International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

On the Design of a Non-invasive Thermal Flowmeter

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Abstract

We present the design for an efficient, non-invasive thermal flowmeter. Accuracy tests for the flowmeter are performed. The flowmeter is optimised to measure the minimum velocity possible.

Keywords: non-invasive, thermal, flowmeter, accuracy, optimisation

1. Introduction

We define an isothermal surface as a surface whose points are all at the same temperature. When a point source of heat in the form of a heater is attached to a pipe, the isothermal surfaces formed in still water may be approximated as spheres centred at the heat source. However, when the water flows, the isothermal surfaces will be deformed. The exact shape of this deformation is unknown, but it should be noted that the deformation is in the direction of water flow and depends on the water flow rate. Thus, two temperature sensors may be set up on either side of the heater. Due to the deformation of the isothermal surface, temperature at one sensor (the one in front of the heater with respect to the water flow) will rise at a faster rate than at the other sensor, as a greater flow rate will bring a hotter isothermal surface to the sensor. The magnitude of this difference will depend on the flow rate of the water and thus by measuring the difference in the rate of temperature change, the flow rate of the water inside the pipe can be measured.

2. Theory

Let V represent the rate at which the temperature of the sensors increases as a result of heat transfer through the water. Let c represent the rate at which the temperature of the sensors increases as a result of heat transfer through the pipe. Let θ_0 represent the initial temperature of the surroundings. $\theta_1(t)$ and $\theta_2(t)$ are the temperature of the sensor upstream and downstream from the heater at time t. Then, we have the following:

$$\boldsymbol{\theta_1(t) = (c - V)t + \theta_0} \qquad (1)$$

$$\boldsymbol{\theta_2(t) = (c + V)t + \theta_0} \qquad (2)$$

Using a graph of the temperature vs. time graph for both sensors and solving the equations simultaneously, one may obtain the value of V.

Let the mass flow rate of the liquid inside the pipe be small v. Since the exact conversion from V to v is difficult to do, we can plot a graph of V vs v to use as a calibration curve for the flowmeter. Using this graph, we can determine the flow rate of the fluid inside the pipe.

3. Setup

The setup consists of a PVC pipe with two DS18B20 sensors attached to it. At the centre of the sensors, a hair dryer heater element was used to heat the pipe. The DS18B20 sensors are attached to a Breadboard which in turn is connected to an Arduino Uno microcontroller[1]. The data from the sensors is recorded in the Arduino Serial monitor.

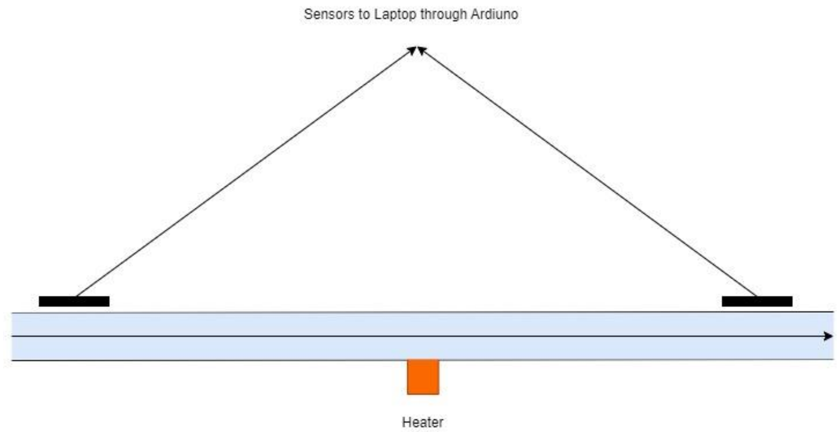

Figure 1. Schematic Diagram of the Setup

4. Data Processing

The data was then converted into a CSV file and then Microsoft Excel was used to extract the data. The extracted data for a single run of the flowmeter was plotted in the Logger pro application in order to measure the slopes of the two sensors.

Two graphs of temperature vs. time may be simultaneously plotted to observe the difference in the rate of temperature change. Note that data collection was started a few moments after the flow started, thus the two graphs do not start at the same point.

