15 mm by 15 mm Actuator with NTC Sensor Spacing

To establish a streamlined data acquisition system to perform multiple tests analyzing NTC spacing simultaneously, a circuit board was designed to gather data from all the sensors at the same time. The setup has the NTCs going across a 10 kΩ voltage divider and being probed by the digital multimeter that reads out to LabView. The voltage probed is then utilized to back calculate the current resistance of the NTC as the flow sensing studies run. Using the calculated resistance, the temperature of the NTC can be derived based on the Resistance-Temperature data sheet provided by the manufacturer. For these studies, the 10 kΩ NTC thermistor in question is manufactured by TDK Corporation.

Measurements are obtained in an insulated environment to eliminate noise. Starting with the device, it is sealed in plastic with special attention given to make sure there are little to no avenues for convection. The plastic seal also has an adhesive face on the bottom side of the device to aid with conforming the device to the phantom skin. Lastly, an insulating foam is placed on top of the device to limit air convection and disruptions in data collection.

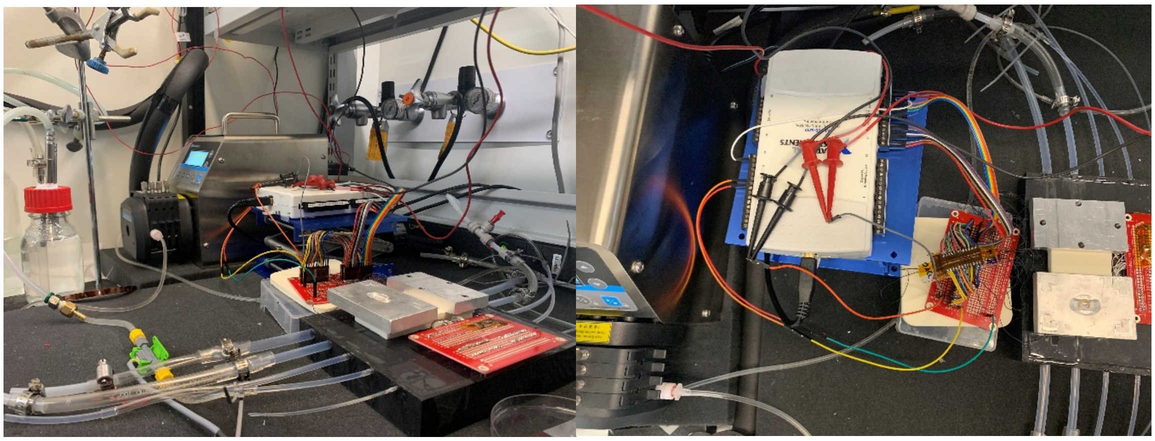

Figure 4. Experimental Setup

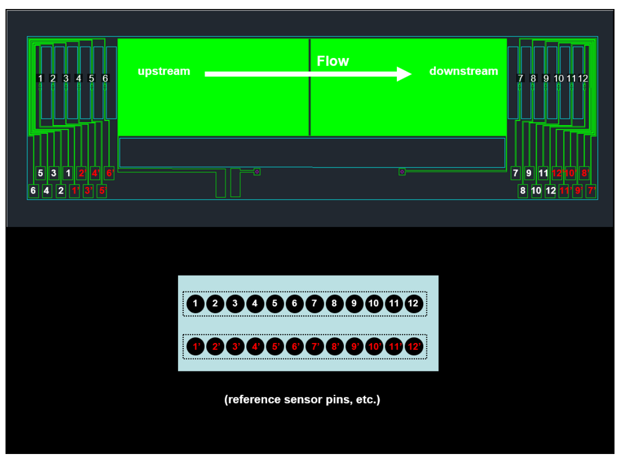

Figure 5. Schematic depicting pin arrangements on Digital Multimeter

Runs are performed for approximately 15 minutes each with a varying power density on the actuator per run. Power densities help gauge how much heat is being applied to the skin phantom as the device needs to be efficient as well as produce heating that is below the pain threshold to avoid burning the skin. The power densities utilized for the study are 0.25 mW/mm^2, 0.4 mW/mm^2, 0.55 mW/mm^2, 1 mW/mm^2 and 2 mW/mm^2 across each actuator geometry.

