EWH - Gas Flow Meter

BME 201
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Client: Engineering World Health
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Abstract

Flow meters are a device used to measure the rate of fluid movement at a given point in the 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. A situation in which they can commonly be used is with anesthesia machines (2).

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 no way to monitor gas supply.

Our contact, Dr. John Webster, and our client, Engineering World Health, would like us to create an affordable gas flow meter to be used in these developing countries that can accurately measure the amount of gas supply. Since current products range from approximately $10 to $1000 we need to provide them with a widely available alternative.

I. Introduction and Project Motivation

If doctors do not have access to the proper equipment during an operation they put their patients in more danger than necessary. Flow meters are used to maintain the correct intake of gases during a patient's stay in the hospital. Since some of the gases are clear the flow rate is not noticeable in the tubes. Therefore, 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 air. For example, if an anesthesiologist fails to supply the proper amount of these gases during a surgery dire complications could arise (2). The rates needed in the health care profession vary but are usually between 0.5 to 15 LPM (6). Current products are effective but costly. Depending on the accuracy desired products can cost well above $1000 (7). Some cheaper flow meters do exist that cost around $10 but these are still too expensive for developing countries.

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 (10). Many of these developing countries are also in a state of economic peril and their governments have difficulty helping the poor. This means that many of the people within the countries are faced to live off of little or no money (14). This is why an inexpensive alternative to current flow meters is needed for these countries. Even if the prospective patients do not understand the importance of having a flow meter, the potential benefits are many. The quality and longevity of life for both adults and children would improve. There are also many other benefits that improved health care would provide, including better economic conditions since more people will be physically able to take 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 numerous times. 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 looks like a cone and the velocity of the gas changes throughout the device (2). 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 (11). A manometer is a U-shaped piece of tubing filled with a liquid, like water, that measures the difference in pressures at both ends (17). 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 (2). It is shown in Figure 1.

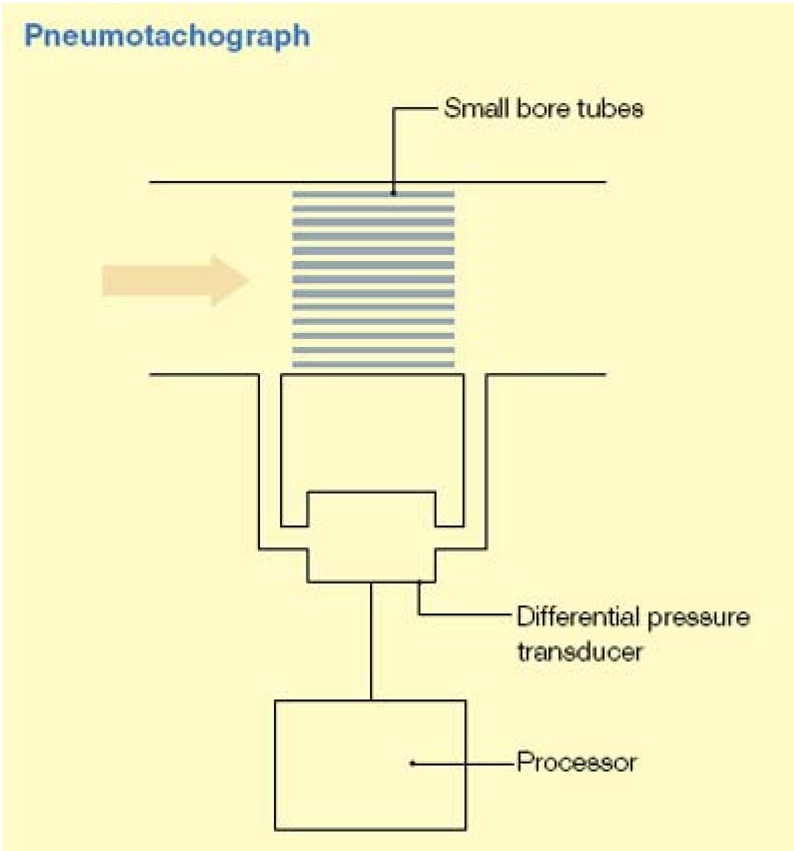


Figure 1: Pneumotachograph Schematic (2)