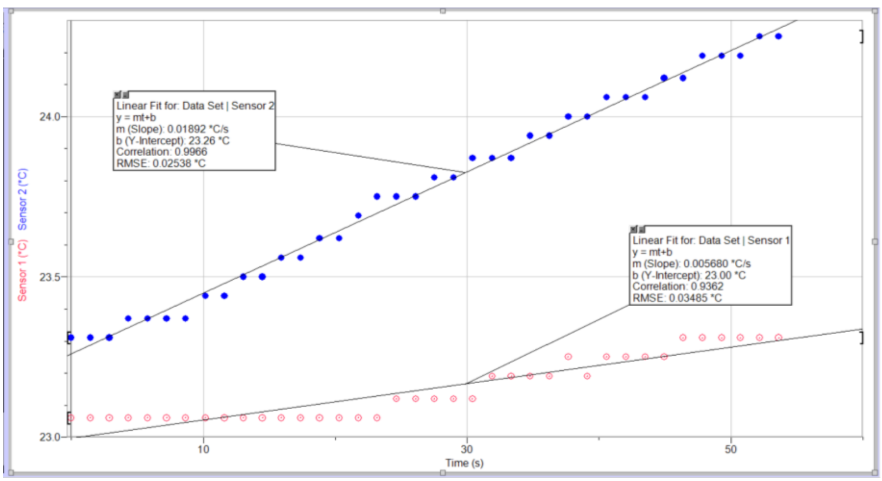

Figure 2. Graph of temperature vs. time for the two sensors

The fact that both graphs are straight lines with different slopes shows that our hypothesis is true.
We may calculate the values of c and V given the slopes of both lines.
Solving simultaneously, we can get the value of V.
In order to calculate the flow rate, we have to calibrate the flowmeter. This was done by attaching an external flowmeter to the pipe. This was used to calibrate the flowmeter by measuring the actual flow rate v and plotting a graph of V vs. v.
The calibration was done using four different flow rates. These were measured using a volumetric flow meter which measured the flow rate of the pipe. The following graph was obtained:

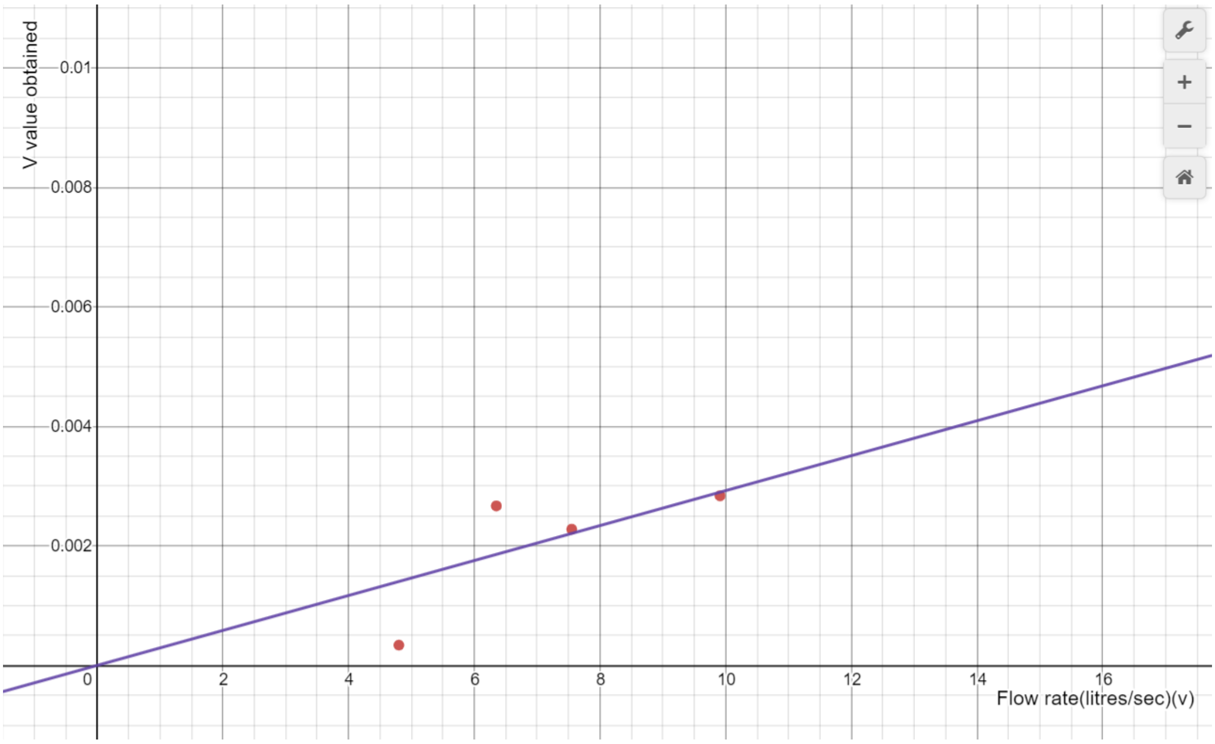

Figure 3. Calibration curve for initial setup

Using this, we can derive an equation for the flow rate given the value of V. Note that the relationship between the two may be approximated as direct proportionality as when the flow rate is 0, the value of V must correspondingly be 0 and for small scales, direct proportionality can be used to approximate the results.

