EWH - Gas Flow Meter

BME 201
Spring 2006
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28 April 2006

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Abstract

Flow meters are devices used to measure the rate of fluid movement through a pipe or tube. The flow meter is usually secured to a break in the pipe and the fluid is allowed to move through it. This project specifically deals with gas flow meters used in medical practices. The flow meter's measurements can then be used to make sure the amount of gas supplied to a patient is correct.

The current flow meters used in medical practices are too expensive for use in third world countries because of their economic state. The hospitals cannot afford current flow meters, and without a flow meter there is not an accurate way to monitor gas supply.

Our contact, Dr. John Webster, and our client, Engineering World Health, wanted us to create an affordable gas flow meter to be used in these developing countries that can accurately measure the rate of gas supply. We developed two designs that could be used widely used as a cheap alternative.

I. Introduction and Project Motivation

Flow meters are used to maintain the correct intake of gases during a patient's stay in the hospital. If doctors do not have access to the proper equipment during an operation, they put their patients in more danger than necessary. For example, if an anesthesiologist fails to supply the proper amount of these gases during a surgery dire complications could arise (Anaesthesia, 2006). Since guessing at flow rates is not acceptable, a device is needed to measure the rate of flow. The gases can be pure or mixtures and usually include O_2, CO_2, and medical grade air. The rates needed in the health care profession vary but are usually between 0.5 to 15 LPM (Engineering World Health, 2006). Current products are effective but costly. Depending on the accuracy, desired products can cost well above $1,000. Some less expensive flow meters do exist that cost around $10, but these are still too expensive for widespread use in developing countries (Froogle, 2006).

Third world countries are faced with many hardships in their quest to become a healthy living environment. Health of adults is commonly compromised by chronic diseases and early deaths. This leaves children to raise themselves and causes them to be highly susceptible to similar diseases (Gerhart, 1985). Many of these developing countries are also in a state of economic peril and their governments have difficulty providing medical aid to the general population. This means that many of the people within the countries are forced to live with little or no health care (Pyramid Air Gun Mall, 2005). This is why an inexpensive alternative to current flow meters is needed for these countries. The potential benefits of having a flow meter in the developing countries are many. More adults' and children's lives could be saved because accurate gas flow meters can improve the safety of surgery. There are also many other benefits that improved health care would provide, including better economic conditions, since more people will be physically capable of taking a job.

II. Current Products and Materials

Flow meters are not a new invention. They have been around for a long time and have had the chance to be improved upon over the years. Common flow meters include the rotameter, turbine, venturi, ultrasonic, and pneumotachographs. Rotameters, venturis, and pneumotachographs change the area that the gas flows through to be able to relate the resulting change in pressure to the flow rate. The rotameter is conical, and the velocity of the gas changes throughout the device (Anaesthesia, 2006). A float inside the cone rises or falls depending on the rate of flow through the tube. The venturi flow meter has a partial blockage or narrowing in an otherwise straight piece of tubing and the resulting change in pressure is either measured electronically or with a manometer (Jamison, 1991). A manometer is a U-shaped piece of tubing filled with a liquid that displaces because of the difference in pressures at either end (Webster, 1999). The liquid level is higher on the side with lower pressure, and the difference between the pressures can be related to the flow rate. A pneumotachograph has resistance put in the gas pathway and the pressure drop is measured with a differential pressure transducer or a manometer (Anaesthesia, 2006). It is shown in Figure 1.

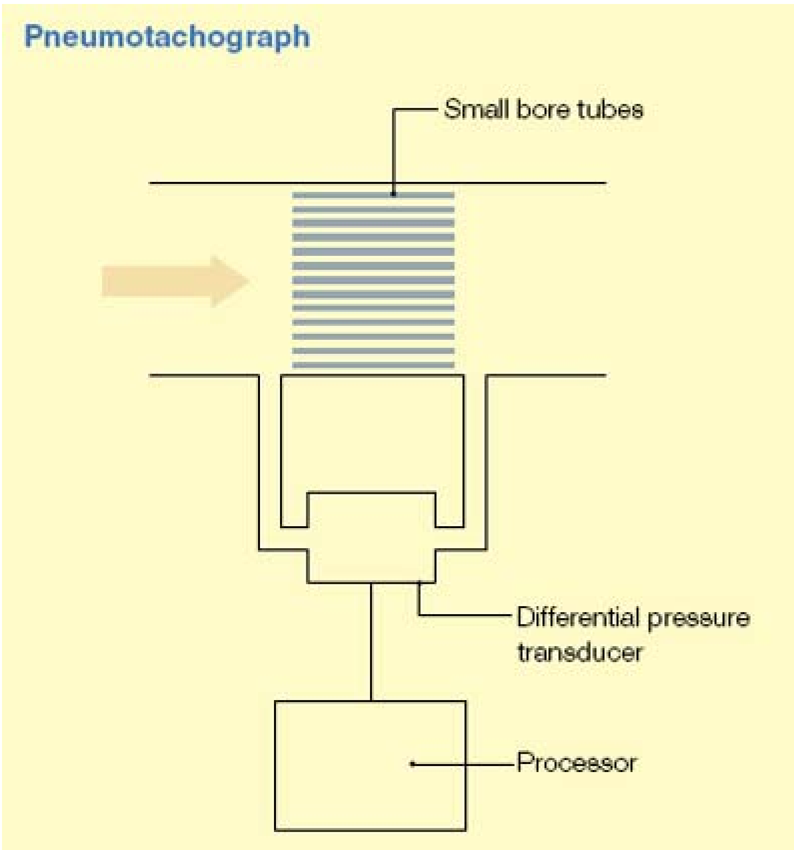


Figure 1: Pneumotachograph Schematic (Anaesthesia, 2006)

The Turbine flow meter uses the force the gas exerts to cause a propeller within the pipe to rotate at a speed proportional to the gas flow (Cole Parmer, 1999). The ultrasonic flow meter uses the Doppler Effect by measuring the change in frequency of the sound emitted by an attachment to the tube to calculate the speed of gas. All of these methods are currently in use today (Anaesthesia, 2006).

The materials that flow meters are composed of vary with the design. Rotameters can be composed of glass, polyethylene, polysulfone, or other kinds of clear plastics (Froogle: Gas Flow Meters, 2006). Other flow meters are also usually made out of durable plastics or glass, since these materials are widely available.

III. Client Information

The contact, Dr. John Webster, would like us to work on the project presented by our client, Engineering World Health (EWH). Dr. Webster is a professor in the Biomedical Engineering department and has edited numerous books on bioinstrumentation. EWH is an association that works to improve hospital conditions around the world and especially in developing countries. They present design competitions each year and fund the building and testing of promising ideas. (Engineering Fundamentals, 2006)

IV. Design Requirements

Engineering World Health set specific design requirements for us to follow. Our flow meter must be able to be attached to an O_2, CO_2, and medical grade air source. We had the choice of designing a single or continuous readout flowmeter, each being no greater than 1” x 1” x 4” or 4” x 4” x 1”, respectively. Our flow meter must measure the flow rate within 10% of the actual value, and we are challenged to reduce the error to within one percent of certain flow rates. We must be able to manufacture the device at less than $2 apiece when produced in quantities of 500.

In addition to the requirements set by Engineering World Health, we decided that our flowmeter must work over the range of 0 to 15 liters per minute, which is common in current medical flow meters.

Most Important Design Constraints

When evaluating all of our design specifications we decided that cost, size, and accuracy were the most important constraints to consider. Our client emphasized the importance of cost because these devices need to be distributed to developing countries. Size is important so the device can be easily shipped and used within the specified environment. Even if the design met the cost and size requirements, it would be useless if it failed to meet the accuracy specifications.

