ENGR 83 Final Project

Affordable Flowmeter for Measurement of Low-Flowrate Suspended-Particulate Flow

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Introduction

Measurement of fluid flow is an important topic in fluid mechanics, and has been the subject of significant study. A number of generalized methods exist for measuring fluid flow, including differential pressure methods, momentum transfer methods, optical methods, and ultrasonic methods. However, despite the thorough development of fluid measurement methods and the breadth of scholarship in the field in general, each fluid measurement application presents unique engineering challenges, which must be overcome through creative design.

In this project, a device (a flow meter) to determine the flow of smoke through a hookah waterpipe was designed, produced and calibrated. This was done through a four-step design process, comprising problem identification, analytic design, computer simulation and construction. This report outlines each of these steps as well as the calibration process for the meter, and presents the flow meter's resultant performance. It concludes by examining current issues with the meter, and identifying avenues for future work.

Design Process

The design process for this flow meter comprised four steps: problem identification, analytic design, computer simulation and construction.

Problem Identification

In order to design a satisfactory flow meter, the constraints and requirements imposed both by the system to be measured as well as by the design specifications of the meter must be identified. For this system, the primary requirements for the flow meter were identified to be:

- **Sensitivity at low flow rates/low Reynolds numbers**: The flow extant in a hookah has an extremely low flow rate (estimated to be 2.15×10^{-4} m^3/s) and consequently low Reynolds numbers (between 1000 – 3000), due to the small pipe diameter[1]. A flow meter designed for this application must be able to accommodate these flow characteristics.

- **Resistance to clogging/fouling and corrosion**: Hookah smoke contains sticky, corrosive particulate, which can foul moving parts and clog orifices. A flow meter designed for this application should consequently avoid both of these components: additionally, the surfaces of the meter in contact with the flow should be corrosion-resistant (either stainless, plastic or the like)
- **Low impedance meter**: As shown by Shihadeh[1], the head loss caused by the meter must be low to prevent interference with the user's smoking, preferably under .1 kPa. However, if the meter is a differential pressure producer – likely, due to the simplicity and relative durability of differential producers – then it must also be sensitive to extremely low differential pressures, as the pressure differential produced by the meter is the primary component of the meter's introduced loss.

Additionally, a number of design goals were specified for the meter.

- **Measurement of flow rate**: The meter should allow instantaneous measurement of flow rate to within ±10% of the full scale value.
- **Cost**: The cost of the meter and all auxiliary components should remain under $100
- **Reliability**: The system should remain functional for multiple smoking sessions without requiring recalibration, extensive cleaning or component replacement.

Using these specifications, a flow meter design was selected. The meter design used for this project was a wedge-type meter, an extremely simple differential pressure meter which comprises a circular flow channel with a wedge shaped obstruction protruding into the channel, as shown in Figure 1.

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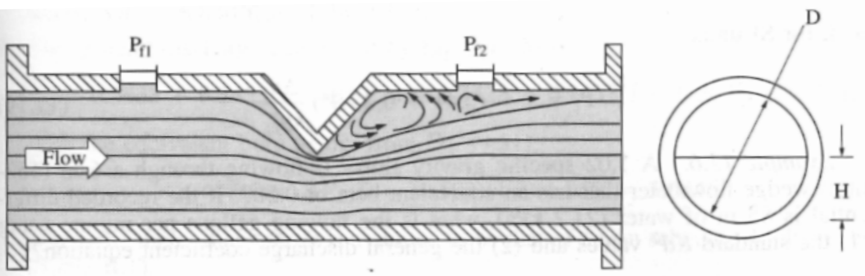
[1] Alan Shihadeh, "A portable, low-resistance puff topography instrument for pulsating, high flow smoking devices," <http://webfea.fea.aub.edu.lb/aerosol/downloads/MS-03-63_revised.pdf>.



$$\beta_{Wedge} = \frac{d}{D} = \left(\frac{1}{\pi} \left\{ \arccos\left(1 - \frac{2H}{D}\right) - 2\left(1 - \frac{2H}{D}\right)\left[\frac{H}{D} - \left(\frac{H}{D}\right)^2\right]^{1/2} \right\} \right)^{1/2}$$

Figure 11.25 Wedge Flowmeter. *(Courtesy ABB-Kent Taylor.)*

Figure 1 - Wedge-type Flow Meter

The wedge-type meter has a number of characteristics that make it ideal for this flow measurement scenario. It is functional at extremely low Reynolds numbers and flow velocities[2]. Furthermore, it contains no moving parts (preventing the possibility of fouling) and is considered a self-scouring meter (indicating that it automatically removes contaminants from the flow surfaces, which would prevent the meter's flow characteristics from changing over time as contaminant buildup occurs). Finally, the wedge-type meter is comparatively simple to construct, as it does not require sophisticated electronics or precision mechanical components.