The Turbine flow meter uses the force the gas exerts to cause a propeller to move that is within the pipe. The speed of the rotation of the blades is directly related to the rate of gas flow (9). The Ultrasonic flow meter uses the Doppler Effect and the change in velocity of the sound an attachmen.t to the tube emits to measure the speed of gas. All of these methods are currently in use today (2).

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 (8). The other kinds of 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 Engineering World Health (EWH), our client. 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. (5)

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 air source. We had the choice of designing a single or continuous readout flowmeter, each being no greater than 1" by 1" by 4" or 4" by 4" by 1" respectively. Our flow meter must measure the flow rate accurate within ten percent of the actual value, and we are challenged to narrow this range to within one percent of certain flow rates. We must be able to sell the device at less than two dollars each when produced in quantities of 500 (6).

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.

V. Design Alternatives

Design Alternative I:

Our client, Dr. John G. Webster first presented to us the idea for design one, and called it the Drag Flowmeter. 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 (4). Our design consists of a clear tube with a circular piece of thin metal placed in a cross-sectional area of the tube. This piece will 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 will 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 bounce 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 during the deflection.

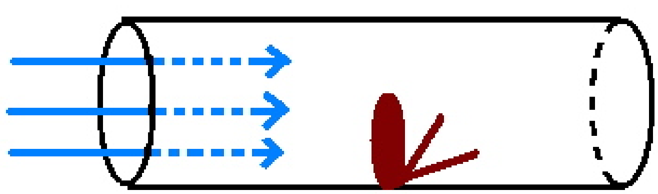


Figure 2: Drag Flow meter

Taking measurements with this device would be fairly simple. We would calibrate the clear tube using another, accurate flowmeter. The person taking the measurement will 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 will be spaced about every five degrees within the 90-degree range of deflection behind the metal disk. The scale will be small enough to be reasonable accurate, but large enough to be read with ease.

The Drag flow meter has several advantages and disadvantages that will affect our choosing the appropriate design for the client. The design is extremely simple, with only two parts and will be inexpensive to manufacture. The training required to use the device would be minimal since the operation is fairly self-explanatory. Our design will work in most normal weather conditions, and held at all angles, although horizontally will be preferred because otherwise gravity will have a small effect on the position of the metal disk.

There are few disadvantages to this design which must be considered as well. The durability of the parts is questionable, as the brass piece might break off or lose its elastic modulus after many uses. The design will be difficult to calibrate correctly, because there are not many designs like this already and it is difficult to calculate the angular deflection of a specific piece of metal. The deflection will depend greatly on the thickness of the brass piece, and although we will attempt to be accurate in cutting the metal, a fraction of a millimeter of difference between two disks' thicknesses will lead to different calibrations. Because of the difficulty in calibration, and the possibly changing elastic modulus of the brass, we expect our measurements to be inaccurate.

Design Alternative II:

Design alternative two is a rotameter with slight modifications that will 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 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 upon its height. At a flow rate of zero L/min, the float will rest at the bottom of the tube, and as the flow rate increases, the float will rise. 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, we will be using a spherical float. This float is typically less accurate, but it is the only viable option within our price range. The weight of the float is also important. With a few simple calculations, we will determine the weight of the float, and using the correlating density, choose a

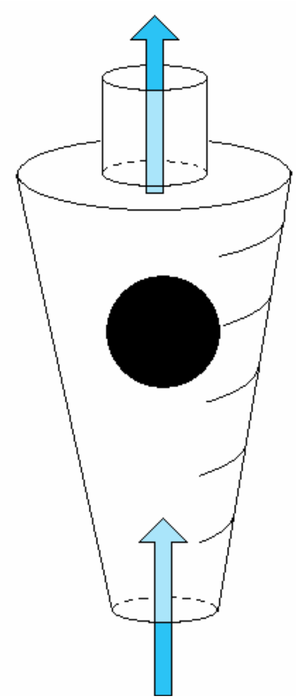


Figure 3: Rotameter

material that best suites the project from that point. Production of the float may prove to be more difficult, as the float must be completely smooth. Any seams left by careless manufacturing will result in inaccurate flow meter.