Using the cost constraint as one of the most important considerations helped us to reach several conclusions and to come up with some of our own sub-requirements within the cost area. The fact that the overall cost needed to be under $2 per flow meter helped us rule out some strategies immediately. Any device using electronics was outside the budget and this lead us toward some simple mechanical approaches: the rotameter, the venturi, and the drag flow meter. The $2 per flow meter constraint limited us in many other areas as well. Our final design needed to contain relatively few parts and be made of very inexpensive materials. Any kind of device involving stainless steel or other expensive materials would be too expensive. Another important issue that the cost requirement brings up is the labor component of the design. The final product would need to be simple to construct since man-hours contribute significantly to the overall cost of a product. For example, the final design could be made of two very inexpensive parts, but if each part required intensive physical labor, it would be unlikely that the final design would still be within the budget.

Our other main concern was the size constraint. The specifications state that the design should be 1” x 1” x 4” for a single readout device or 1” x 4” x 4” for a continuous readout device. This constraint is important to our client and should be met under almost all circumstances. For a device that has less that 1% error, the size specifications are flexible. The device must be this small to keep shipping costs down.

The size constraint put several things into perspective. We recognized that during construction of the design we would need to be very precise. The fact that the device is very small leaves little room for machining errors. The smallest mistakes can be amplified significantly when a product needs to be so small. Another factor to consider from the size is the durability of the design. If a product is relatively small it may be easier to drop, damage, or break. Therefore, the final product should incorporate a sound overall structure and must be constructed of relatively sturdy materials.

While the accuracy will be important in testing, it is difficult to incorporate into the design of the product. The final product needs to be reasonably accurate since it will be used in a medical environment where a patient’s life may depend on it. There is, however, a tradeoff between accuracy and other constraints like cost and size. Typically, the more accurate a product is, the more expensive it will be to manufacture. In our case, we decided that the cost constraint should override the others. If we are to try to achieve the cost requirements, it is not practical to expect the final product to be as accurate as more expensive products already on the market. The product should ensure a reasonable amount of accuracy (up to 10% error), but making a very precise final product was not be our highest priority.

V. Design Alternatives

Design Alternative I:

One of our alternative solutions was first presented to us by our client, Dr. John G. Webster, who called it the drag flow meter. There are not many current products with exactly the same design, but a few that are close are referred to as drag force flow meters, or target flow meters (Engineering Fundamentals, 2006). Our design consisted of a clear tube with a circular piece of thin metal placed in a cross-sectional area of the tube. This piece would deflect proportionally to the air flow entering the tube (see Figure 2). We designed the tube to be cylindrical, with a diameter of 1” and a length of 4”. We would make it out of acrylic, which is a transparent, durable plastic that tolerates adverse weather conditions. We designed the metal piece to be made of brass because it does not react readily with O_2, CO_2, and medical air. Also, like other metals, when brass is cut thin enough it acts as a spring and bounces back to the original vertical position when there is no air flow through the tube. We would make the brass disk slightly smaller than the cross-sectional area of the tube so that there is less friction between the tube and the metal piece during the deflection.

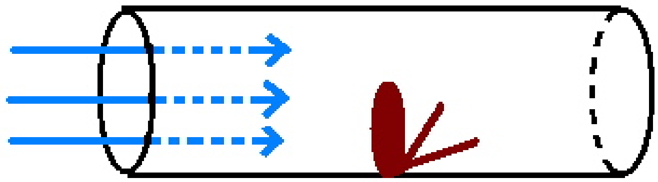


Figure 2: Drag flow meter

Taking measurements with this device would be fairly simple. We would calibrate the clear tube using an accurate flow meter. The person taking the measurement would only need to see to what marking the brass piece is deflected and read off the flow rate next to the calibration lines. These lines would be spaced about every five degrees within the 90-degree range of deflection behind the metal disk. The scale would be small enough to be reasonably accurate, but large enough to be read with ease.

The drag flow meter had several advantages and disadvantages that affected our evaluation of the design. This design is extremely simple, with only two parts. It will be inexpensive to manufacture. The training required to use the device would be minimal, since the operation is fairly self-explanatory. Our design would work in most normal weather conditions. Additionally, it can be held at all angles, although horizontally will be preferred because gravity may have a small effect on the position of the metal disk.

There are few disadvantages to this design which were considered as well. The durability of the parts is questionable, as the brass piece might break off or lose its elasticity after many uses. This would cause our measurements to be inaccurate. The dimensions of the design would be difficult to calculate because there are not many known equations for drag flow meters. Also, the deflection would depend greatly on the thickness of the brass piece; therefore, replication of the manufacturing would be difficult.

Design Alternative II:

Design alternative two is a rotameter with slight modifications that would make it easier to produce and more reliable in the field. A rotameter consists of a transparent conical tube, with the narrow end connected to the gas source and the wider end open to the air. Within the conical tube is a float which provides an indication of the flow rate of the fluid based on its height. At a flow rate of zero LPM, the float rests at the bottom of the tube, and as the flow rate increases, the float rises. On the conical tube there are markings to indicate flow rates. There are many different shapes to choose from when selecting a float, and each has an advantage. For our design, the float is spherical. A float of this shape is typically less accurate, but it was the only viable option within our price range. The weight of the float is also important. With a few calculations, we determined the approximate weight of the float, and using the correlating density, planned to choose a material that best suited the project from that point. Finding a float was difficult. We were unable to find a float that was light enough for our specifications. Production of the float was considered, but the float must be completely smooth. Any seams left by careless manufacturing would have resulted in an inaccurate flow meter (O'Neal, 2006), and it is questionable if calibration would correct the problem. It was therefore determined that with our resources, it would not be feasible to manufacture the float.

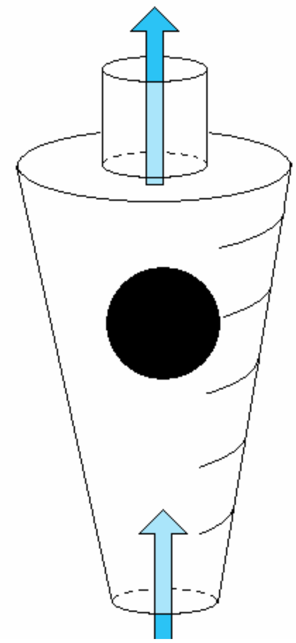


Figure 3: Rotameter

The conical tube, shown in Figure 3 was to be made of acrylic, which is transparent. It is also durable, which is beneficial, given the environment in which this device will need to function. In addition, acrylic is relatively inexpensive when purchased for mass production. We planned that the rotameter would be ⅛" in diameter at the narrow end and no larger than 1" in diameter at the wide end. It was to be no longer than 4". At the input end, there were to be ridges that would make a stronger connection to the gas source and simplify operation by the user.

There are many advantages to this design. The greatest advantage is cost. We anticipated that this design would be the least expensive to produce on a large scale because there are few parts involved. Another key advantage is reliability, which is also due to the small number of parts. We believe that this product would remain reliable in most environmental conditions.

Disadvantages of this design include accuracy and gravity-dependence. Within the boundaries of the design specifications, we believed that this design would be accurate, but because of cost and size limitations, it might not have been as accurate as we would have liked. This is mainly due to the shape of the float, but could also depend on the method of manufacturing chosen. The device is also gravity-dependent, which means that the user must hold it completely vertical for the device to work properly. This limits the number of situations in which the device can be used. Another disadvantage is the possibility of the float getting lodged inside the tube. A potential solution to this problem is simply shaking the device until the float is freed. This process will not cause any significant damage to the device.