Analytic Design

In the analytic design phase, the flow meter was modeled using analytic techniques to determine the optimal design dimensions as well as the required performance parameters for the flow-sensing element. Using equations derived in Miller[2], a spreadsheet was developed that determined flow rate, Reynolds number, beta ratio and expected differential as a function of pipe diameter, opening height (*H* in Figure 1), flow velocity and fluid characteristics. This spreadsheet was then used to plot differential pressure as a function of flow velocity for a number of different *H* values.

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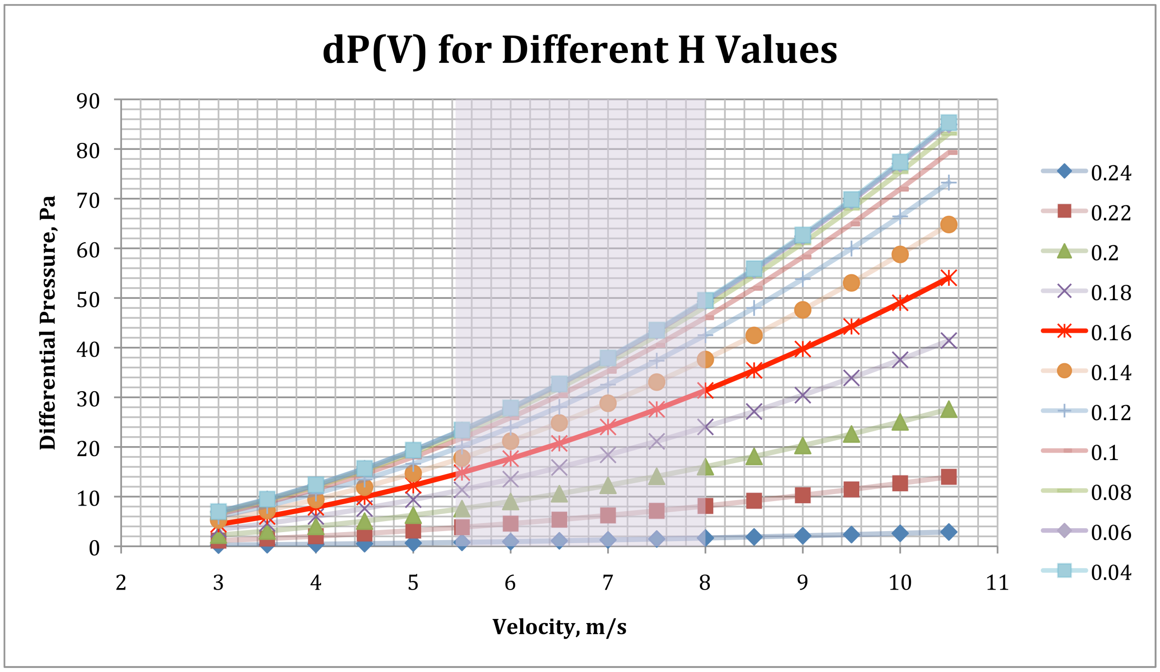
[2] Richard W. Miller, Flow Measurement Engineering Handbook, 3rd (McGraw Hill, 1996).



As this plot shows, smaller values of *H* (corresponding to smaller gaps) produce greater pressure differentials, with the pressure differential decreasing as *H* increases. The region of expected flow velocities –between 5.5 and 8 m/s – is shown by the shaded rectangle. Within this range of flow velocities, differential pressures as high as 50 Pa would be possible: however, a flow meter with the required *H* to produce this differential would almost indubitably introduce significant head loss, and would likely be prone to clogging. Consequently, the value of *H* selected was the lowest value before significantly diminishing returns to further reduction in gap size were observed – in this case, .16 inches, corresponding to an average produced differential of 25 Pa and a maximum produced differential of 55 Pa.