Results

As it stands, studies have begun with the 15mm by 15mm device as well as the 15 mm by 60 mm device. Below, the results from a run with the 15mm by 15mm device at a power density of 2 mW/mm^2. The device was placed on the second smallest PTFE tubing with an inner diameter of 3.2 mm. The experiment was run with a flow rate of 0 mL/min first to make sure the data being received was logical. As observed, there is no thermal anisotropy present with no flow providing confidence that the setup is in proper order. Moving over to 0.35 mL/min, thermal anisotropy is evident as the temperature varies over time as flow occurs. The data so far shows that there is an observable delay in heating as the space between the NTC thermistors is increased. This is likely to be a product of more space for blood temperature to adjust naturally over time before and after heating. The 2 mm, 6mm and 4 mm spacing currently show the most promise as it stands with this particular run. It appears that as the NTC spacing reaches 8 mm, there is a noticeable drop in observable anisotropy over time and this drop progresses with both the 10 mm and 12 mm spacing. It is understood that this is subject to change as higher flow rates are studied but this data is a critical first step as more information will be collected to give a full picture of how all the variables present will affect the flow studies.

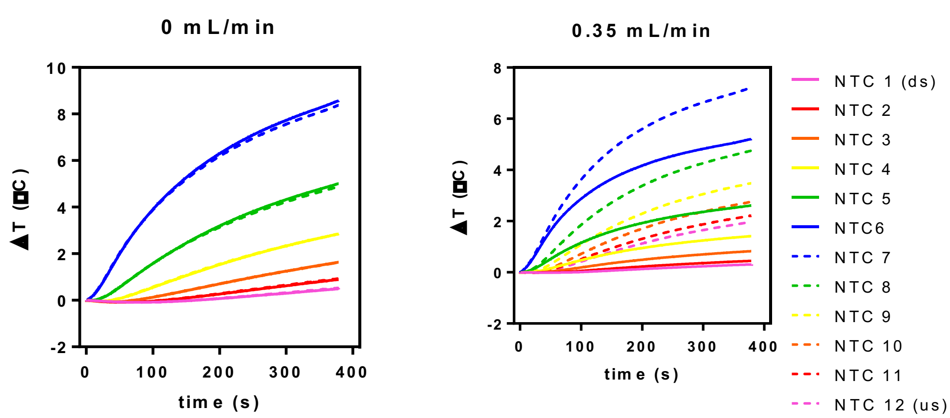

Figure 6. Impact of Directional Flow

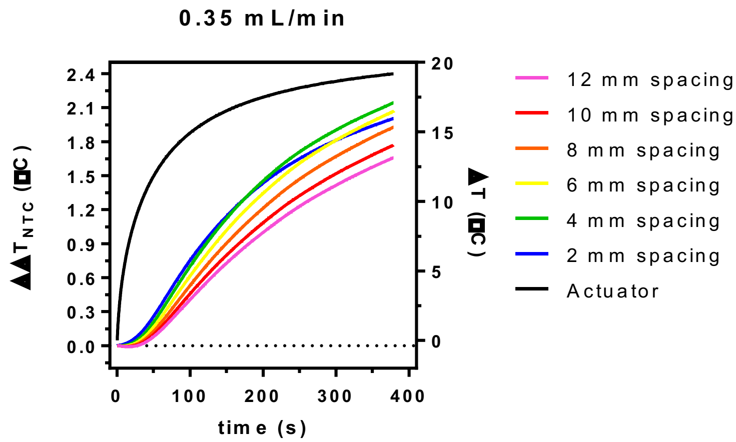

Figure 7. Temperature difference over time for different NTC spacings

Discussion

$$\textbf{Sensitivity (\%)} = \frac{\Delta T_{NTC(ds)} - \Delta TNT_{C(us)}}{Q_{flow}} x100 \qquad \textbf{613.5\%}$$

$$\textbf{Performance (\%)} = \frac{\Delta T_{NTC(ds)} - \Delta TNT_{C(us)}}{\Delta T_{actuator}} x100 \qquad \textbf{11.2\%}$$

$$\textbf{Working Performance (\%)} = \frac{\Delta T_{NTC(ds)} - \Delta TNT_{C(us)}}{\Delta T_{actuator} * \chi A_{tubing}} x100 \qquad \textbf{35.0\%}$$

The equation above is what is utilized to define the sensitivity of the device wrt flow. The performance equation refers to the quality of the optimal power usage for sensing. The working performance equation refers to the quality of optimal power usage wrt heating over tube. These values are calculations of the equilibrium heat profiles over a time of 380 seconds heating. These equations aid in quantifying the effectiveness of this procedure.

Future work

Unfortunately, data collection was cut short by the rise of the COVID-19 pandemic, However, upon return, this study has a lot of room for growth and exploration. As work proceeds with this study, the remain actuator geometries will be explored. This is a study that relies on gathering as much information as possible so as more data is collected, comparisons will be made across variables and conditions to determine what the most effective setup for thermal flow sensing is. This project has the capability to be transferred on to more testing closer to assessing biological compatibility.