Design Alternative III:

Design alternative three, which is based off of current venturi tube designs, uses difference in pressure to give feedback on the gas flow rate through a tube. The design is depicted in Figure 4 and consists of three main parts: a main body tube, a manometer, and an obstruction in the tube (Jamison, 1991). The obstruction creates a pressure difference between the two sides of the main tube as gas flows through it. This pressure difference is then read by the manometer (Jamison, 1991). The manometer senses the pressure difference by varying the height of the liquid. The difference between the heights of the two sides corresponds to the difference of the pressure across the obstruction. This measured difference of pressure then corresponds to the flow rate through the tube. By using several equations, the manometer can be calibrated and marked to give readouts for the flow rates through the tube. Another important feature of the design is the ridged tubes attached on either side of the obstruction. These ridges allow for the manometer tube to be easily detached by the user. This is a key feature because when liquid evaporates from inside the manometer it will need to be refilled by the user. A detachable manometer simplifies this process. The manometer includes different fill markings on it to let the user know how much liquid to add. In order to keep expenses down as much as possible, this design incorporates acrylic for the main body tube and the obstruction, plastic tubing for the manometer, and water to place inside of the manometer.

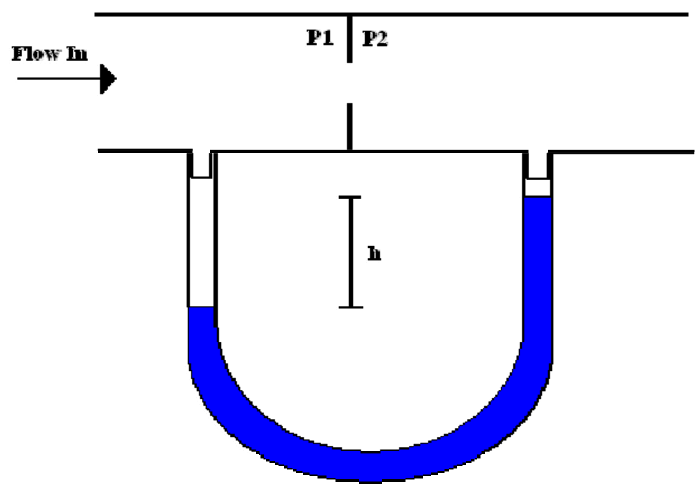


Figure 4: Venturi flow meter

The venturi design intrigued us to start with because of several of its unique advantages. One of the biggest advantages to the venturi approach is that it does not rely on any moving parts. This makes the design more reliable in a variety of environments and also makes it easier to maintain over a great period of time. Another advantage is that it can be scaled down from current designs to make it less expensive. Current products use durable materials like aluminum for the tube body, but these parts can be replaced with the less expensive alternatives already described to maintain a low overall cost. The final advantage of this design is its simplicity. The venturi does not require any kind of special training to use and could be put into use immediately.

There are some drawbacks to this design. One area of concern with the design centers on its use of the manometer in general. Another disadvantage associated with the manometer is the fact that it is gravity-dependent and must be kept level. Additionally, the need for the water inside the manometer to be refilled is a disadvantage. Both of these requirements are added hassles for the user and make operating the device on a continual basis more difficult.

Upon preliminary analysis, we believed that the manometer of the venturi would exceed our size limitations. After consulting with Professor Chesler and performing some tentative calculations, we concluded that our size concerns could be avoided by making the venturi tube 1” in length, and allowing up to 4” for the height of the tube and the manometer. Our calculations indicated that these dimensions were possible.

VI. Design Matrix

After considering the advantages and disadvantages of each of the proposed designs, we constructed a design matrix to evaluate each design and to help decide with which design to proceed.

Design	Cost (1-10)	Accuracy (1-5)	Size (1-10)	Simplicity of Use (1-5)	Total (4-30)
Drag flow meter	5	3	10	3	21
Rotameter	8	4	10	4	26
Venturi flow meter	9	4	8	4	25

Table 1: Design Matrix (Best—10, 5; Worst—1)

We chose several criteria to evaluate the design; the more important criteria were weighted more heavily. The two categories weighted the most important are cost and size of the potential design because they are among the most important design specifications. If a design did not meet either of these two requirements, it was unlikely that it would be accepted by Engineering World Health. The highest score that a design could receive on this scale is 30 points, and the lowest that it could receive is 4 points.

After evaluation, the rotameter design scores the highest with the venturi in a close second and the drag flow in last place. The rotameter and the venturi designs scored well in each of the categories, while the drag flow design did poorly in cost. Our tentative calculations (see Appendices A and B) showed that the rotameter and the venturi were both plausible given the size and cost limitations, so we decided to continue pursuing construction of prototypes for both the rotameter and venturi designs.

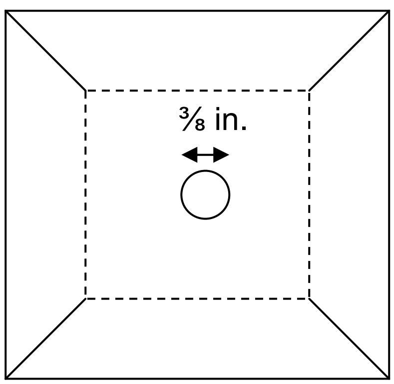
VII. Final Designs

We chose to follow through on two designs, the rotameter and venturi, after encouragement from Dr. Webster and Dr. Chesler. Since both showed a lot of promise and we were presented with a simpler way to manufacture both designs, we decided there would be enough time to build and test two prototypes.

Rotameter

Specifications

Figure 5: Top View



Our final rotameter device is shown in Figures 5 and 6. We chose to make our design trapezoidal rather than conical to reduce costs. It was constructed from 6 pieces of ⅛" thick Plexiglas that were glued together with acrylic epoxy. Plexiglas is both transparent and durable, which is beneficial given the environment in which the device will need to function. The parallel sides are 4" x 1", and the slanted sides are 4" x ½". Two square inch bases with ⅜" holes through the middle were attached to the top and bottom of the device. Medical tubing with ⅜" outer diameter was inserted securely into these holes for testing. There are many different shapes to choose from when selecting a float, and each has an advantage. For our design, we used a spherical float. This float is typically less accurate, but it is the only viable option within our price range.

Calculations

We used several equations to find the dimensions of the rotameter. The equations used to find the drag force from the gas exerted on the ball are the following:

- $F_d = \rho_b V_b g - \rho_f V_b g$ (Webster, 1999)
- $F_d = C_T \rho_f D_b^2 U_{an}^2$ (Webster, 1999)
- $D(z) = D_1 + (D_1 - D_2)z / L$

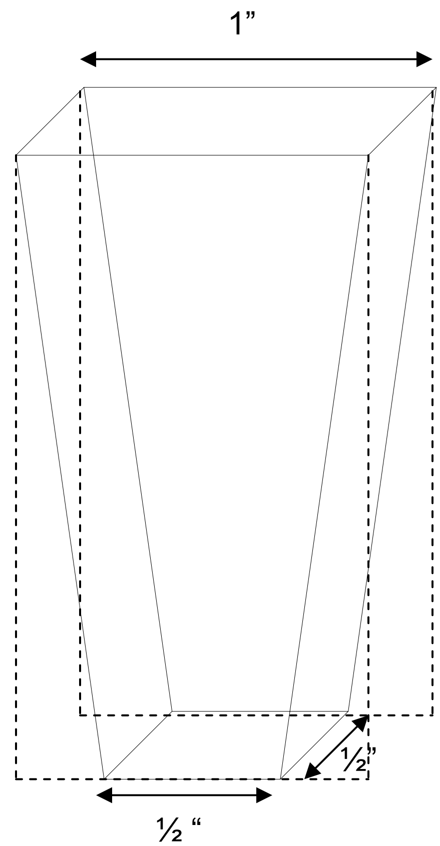
The variables used in these equations are defined below:

F_d	drag force
ρ_b	density of the ball
$\cancel{V}_b$	volume of the ball
g	acceleration of gravity (constant)
ρ_f	density of the fluid (constant)
D_b	diameter of the ball
U_{an}	velocity of the fluid at the annulus
$D(z)$	diameter of the tube at a height z above the bottom of the tube
D_1	diameter of the bottom of the tube
D_2	diameter at the top of the tube
L	length of the tube

Table 2: Rotameter design variables

These equations look complicated, but since the rotameter is a frequently used device, they are fairly common. They are solved by assuming that the rate of change in area of the tube is dependent on the third equation. Many other equations go into solving for the drag force, but they are complex and unnecessary to explain further. These equations were used to determine the necessary top diameter of the tube for the ball to float at the desired height based on several chosen ball sizes and masses. These floats included three air pellets of different masses, a round ball and a glass bead. The bottom tube diameter was set to ⅛” and top diameters were found for each of the different floats. These top diameters varied from 0.208” to 0.399”(Appendix A).