Using this predicted differential, a pressure-sensing element was selected. The element used in this meter was a Sensirion SDP 1000-L025 bidirectional differential pressure sensor, capable of measuring within a range of ±62 Pa with a resolution of .1 Pa and a stated accuracy of .31 Pa. This pressure sensor is highly durable, and is stated as being suitable for moist or slightly dirty flows.

It should be noted that the analytical model developed relies on one major assumption, which may have affected the model's accuracy. The model incorporates the coefficient of discharge for a wedge-type meter, which is a function of pipe diameter and beta ratio. The coefficient of discharge is defined in the literature for ranges of pipe diameters down to 1.5" - .5", which was used for this model. However, since the pipe diameter in this project is significantly smaller - .25" – the coefficient of discharge equation used may be inapplicable. Further testing will be required to examine this.

Computer Simulation

Computer simulation of the flow meter's behavior was used to examine the accuracy of the analytic model, and double-check that the specified flow sensor would be appropriate. The meter was modeled in Dassault Systemes *Solidworks 2011*, as shown in Figure 2.

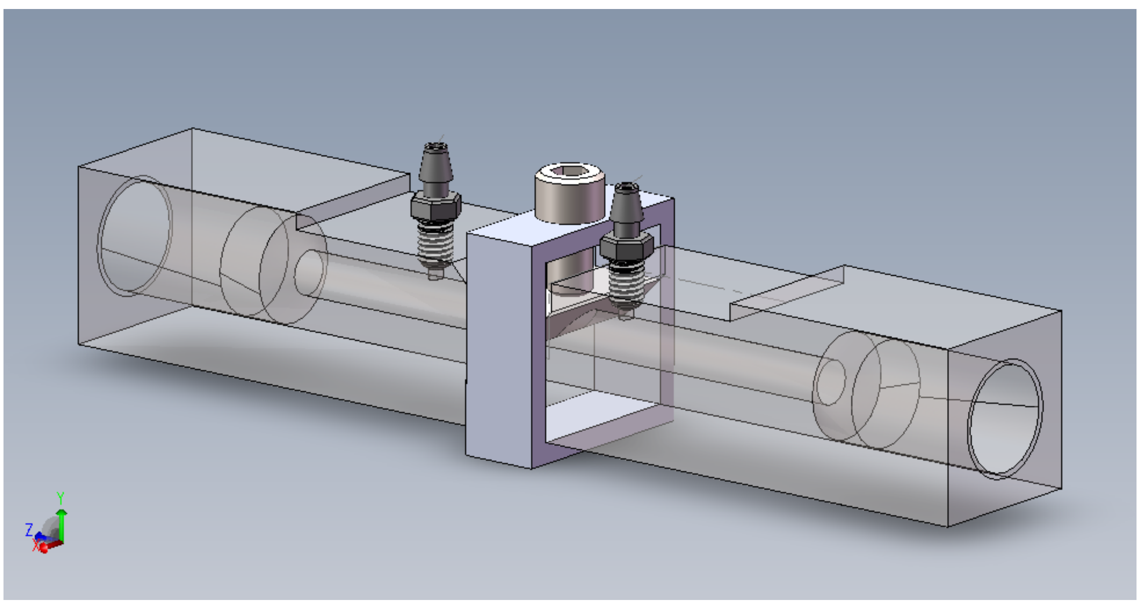


Figure 2 - Flow Meter CAD Model

The flow meter's behavior was then simulated using *FlowWorks 2011*, an add-on to Solidworks. The simulation conditions were atmospheric pressure at the meter entrance, a mean flow velocity of roughly 6.5 m/s at the meter exit, no heat transfer to the meter, and air flowing through the meter. The meter was simulated at a medium resolution, producing the following differential pressure topography.