The conical tube, shown in Figure 3 will 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. Acrylic is also relatively inexpensive when purchased for mass production. The rotameter will be 1/8” in diameter at the narrow end and no larger than 1” in diameter at the wide end. It will be no longer than 4”. At the input end, there will be ridges that will 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. This design will be the less expensive to produce on a large scale because there are few parts involved. Another key advantage is reliability, also due to the small number of parts. We believe that this product will remain reliable in most environmental conditions.

Disadvantages of this design include accuracy and gravity-dependence. Within the boundaries of the design specifications, we believe that this design will be accurate, but because of cost and size limitations, it may not be as accurate as we would like. 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 differences in pressure to give a feedback on the gas flow rate through a tube. The design is depicted in Figure 4 and consists of four main parts, a main body tube, a manometer, an obstruction in the tube and a U-shaped tube with ends on either side of the obstruction (11). The obstruction creates a pressure difference between the two sides of the main tube as gas flows into it. This pressure difference is then read by the

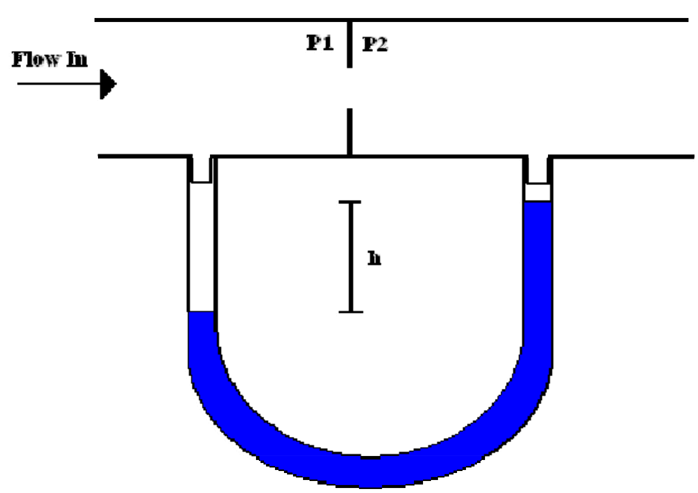


Figure 4: Venturi Flow Meter

manometer (11). The manometer senses the pressure difference by varying the height of the liquid in it. The difference between the heights of the two sides corresponds to the difference of the pressure. This measured difference of pressure then corresponds to some flow rate through the tube. By using several equations the manometer can be calibrated with markings 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 and making the manometer detachable simplifies this process. The manometer would also incorporate 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 would incorporate acrylic for the main body tube and the obstruction, plastic tubing for the manometer and water to place inside of the manometer.

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 much easier to maintain over a great period of time. Another advantage is that it can be scaled down from current designs to be made for cheaper. Current products use more accurate liquids like mercury and more durable materials like aluminum for the tube body. However, these parts can be replaced with the cheaper alternatives already described to maintain a low overall cost. The final important advantage of this design is its simplicity. This design would not require any kind of special training to use and could be put into use almost immediately.

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

At first we thought 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 tube diameter and the manometer. Our calculations indicate that these dimensions are 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 statistically and to help decide which design to proceed with.