Figure 6: Front View



Because these calculations are based on a small cone-shaped device and we chose a trapezoidal design, our dimensions were altered. Our final design has a ½” x ½” base, a 1” x ½” top, and ⅜” holes in each for an air-tight connection to the medical tubing (see Figures 5 and 6).

Testing

We tested the rotameter with an air source and a calibrated rotameter (Figure 7) from Dr. Chesler’s laboratory, which we assumed to be accurate. We tested with several floats including various beads filled with epoxy and air pellets. Vaseline was used to create an air tight seal between the tubing and the rotameter as well as along the edges of the device in case our gluing had imperfections. An initial test was done without the calibrated rotameter to see whether or not the float would rise at any flow rate. We noticed that most of the air went around the float and out the top of the device; the float did not rise. Tape was then used to cover the unsecured top to minimize air leakage, and lighter floats were tested.

Figure 7: Calibrated rotameter used to find actual flow rate

Unfortunately, the rotameter did not produce adequate results. The float only rose when subjected to flow rates much higher than the medically useful range of up to 15 LPM (Figure 8). To enable our device to work at lower flow rates, we would need to alter our design to have a greater change in diameter from the bottom to the top of the flow meter. The dimensions needed would not meet design requirements set by Engineering World Health. Although our particular device failed at low flow rates, future work can be done to make improvements on the design and construction.

Figure 8: This picture shows the rotameter float failing to rise in spite of air flow through the tube

Budget

All of the materials necessary for the rotameter are available to order online. Below is a spreadsheet of the necessary materials and cost of tubing and Plexiglas sheets in order to make flow meters in quantities of 3 and 500. The Plexiglas sheets are from U.S. Plastics Inc. (order numbers 44292 and 44308 for 3 and 500 meters, respectively). The acrylic cement is Weld-On #16 Plexiglas Glue, from RPlastics.com ordered in quantities of 16oz to build 3 flow meters and 1 gallon to build 500 flow meters. The floats we used can be bought from Wal-Mart for $4.00.

Amount needed	Plexiglas	Acrylic Cement	Floats
For 3 meters	1 sheet of 12 x 24 inches	16 oz tube	Circular beads
For 500 meters	3 sheets of 48 x 48 inches	1 gal	Circular beads

Cost($)	Plexiglas	Acrylic Cement	Floats	Shipping	Total
For 3 meters	$4.40	$13.13	$1.50	$13.24	$32.27
For 500 meters	$107.52	$78.08	$250.00	$39.26	$474.86

Tables 3 & 4: Rotameter budget

Venturi

Specifications

The venturi tube was constructed from a 1” x 1” x 1” block of acrylic. The block was machined to create a venturi tube with an inner diameter of $^1/_8$” and ¼” connections on either end to attach to an external gas source. The inner diameter of the tube was created by drilling a $^1/_8$” hole through the tube. Then additional ¼” diameter holes were drilled $^1/_8$” in to both sides of the tube. These holes are concentric with the original $^1/_8$” hole drilled through the entire tube. Brass tubing with an inner diameter of 0.22” and an outer diameter of ¼” was then secured with epoxy into these holes to use as connectors for the medical tubing (see Figure 9).

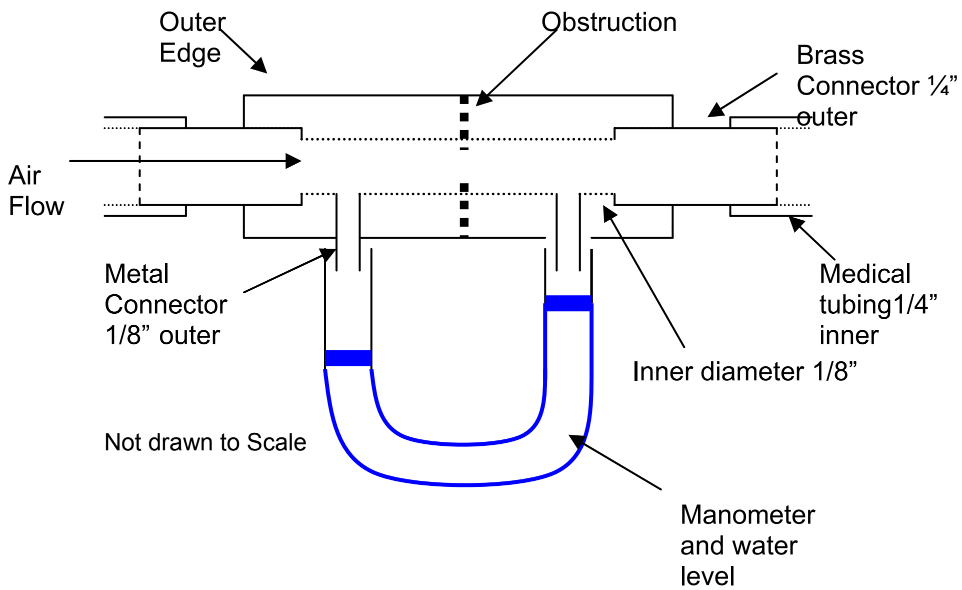


Figure 9: Side view of venturi design

The obstruction in the tube was cut from another rectangular piece of acrylic and a $^{7}/_{64}$” hole was drilled into it. The main body of the meter was cut in half and the obstruction was glued in between both sides. This piece was then accurately aligned with the outer tube so that the obstruction would be accurately centered inside the main tube. We produced one obstruction with dimensions based on our calculations (see below). Upon testing, it was determined to be quite accurate, and we did not need to make another. The manometer attaches to the main tube with removable ends to allow water refilling. The connections for the manometer were made by drilling two $^{1}/_{8}$” hole upward to connect with the main $^{1}/_{8}$” hole running through the entire tube. These holes were drilled ¼” from the edge of the tube on either side. Brass tubes with an outer diameter of $^{1}/_{8}$” were then glued in and used to fit on the manometer tubing, which extends about 3” below the main tube. To use, the manometer is filled with water, which serves as the indicator. The manometer tube was calibrated for a single readout design with a proper range indicated on the tube. Therefore, when the flow rate is in the desired range the water inside the manometer is between two markings indicated on the manometer tube. The final prototype is seen in Figure 10.