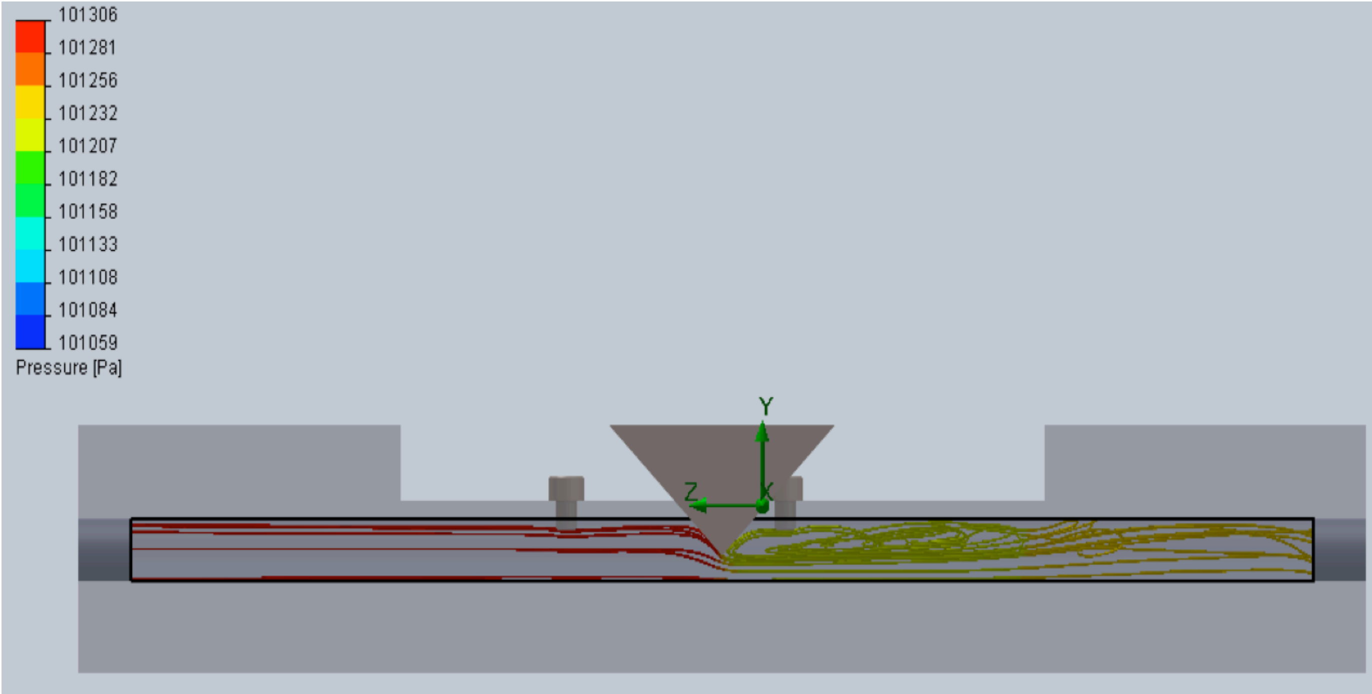


Figure 3 - Simulation Results

As shown in Figure 3, the pressure differential predicted by the flow simulation is significantly higher than that predicted by the analytical model – around 100 Pa. This result was initially regarded as erroneous, as the flow simulation parameters listed above specify that conditions which are actually observed across the entire hookah pipe must also exist purely across the flow meter (e.g, the shift from atmospheric pressure to the specified flow rate occur entirely over the length of the flow meter), which overestimates the differential produced by the meter. Consequently, the results of this test were disregarded.

Construction

Construction was conducted over a period of 2 weeks in the machine shop at Swarthmore College. The meter body was machined from 314 stainless steel: care was taken to ensure the highest-quality surface finish possible in the flow region. A section of 314 precision-ground stainless steel bar stock was used to create the wedge element. The mating surface between the meter body and the wedge element was cleaned using acetone, coated with a thin bead of food-safe hydraulic sealant (positioned far from the flow channel to ensure that no sealant entered the channel) and clamped in place using the square clamp shown in Figure 4.