5. Testing

In order to test the flowmeter, we used the calibrated flowmeter to measure three different flow rates and compare these flow rates to the actual flow rate that was measured using a flowmeter.
A graph of measured flow rate vs. Actual flow rate was plotted to check the accuracy of the flowmeter.

6. Optimization

In order to optimise the accuracy of the flowmeter, the distance between the sensors and the heaters was optimised.
The initial data set of the sensors consists of the two sensors at a distance of 97 cm from each other.

In order to optimise the distance between the sensors, we used four different distances between the sensors - 44 cm, 58 cm, 71 cm and 84 cm.

For each distance, five data points were used to calibrate the sensors and three to four data points were used to test the sensors and get a graph of the measured flow vs. the actual flow values.

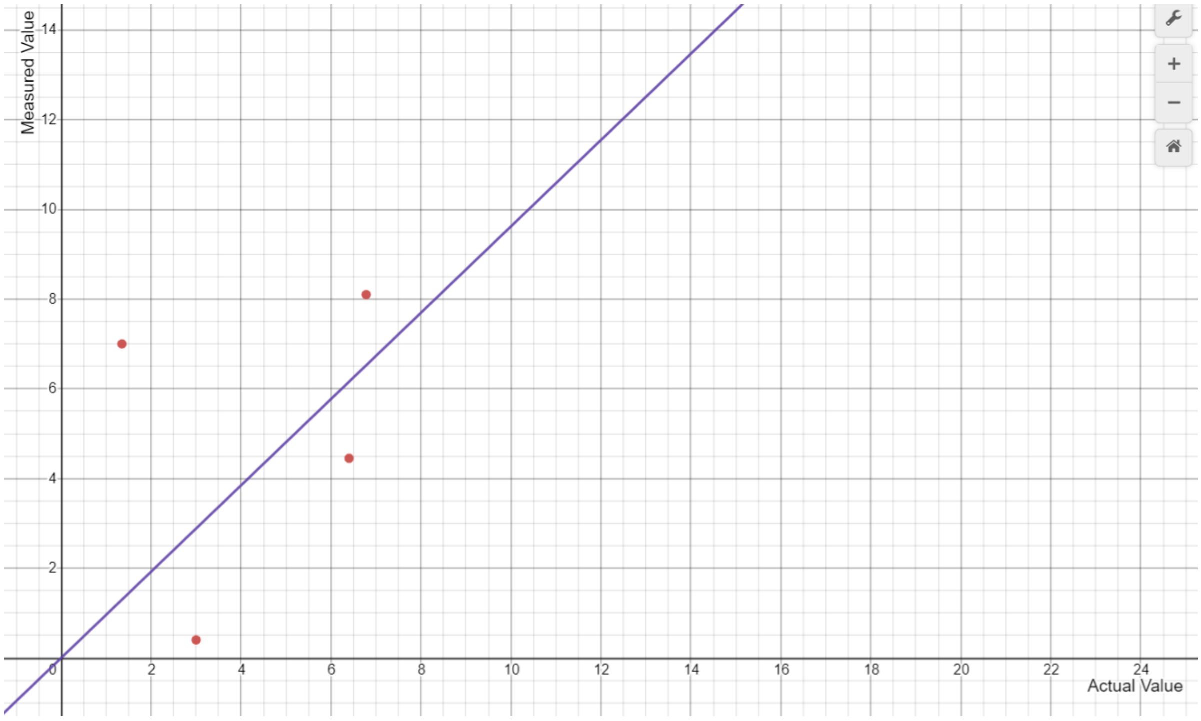