Figure 10: Glued venturi prototype

Calculations

The flow rate through the tube can be calculated from the pressure drop across the constriction via the venturi equation:

$Q = C\, \varepsilon\, \pi\, D_1^2\, (2\, \Delta P/ \rho_g)^{1/2}\, /\, (4(1 - \beta^2)^{1/2}$ (Webster, 1999)

With the following parameters:

Symbol	Description
D_1	Inner Tube Diameter
D_2	Obstruction Diameter
C	Discharge Coefficient (based on machining of tube)
ΔP	Pressure Drop across obstruction
ε	Expansibility Factor, $[1/(1-(D_2/D_1)^4)]^{1/2}$
β	D_2/D_1
ρ_g	Density of the Gas (1.275 kg/m^3 for air)

Table 5: Venturi design variables

The calculations that we performed for our venturi design helped us in several different ways. First of all, they gave us an idea of the relationship between the different parts of the tube. Our calculations showed us that by decreasing the diameter of the obstruction, we would be able to more accurately measure smaller flow rates through the tube. We also found that if the diameter of the obstruction was too small compared to the diameter of the main hole, this would cause an unreasonable amount of pressure difference. This pressure difference would be so great that the liquid in the manometer would vary in height by large amounts, and the manometer would need to be longer. This shows a tradeoff between accuracy and size. The design constraints were the most important factor in the final decision, and the project specified that the manometer could extend no more than 3” below the main body of the tube (resulting in a final product within the 4” x 4” x 1” size constraints). This forced us to consider diameters for the obstruction that were very similar to the diameter of the tube.

During the construction of our prototype we chose a $^7/_{64}$” obstruction that would be slightly smaller than the tube’s main diameter of $^1/_8$”. After testing (see below) we found that this size of $^7/_{64}$” worked well, so testing additional sizes of obstructions was unnecessary based on both our calculations and experimental observations.

Testing

To assess the venturi, it was necessary to get quantitative data through testing to determine if the device worked and if its accuracy met the design requirements. The goal was to find at least one flow rate that had less than 10% error, since it is a single read out design. The first step was to decide on a length of the manometer tubing. We decided that the manometer would work best if it was at its maximum length, 3” per side and 6” total, to allow for the greatest difference in water levels possible. We then tested to see if the obstruction had an accurate diameter by securing the pieces together with Vaseline and zip ties (see Figure 11). The Vaseline was to ensure that the connections were air tight, and the zip ties held the pieces together so there was no change in positions of the obstruction or the two end pieces. The obstruction was determined to be of accurate diameter by an initial test of changing the flow rate between 5 LPM and 8 LPM and measuring the actual flow rates on a rotameter provided by Dr. Chesler.

Figure 11: This picture shows our venturi flow meter in testing.

After we obtained the initial data, we decided that human error had been a factor, and that it would be best to glue the obstruction in place and test it again for two different gases using 3 practice tests to account for human error. Air and nitrogen were the chosen gases for the two separate tests.

Figure 12: This picture shows our glued venturi meter tested in series with an accurate rotameter.

In order to test these flow rates, we first glued the venturi pieces together with acrylic cement supplied by the machine shop. For air testing, we connected one end of our flow meter in series with the accurate rotameter and the other end of the venturi to the air source. We taped it to the glass door of the fume hood on top of black plastic to give it a solid background, ensure that no pinching of the manometer occurred and to guarantee the flow meter and the manometer would stay level (Figure 12). The flow rates were initially marked with differently colored, fine-tipped permanent markers and three initial tests, by reading the water levels from the bottom of the marked lines, were done on each to make certain the error being observed was no longer due to inconsistencies on our part. After learning how to read the manometer, 5 trials air were done by finding the flow rate on the manometer and recording the actual rate being displayed on the calibrated rotameter device.

The data from the air trials are shown in Appendix C. We attempted to find data for a flow rate of 2 LPM, but this rate was too slow for the flow meter to measure. This rate could be measured if the obstruction diameter was decreased, allowing for a greater change in pressure.

For the nitrogen testing the device was set up in the same format, except it was connected to a nitrogen air source. The nitrogen air source had a pressure regulator that could change how fast the nitrogen was coming out of the tubing, unlike the air source. The rotameter being used was also not calibrated for nitrogen so the readings were inaccurate and are not actually at 2, 5 and 8 LPM as the testing results in Appendix D suggest.

We were able to obtain a reading at the slower rate of 2 LPM with nitrogen, but this is unlikely the actual speed since the flow meter was inaccurate. The percent error at this rate is also too high, so the prototype is unable to measure this flow with nitrogen. The flow rates also seem to fluctuate much more than the air trials. This could be because the pressure regulator caused the gas to be inconsistent or the air source was not at a steady speed. We noticed that the ball in the rotameter tended to vary more with the nitrogen gas, leading us to believe the gas might not be leaving the source at a constant speed. Because of these factors, we are not able to conclude if the venturi is less accurate or inconsistent for nitrogen gas.

Budget

Below is a spreadsheet of the necessary materials and cost of tubing and acrylic blocks in order to make flow meters in quantities of 3 and 500, as well as the amount we requested from Engineering World Health to make our prototype. Our calculated amount is based on the fact that one of the companies we are purchasing from, United States Plastics Corp., only sells the acrylic blocks in lengths of 6', the manometer tubing in 50' increments and the medical tubing in 10' increments. The brass tubes, from McMaster-Carr, come in a pack of 8 or are sold separately, each 12" long, for the ¼" outer diameter and a pack of 15, each 12" long, for the $^1/_8$" outer diameter. The epoxy is for connecting the brass tubing to the flow meter, as well as securing the obstruction in the middle. We requested money to buy the medical tubing in order to perform the tests to accurately calibrate our device. With these materials we were able to make one flow meter, but we have enough materials to make several more, had the first one failed. We do not believe that the person hours required to put this device together will be over our budget after the process is perfected. There is also the possibility for a mold to be made for the main body of the flow meter that would greatly reduce the manufacturing time to make a single meter.

The materials we purchased with the requested money include:

- Acrylic rods – 1" x 1" x 6' (item number 44141 from http://www.usplastic.com)
- Medical tubing – ¼" inner diameter, ⅜" outer diameter, length of 10' (item number 54003 from http://www.usplastic.com)
- Manometer tubing – ⅛" inner diameter, ¼" outer diameter, length of 50' (item number 59002 from http://www.usplastic.com)
- Epoxy – 115 in^2 (item number 506/19 from http://www.mcmaster.com)
- Brass Tube – ¼" outer diameter (item number 8859K24 or 7782T111 from http://www.mcmaster.com)
- Brass Tube – 1/8" outer diameter (item number 8859K19 from http://www.mcmaster.com)

Amount of items needed	Tubing (ft)	Acrylic Block (ft)	Medical Tubing(ft)	Epoxy (bottles)	Brass Tubing ¼” (ft)	Brass Tubing 1/8” (ft)
For 3 flow meters	50	6	0	1	1	15
For 500 flow meters	500	84	0	10	48	45

Cost($)	Tubing	Acrylic Block	Medical Tubing	Epoxy	Brass Tubing ¼”	Brass Tubing 1/8”	Shipping	Total
For 3 flow meters	4.00	27.12	0.00	11.70	4.38	13.33	20.00	80.03
For 500 flow meters	40.00	379.68	0.00	117.00	65.56	39.99	50.00	692.23

Tables 6 & 7: Venturi budget

VIII. Conclusion

Ethical Considerations

The biggest constraint in the design of this flow meter was cost. Anytime a medical device is designed within a tight budget, there are ethical considerations to be taken into account. The design constraints also limited the allowable error in the flow meter to 10%, with the provision that if error is within 1%, the budget is flexible. To compromise the reliability of a medical device to stay within the budget is questionable. Of course, if the device is less expensive, it will be more available to those who need it in third world countries. Ideally, though, the device’s accuracy will not be compromised even though it will be made for less. This design, once tested, proved to be within 0.25% error at 8LPM and 6.4% error at 5LPM for air, and 2.68% error at 8LPM, 5.66% error at 5LPM and 18.03% at 2 LPM for nitrogen. The results prove that the device is safest with the higher flow rates with this obstruction.