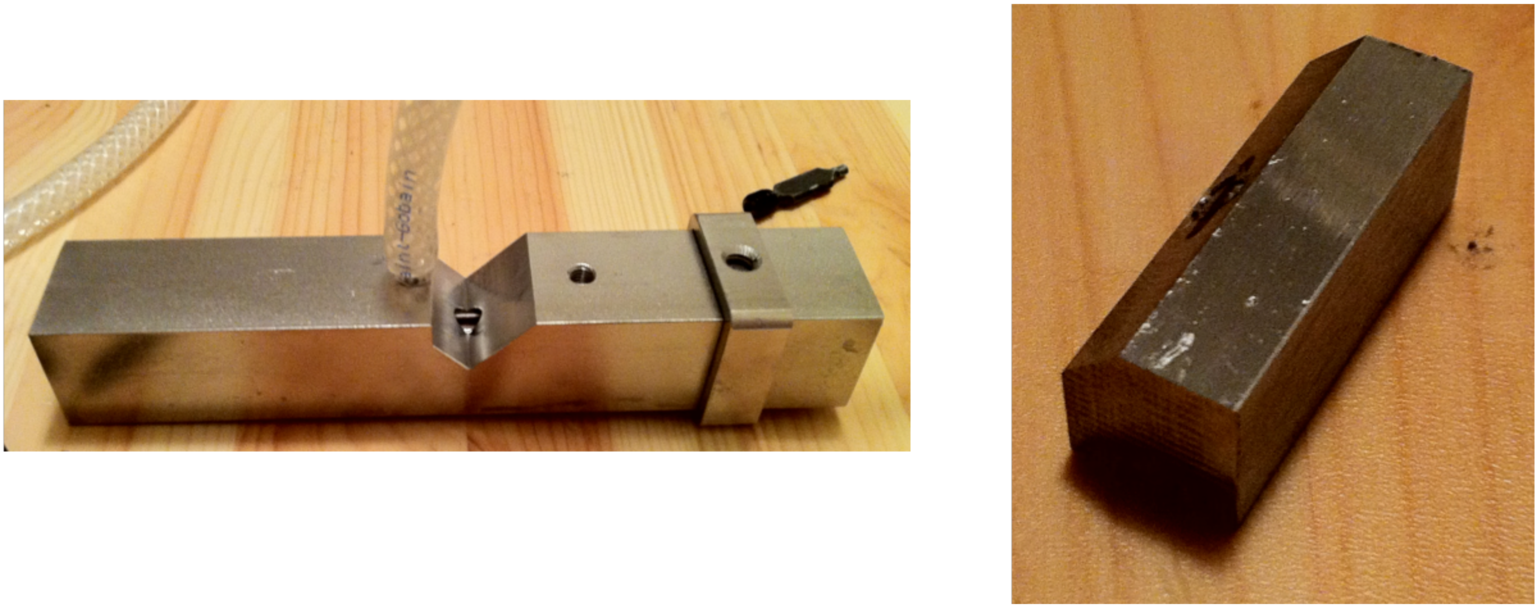


Figure 4 - Flow Meter

There are a number of construction-related problems with the flow meter that need to be addressed. There is a gap in the junction between the inlet pipe and the flow meter body, which may produce disturbances in the flow. Additionally, the surface finish of the interior of the flow meter has not been checked, and patches of roughness, burrs or sealant fragments may exist.

Testing and Results

The completed flow meter was calibrated: its performance was then evaluated in a number of tests.

Calibration

Since the flow meter was intended to be read by a microcontroller, which would automatically convert measured differential pressures to flow ranges, a pressure-flow calibration was required. This calibration was created by placing the flow meter in series with an anemometer, with the anemometer installed such that all flow into the flow meter first passed through the anemometer. Nitrogen gas was then passed through the system: the flow velocity and pressure differential were recorded, and the flow velocity was converted to a volumetric flow rate. The setup used to perform this calibration may be seen in Figure 5.