Figure 4. Graph for a distance of 44 cm between the sensors

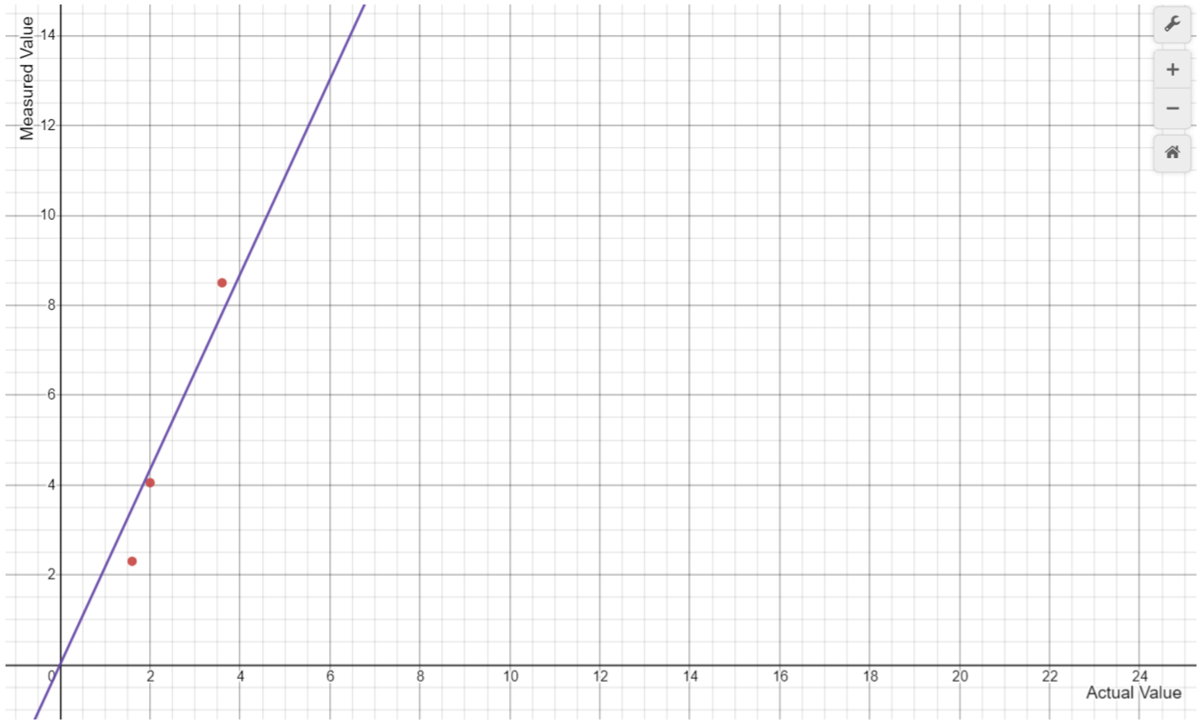

Figure 5. Graph for a distance of 58 cm between the sensors

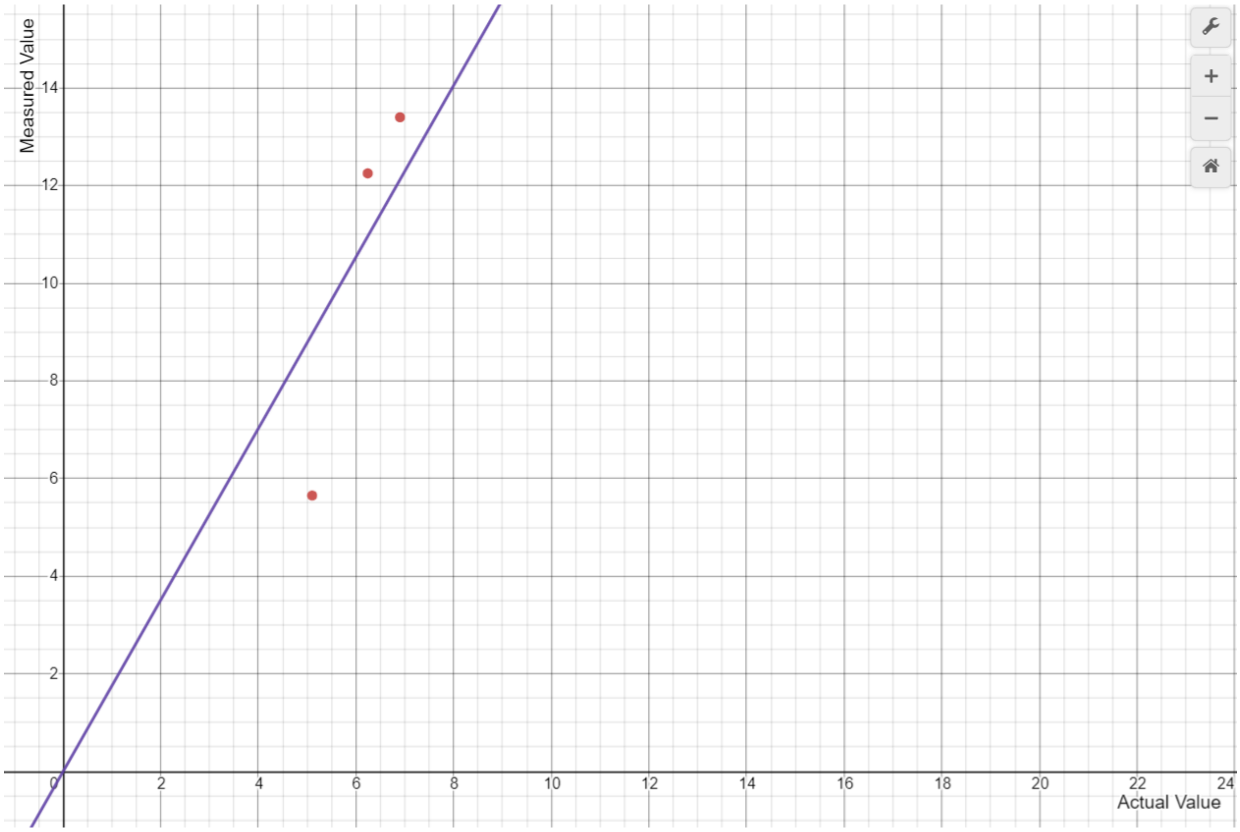

Figure 6. Graph for a distance of 71 cm between the sensors

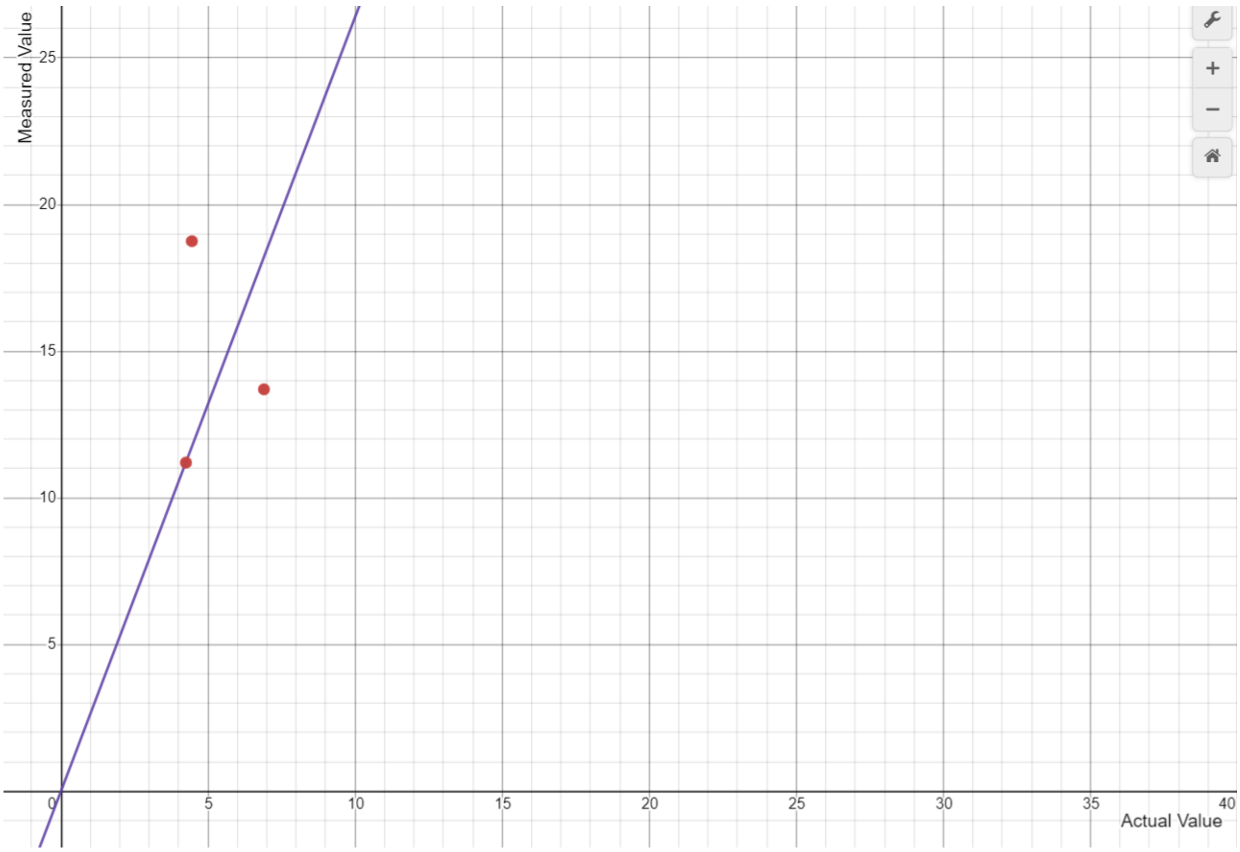

Figure 7. Graph for a distance of 84 cm between the sensors

For each graph, two numbers were extracted - the R^2 value and the value of the slope of the graph.