Also, in an effort to keep the price down, the least expensive materials were chosen. Poorly chosen materials may compromise the device. It may fail before it should, or, even worse, compromise the health of the patient. Therefore, when materials for the prototype were chosen, careful consideration was paid to how the materials would wear. The materials used in the prototype are of high quality, and there are no issues with wear or degradation anticipated with extensive use.

Future Work

Venturi

While this project is almost at completion, there still remain a few key items on the agenda to resolve, including a final report to Engineering World Health. As part of the contract made with EWH when they approved the proposal and granted the design project its budget, a report must be submitted so they can monitor the progress of the design process, and possibly manufacture the design for use in third world countries. Before this can be completed, however, the issue of production still exists. It took the design team two weeks in the machine shop to manufacture the venture prototype. To pay a skilled machinist to make the flow meter will cost much more than is reasonable unless the process can be streamlined. The client has suggested exploration of injection molding, or assembly of the product from a kit. These ideas may help to cut the cost of the flow meter and make it more available to those who need it.

Rotameter

The rotameter prototype was not as successful as the venturi. To make our current prototype viable, we need to find a lighter float. Also, when producing more prototypes, we can make the change in area more dramatic. Additionally, there is some question as to whether the seams of the rotameter were air-tight. By gluing the prototype together more carefully and taking these other factors into account, the rotameter may become more accurate.

Appendix A: Rotameter

Variables:

- F_d is the drag force
- ρ_b is the density of the ball
- $\cancel{V}_b$ is the volume of the ball
- g is the acceleration of gravity (constant)
- ρ_f is the density of the fluid (O_2) (constant)
- C_T is the coefficient of turbulent drag
- D_b is the diameter of the ball
- U_{an} is the velocity of the fluid at the annulus
- Q is the rate of flow of the fluid (constant)
- A_{an} is the cross-sectional area of the tube at the annulus
- D(z) is the diameter of the tube at a height z above the bottom of the tube
- D_1 is the diameter of the bottom of the tube
- D_2 is the diameter at the top of the tube
- L is the length of the tube (constant)
- R_e is the Reynold's number
- V_{in} is the velocity of the fluid entering the tube at the bottom (constant)
- μ is the viscosity of O_2 (constant) (Anaesthesia, 2006)

Assumptions:

- The assumed gas is Oxygen
- Q is the assumed flow rate
- D_1 is the assumed small diameter
- L is the assumed length of the rotameter
- z is the assumed height for the ball to sit
- Based on calculated Reynold's numbers, we assumed that the that the flow is turbulent

Equations:

I. $F_d = \rho_b \cancel{V}_b\, g - \rho_f \cancel{V}_b\, g$ (Webster, 1999)

II. $F_d = C_T\, \rho_f\, D_b^2\, U_{an}^2$ (for turbulent flow) (Webster, 1999)

III. $U_{an} = [F_d / (C_T\, \rho_f\, D_b^2)]^{1/2}$ (from [II]) (Webster, 1999)

IV. $U_{an} = Q/A_{an} \rightarrow A_{an} = Q/U_{ans}$

V. $A_{an} = (\pi/4)\,(D(z)^2 - D_b^2)$

VI. $D(z) = (4A_{an}/\pi + D_b^2)^{1/2}$ (from equation [V])

VII. $D(z) = D_1 + (D_1 – D_2)z / L$

VIII. $D_2 = [(D(z) – D_1)L / z] + D_1$ (from equation VII)

IX. $C_T = 6 / (1 + R_e^{1/2}) + 24 / R_e + 0.4$ (for $R_e > 5{,}000$) (Gerhart, 1985)

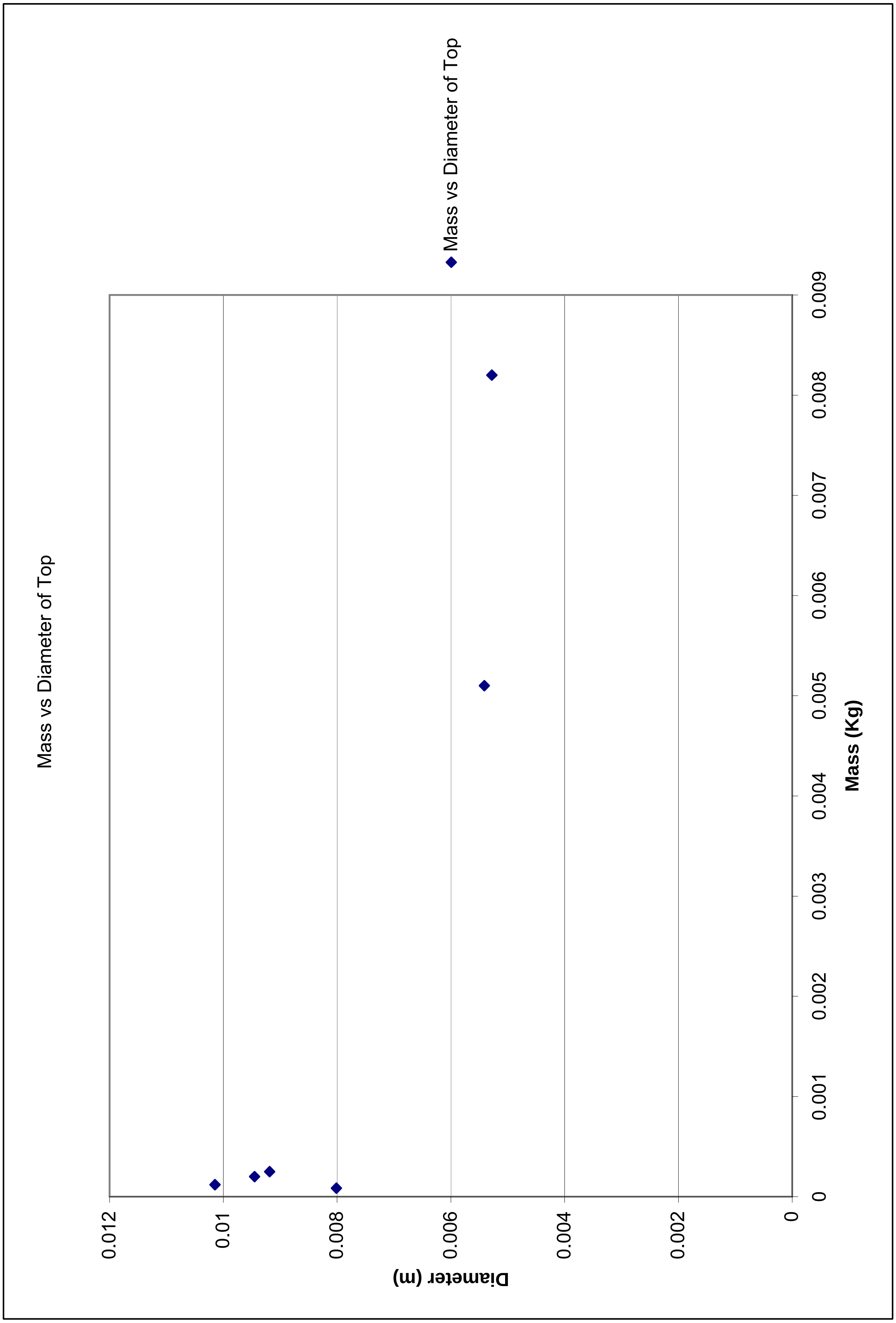
X. $V_{in} = 4Q / (\pi D_1^2)$

XI. $R_e = \rho_f V_{in} D_b / \mu$ (Webster, 1999)

Knowns	
Q (m^3/s)	0.00025
g (m/s^2)	9.81
D_1 (m)	0.003175
Rho_f (Kg/m^3)	1.428
L (m)	0.0762
z (m)	0.0635
mu (kg/(m*s))	0.00001909
V_{in} (m/s)	31.5764039