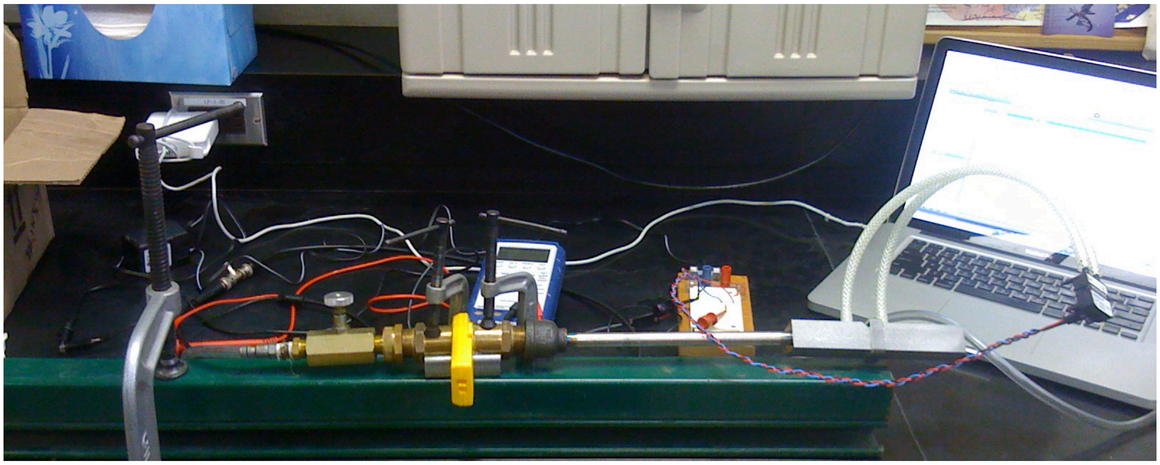


Figure 5 - Calibration Setup

It became immediately apparent that the flow meter was producing significantly higher differential pressures than expected: the flow meter was only able to measure in-meter flow velocities up to 8.2 m/s (corresponding to a pressure differential of 91 Pa) before the flow sensor reached its maximum value. Additionally, the low resolution (.1 m/s) and slow response time of the anemometer meant that the number of datapoints successfully taken was low, and the accuracy of each data point extremely low. Finally, the gas supply began to run low during the course of the calibration, making it extremely hard to maintain a constant flow rate.

Despite these problems, a satisfactory calibration was achieved, as shown in Figure 6. The similarity between the orange calibration curve and the differential pressure curves predicted by the analytic model indicates that the flow meter is behaving roughly as expected. However, the stark difference in magnitude between the theoretical and actual produced differential is striking. Additionally, the calibration curve suggests that at low flow rates, the flow meter may not follow the parabolic behavior predicted by the rest of the calibration curve. However, further testing as well as more refined instrumentation are required to investigate these effects.