In order to find the optimum value of the graph, these two numbers are put through the following formula:

$$R^2 \times \frac{1}{\sqrt{2\pi}} e^{-\frac{(\alpha-1)^2}{2}} \tag{3}$$

Here, $\boldsymbol{\alpha}$ is the value of the slope of the graph. The above value is used in the y axis of the optimization graph.

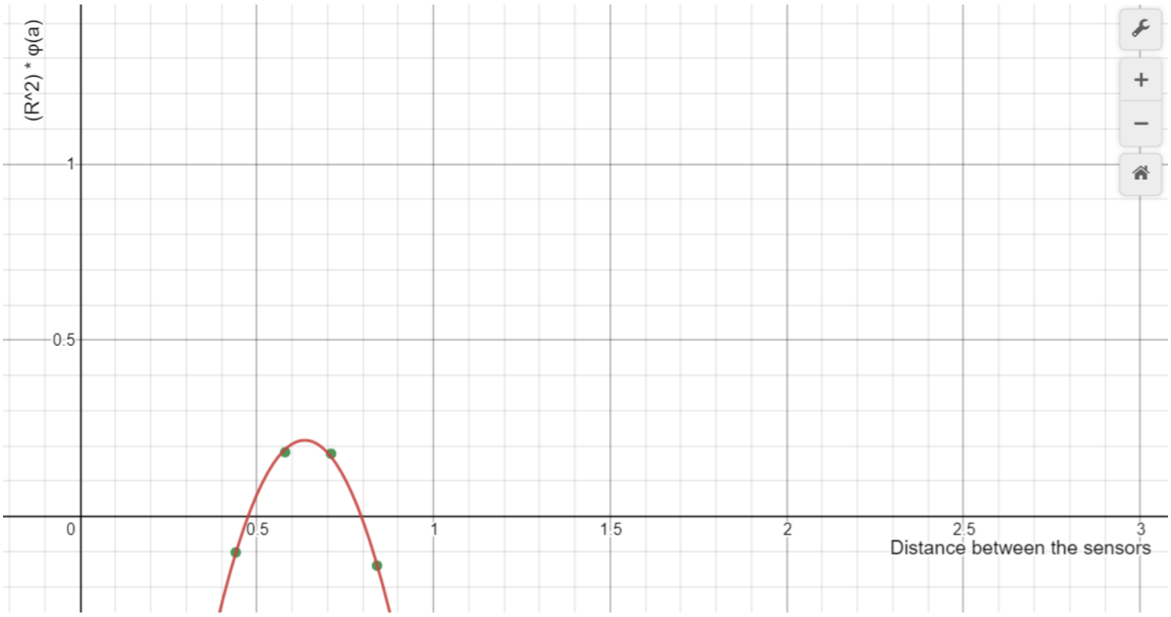

Figure 8. Optimization graph of the distance between the sensors

The x axis of the graph is the distance between the sensors.
Plotting the graph, we can approximate it as a parabola. This is because for maximisation of data points, a parabola is a very good approximation of the graph of a function.
Thus, we can find the approximate maximum for the function by plotting a parabola and finding its maximum point.
From the graph, we obtain a maximum of the parabola at a distance of 63.5 cm between the two sensors. Therefore, the optimum distance between the sensors is 63.5 cm.

7. Conclusion

In conclusion, we have designed and begun to optimise the workings of a thermal non-invasive flowmeter. The workings of the flowmeter work using the fact that isothermal surfaces are deformed in flowing water. Using this, the rate of temperature change for two different sensors upstream and downstream from the heater are obtained and this is used to calculate the flow rate of the fluid inside the sensor.

8. Acknowledgment
Special thanks to Mrs. Neha Jain for providing help with the data collection.

9. References:

1. Engineers, L. M. (2020, December 18). Interfacing DS18B20 1-wire digital temperature sensor with Arduino [Internet]. Last Minute Engineers. Cited December 1, 2021. Available from: https://lastminuteengineers.com/ds18b20-arduino-tutorial/.