Unknowns relating to the ball					
CT	Re	Ball Type	Db (m)	mb (Kg)	Vb (m^3)
0.459925	10619.20317	BB	0.004496	0.0051	4.75795E-08
0.451674	14172.16492	Air pellet 1	0.006	0.00012	1.13097E-07
0.451674	14172.16492	Air pellet 2	0.006	0.0002	1.13097E-07
0.451674	14172.16492	Air pellet 3	0.006	0.00025	1.13097E-07
0.459925	10619.20317	Round ball	0.004496	0.0082	4.75795E-08
0.463639	9448.109946	glass bead	0.004	0.00008478	3.35103E-08

Unknowns found from equations				
Fd (N)	Uann (m/s)	Aann (m^2)	Dz (m)	D2 (m)
0.05003	61.39063804	4.07E-06	0.00504	0.005412
0.001176	7.115490061	3.51E-05	0.008985	0.010147
0.00196	9.188533794	2.72E-05	0.008405	0.009451
0.002451	10.27392329	2.43E-05	0.008184	0.009186
0.080441	77.84398833	3.21E-06	0.00493	0.005281
0.000831	8.858179511	2.82E-05	0.007207	0.008013


Mass vs Diameter of Top
Diameter (m)
0.012
0.01
0.008
0.006
0.004
0.002
0
Mass (Kg)
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
Mass vs Diameter of Top

Appendix B: Venturi

Variables

- D_1: The radius of the opening in the orifice plate.
- D_2: The radius of the tube body.
- Beta: D_1/D_2
- Discharge Coefficient (C): Calculated from a given a D_1 and Reynolds number using equation III and the given constants a, b and c (Flowmeter Directory, 2006).
- Expansibility Factor (ε): Calculated from a given D_1 using equation II.
- Reynolds Number (R_e): Calculated for a given D_1, viscosity, density and the determined Vin using equation I.
- Qmax: Determined maximum flow rate through meter(15Lpm).
- Hmax: Determined height displacement for the maximum flow rate through meter, given D_1. Found using equations IV and V.
- Δh: Change in height of the liquid in the manometer. In all calculations, Δh is Hmax.

Assumptions

- Gas used through flow meter is oxygen
- Liquid in the manometer is water
- D_2 is 3/16"=0.004763m
- Assumed various D_1 values to find optimum D_1 for chosen D_2

Equations

I. $R_e = \rho_f V_{in} D_{1(small)} / \mu$ (Small, 2005)

II. $\varepsilon = [1/ (1- (D_2/D_1)^4]^{½}$ (Flowmeter Directory, 2006)

III. $C= a + b(\log(R_e))^2 +c(\log(R_e))^3$ (Flowmeter Directory, 2006)

IV. $Q_{max}= C\, \varepsilon\, \pi\, D_1^2\, (2(p_1-p_2)/\rho_f)^{1/2} / (4\, (1 - \beta)^{1/2}$ (Small, 2005)

V. $p_1 - p_2 = \rho_L\, g\, \Delta h$ (Gerhart, 1985)

Constants

- Values a,b, and c are constants used to calculate the discharge coefficient using equation 5.
- a: 0.49670
- b: 0.00873
- c: -0.00044
- The values used here for a, b and c are the best values we could find that fit our design, but they seemed to vary widely in the sources we looked at. Therefore, these constants can't be assumed to be perfect.
- Other constants used:
- Density of water: 1000 kg/m^3
- Density of Oxygen: 1.428 kg/m^3
- Qmax (max flow rate): 0.00025m^3/s
- Vin: 14.034m/s

Data

For the Venturi calculations the inner diameter (d2) was kept constant at 1/8" (.004763m) and the diameter of the obstruction was varied. The resulting change in the liquid in the manometer (Hmax) was calculated.

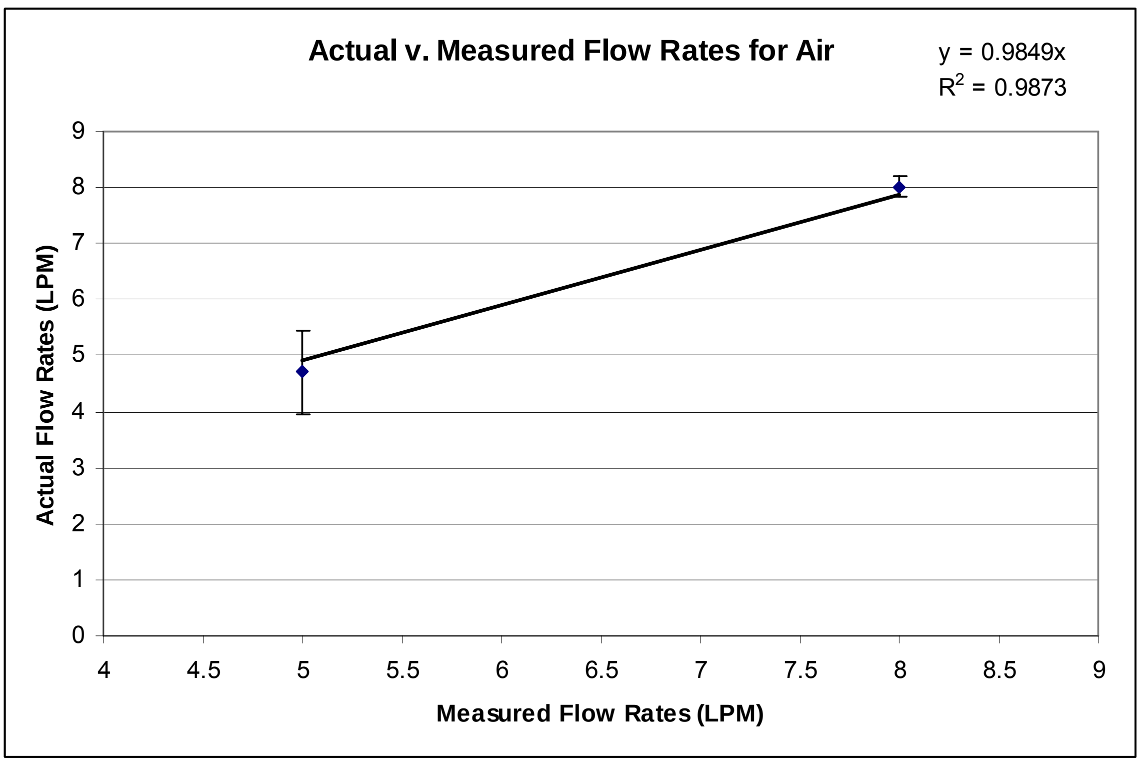
d1(m)	d2(m)	Beta	Discharge Coefficient	Expansibility Factor	Re	Hmax(cm)
0.000612	0.004763	0.128571429	0.555743376	1.000136659	642.808909	16699.56625
0.000918	0.004763	0.192857143	0.562684658	1.000692411	964.213363	3146.690823
0.001225	0.004763	0.257142857	0.567789508	1.002193284	1285.61782	945.5921913
0.001531	0.004763	0.321428571	0.571848198	1.005380243	1607.02227	364.3079497
0.001837	0.004763	0.385714286	0.57522677	1.011254252	1928.42673	162.9190309
0.002143	0.004763	0.45	0.578126025	1.021156043	2249.83118	79.99095411
0.002449	0.004763	0.514285714	0.580668454	1.036926526	2571.23564	41.57267116
0.002755	0.004763	0.578571429	0.582934469	1.061223255	2892.64009	22.23805485
0.003062	0.004763	0.642857143	0.584979797	1.098164162	3214.04454	11.93320524
0.003368	0.004763	0.707142857	0.586844694	1.154739818	3535.449	6.241254719
0.003674	0.004763	0.771428571	0.588559216	1.244322548	3856.85345	3.055666424
0.0047	0.004763	0.98687664	0.593473314	4.407848454	4934.01297	0.005758353

- We decided that our data will not be very accurate, since the calculation of the discharge coefficient was complicated by unreliable values for the constants a, b and c. However, changing these values doesn't change the overall trend showed in the data.
- The data shows us that by picking a diameter for the obstruction that is similar to that of the of the inner tube diameter we get smaller changes in the height. Any obstruction diameter that is significantly smaller than the inner diameter creates too large of a change in the water level for our design.
-The best diameter, which is highlighted, has been singled out because it gives the most reasonable change in height of the liquid.