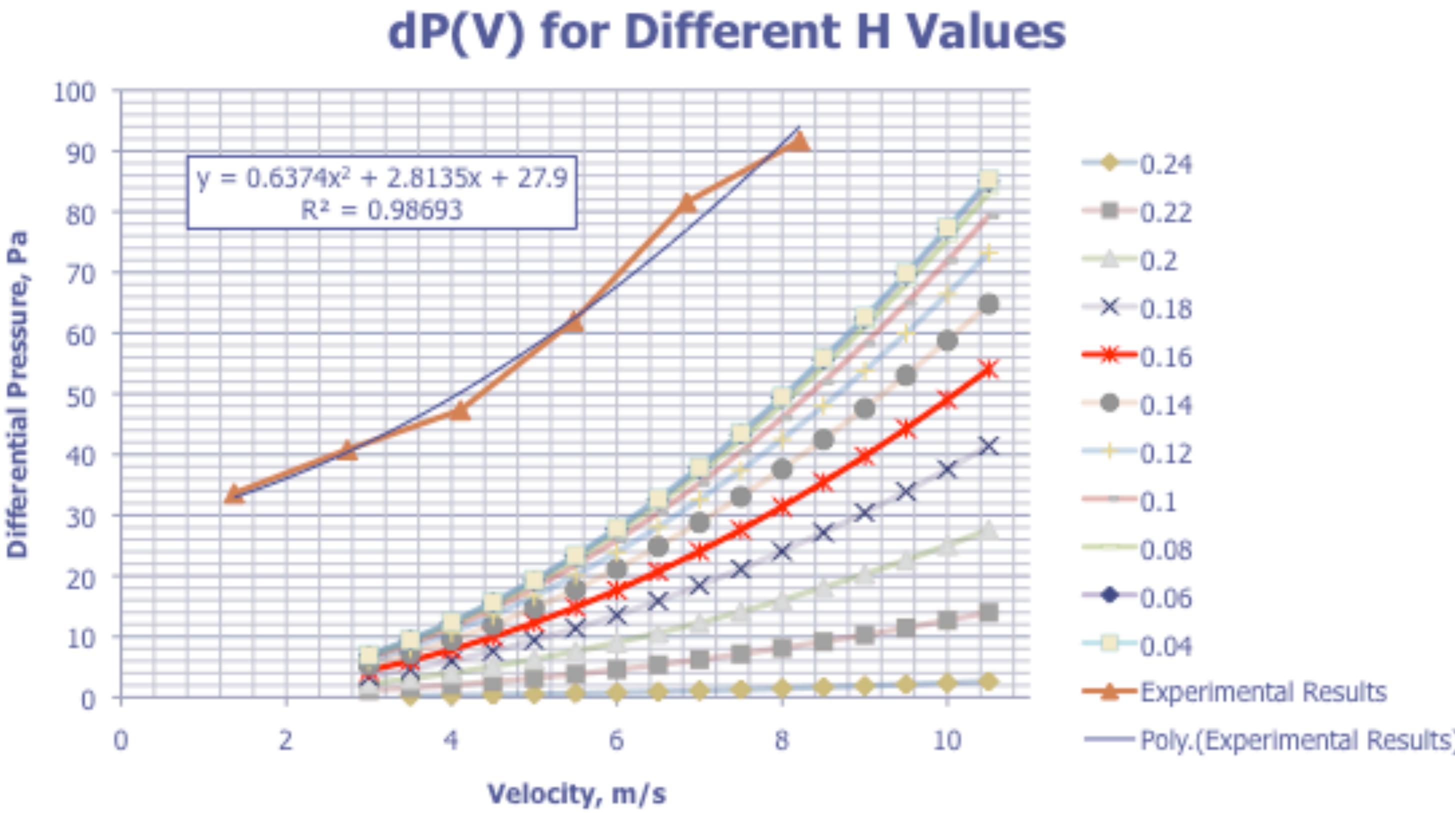


Figure 6 - Calibration Curve vs. Expected Results

Performance Evaluation

With calibration complete, the performance of the flow meter was then evaluated in a number of tests. Although the accuracy of the flow meter could not be determined due to the lack of sufficiently high-resolution instrumentation, the meter's resistance to "bubbling" effects and its performance during smoking were examined.

- **"Bubbling" Resistance**: In a hookah pipe, smoke is drawn through water as a means of filtering and cooling the smoke before it reaches the user. The smoke "bubbling" up through the water introduces significant disturbances to the flow through the system, which can obfuscate the actual flow rate. In order to determine the seriousness of these "bubbling" effects, the flow meter was installed on a hookah pipe, and the output of the flow sensor was measured using an oscilloscope. "Bubbling" effects were noticeable, but not overwhelming: in the current version of the control software used to measure the flow meter's output, a simple low-pass filter eliminates these effects.
- **Smoking Performance**: The meter's performance in smoking situations has only been briefly investigated, but results are not encouraging. Although the physical

meter itself performs well (it does not leak or foul during use, is easily cleaned, and shows no signs of corrosion), the flow sensor was observed to give either slightly positive or slightly negative flow readings. It is theorized that this is due to moisture buildup inside the flow sensor body, which then caused some heat transfer between the thermal generator and one of the thermal sensors, as the meter did not exhibit this behavior after being removed from the hookah for a short time.

Conclusion

This project has made significant progress towards developing a robust, inexpensive method of measuring low flow rates in small channels. Although the flow meter developed here cannot be considered finished, it is already a useful instrument, and an effective proof of concept that wedge-type differential pressure producers can be effectively implemented in micro-measurement situations such as this. Finally, although its cost was not under the $100 limit stipulated at the beginning of this project, it is far less expensive than a comparable commercial meter would likely be.

Avenues for improving this project are numerous. First, a more refined calibration for the meter should be created, with higher data resolution and further investigation of meter behavior at extremely low flow rates. Second, a system of vibration damping bottles should be implemented, both to reduce the effects of “bubbling” seen in this experiment, as well as to provide some filtration for the flow entering the flow sensor. Finally, rigorous determination of the meter’s performance characteristics – accuracy, range, etc. – would allow the meter to be used as a scientific instrument.

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