Appendix C: Venturi Testing Results with Air

Trials for 5 LPM	Readings in LPM
1	5.5
2	4
3	4
4	5.5
5	4.5
Average Rate	4.7
Percent Error	6.38

Trials for 8 LPM	Readings in LPM
1	8.3
2	8
3	7.8
4	8
5	8
Average Rate	8.02
Percent Error	0.25

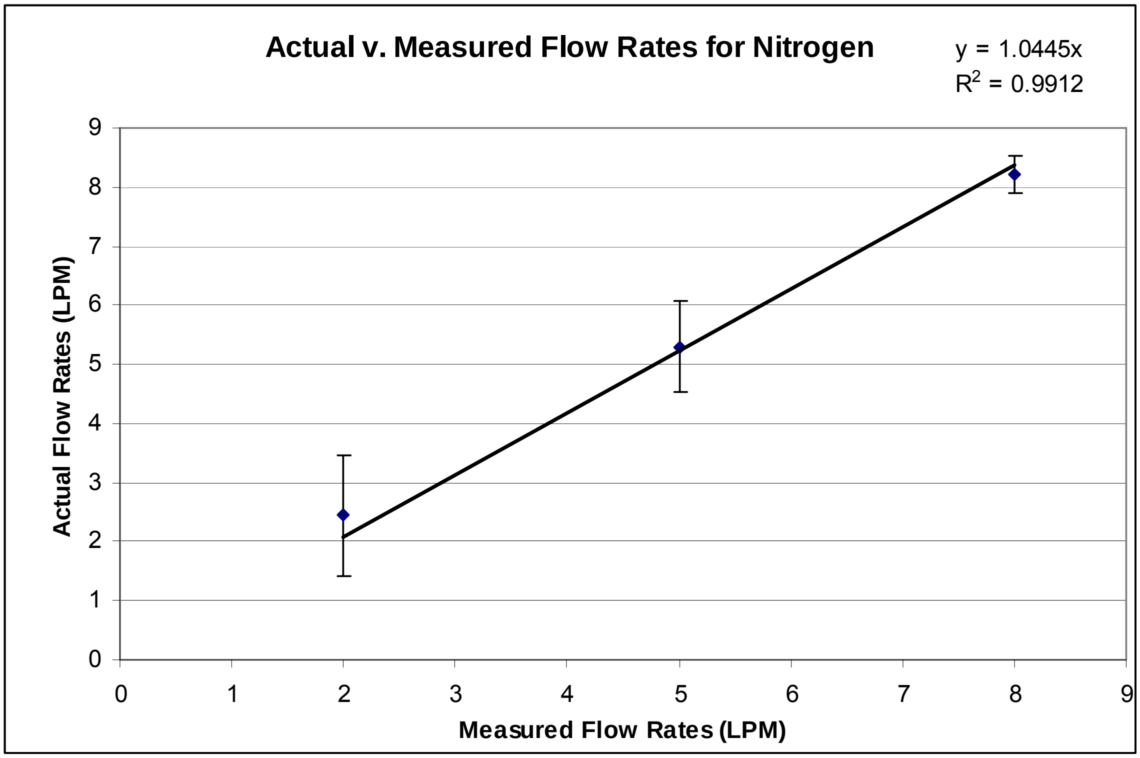


Appendix D: Venturi Testing Results with Nitrogen Gas

Trials for 2 LPM	Readings in LPM
1	3.5
2	1.2
3	3
4	1.5
5	3
Average Rate	2.44
Percent Error	18.03278689

Trials for 5 LPM	Readings in LPM
1	6
2	4.5
3	5.5
4	6
5	4.5
Average Rate	5.3
Percent Error	5.660377358

Trials for 8 LPM	Readings in LPM
1	8.5
2	8.5
3	7.8
4	8.3
5	8
Average Rate	8.22
Percent Error	2.676399027



Actual v. Measured Flow Rates for Nitrogen
y = 1.0445x
R2 = 0.9912
Actual Flow Rates (LPM)
Measured Flow Rates (LPM)
0
1
2
3
4
5
6
7
8
9

Appendix E: PDS

Project Design Specification: EWH – Flow Meter
Anna Moeller, Kailey Feyereisen, Ryan Drake, Gina Stuessy
February 9, 2006
Problem Statement:

Design a flow meter to monitor oxygen and medical air CO_2 with either single or continuous readouts, measuring 1x4x1” or 4x4x1” respectively, that are accurate within 10% of actual flow rate costing less than 2 dollars each when mass produced.

Function:

To measure the gas flow rate in medically useful ranges (0-15 Liters per minute) of single or continuous readout rates.

Client Requirements:

- less than $2 each when mass produced
- single readout: 1x4x1”
- continuous readout: 4x4x1”
- accurate within 10%
- to be attached to an O_2, CO_2, or medical air source.

1. Physical and Operational Characteristics
    a. *Performance Requirements*: Will attach to a flow source tube at both ends. Must be reliable, to be used on a regular basis.
    b. *Safety*: Devices will be labeled with which type of gas they are measuring and sterilized after any contact with patient. Ends of meter will lock smoothly into source tube to prevent any injuries from sharp edges.
    c. *Accuracy and Reliability*: The flow meter needs to be accurate within 10% of the actual value with a reliability of 90%. An excellent device would allow for a value within 1% of the actual.
    d. *Life in Service*: It should have a life span of a minimum of 1 year before losing accuracy.
    e. *Shelf Life*: If it is electrical it should be able to be stored in hot and humid areas without electrical failure. It should also be able to be packed away for up to 6 months, and not decompose.
    f. *Operating Environment*: Needs to work in dry, dusty, humid, hot, cold, and rainy conditions without failure.
    g. *Ergonomics*: Needs to have a simple readout that shows when the gas is at the correct flow rate. People with little or no training should be able to use it.
    h. *Size*: The continuous readout flow meter should be no bigger than 4in x 4in x 1in, and the single readout flow meter should be no bigger than 1in x 4in x 1in.

i. *Weight*: While there is no weight limit on the product, a lighter product will allow for cheaper shipping to consumers. Because the ultimate goal of the product is to create the flow meter as inexpensively as possible, a lighter product is preferable, but not if it comes with higher material cost.
j. *Materials*: No material restrictions aside from cost.
k. *Aesthetics, Appearance, and Finish*: Aesthetics are not a concern, as this product is to be produced as cheaply as possible for use in third world countries. The readout, however, should be clear and easy to read.

2. Production Characteristics
   a. *Quantity*: Produce one working prototype but able to mass.
   b. *Target Product Cost:* The target product cost for the project is less than $2 each when produced in quantities of 500.

3. Miscellaneous
   a. *Standards and Specifications*: Local standards and international standards need to be met.
   b. *Customer:* The customer would ideally like the product to be accurate within 1%.
   c. *Patient Related Concerns:* There are no privacy or sterilization concerns.
   d. *Competition*: There are many similar products and patents, which can not be violated.

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