Best-10, Worst-1

Table 1: Design Matrix

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

We chose several criteria to evaluate the design with the more important criteria being weighted more heavily. The two categories weighted the most important are cost and size of the potential design. It was decided to weigh these categories the highest because they are among the most important design specifications. If a design did not meet either of these two requirements it would be unlikely that it would be accepted by Engineering World Health. The highest score that a design could receive on this scale is 35 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) show that the rotameter and the Venturi are both plausible given the size and cost limitations. Therefore, it was decided to pursue either the rotameter or the Venturi design for our future work.

VII. Ethics

Because this device is used on people for medical purposes, it is important that it performs its task reliably and accurately. Fortunately, it is fairly easy to test both without putting anybody at risk. To test the final prototype, the flow meter will be connected to a gas flow and another flow meter that is known to be accurate. Using the known flow meter as a standard, we can assure that our meter is accurate within the range we desire.

VIII. Conclusion

Now that we have evaluated our three design alternatives, we will make a final decision between the rotameter and the Venturi designs. After selecting one or the other we will fine-tune our design and construct a prototype. EWH will then look over the proposed design and decide whether or not to fund the building of the working prototype. Before building a prototype we will need to make decisions on the exact specific dimensions of the design components.

After the building of the prototype testing will be done to ensure the accuracy of the device. This is important since it will hopefully be used on humans in the future and we want to guarantee the best treatment available. Finally, data on the price to mass produce the final design needs to be found in order to present to EWH.

Appendix A: Equations

Rotameter

Variables:

- F_d is the drag force
- ρ_b is the density of the ball
- 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) (1)

Equations:

I. $F_d = \rho_b V_b g - \rho_f V_b g$ (15)

II. $F_d = C_T \rho_f D_b^2 U_{an}^2$ (15)

III. $U_{an} = [F_d / (C_T \rho_f D_b^2)]^{1/2}$ (15)

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

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

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

VII. $D(z) = D_1 + (D_1 - D_2)z / L$

VIII. $D_2 = [(D(z) - D_1)L / z] + D_1$

IX. $C_T = 6 / (1 + R_e^{1/2}) + 24 / R_e + 0.4$ (9)

X. $R_e = \rho_f V_{in} D_b / \mu$ (15)

Venturi

Variables:

- R_e: Reynolds Number
- ρ_f : Density of Fluid
- V_{in} :Velocity of Air Into Tube
- D_1 : Diameter of Orifice Plate Opening
- D_2 :Diameter of Tube Body
- μ: Viscosity of Fluid
- ε: Expansibility Factor
- C: Discharge Coefficient
- a, b, c: Constants (6)
- Q_{max} : Maximum Air Flow Rate
- p1-p2: Pressure Difference Between Two Sides
- β: D_1/ D_2

Equations:

I. $R_e = \rho_f V_{in} D_{1(small)} / \mu$ (15)

II. $\varepsilon = [1/ (1- (D_2/D_1)^4]^{½}$ (7)

III. $C = a + b(\log(R_e))^2 + c(\log(R_e))^3$ (7)

IV. $Q_{max}= C \varepsilon \pi D_1^2 (2(p_1-p_2)/\rho_f)^{1/2} / (4 (1 - \beta^2)^{1/2}$ (15)

V. $p_1 - p_2 = \rho_L g h$ (9)

Appendix B: Data and Graphs

Rotameter

Variables:

- V_{in} based on D_1 and found through rotameter equation IV
- CT is based off of the different Re values and found through rotameter equation IX
- Re is based off of the different Db values and found through rotameter equation X
- mb (mass of the ball), V̶b, and Db depend on ball type
- Fd depends on mb(ρ_bV̶b) , and V̶b, and found through rotameter equation I
- Uann depends on Fd, Db, and CT and is found through rotameter equation III
- Aann depends on Uann and is found through equation IV
- Dz is the diameter of the tube where the ball will sit and depends on Aann and Db and is found through rotameter equation VI
- D_2 depends on Dz and is found through equation VIII
- The graph is the mass of the ball versus the diameter of the tube at which it sits (Dz)

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

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

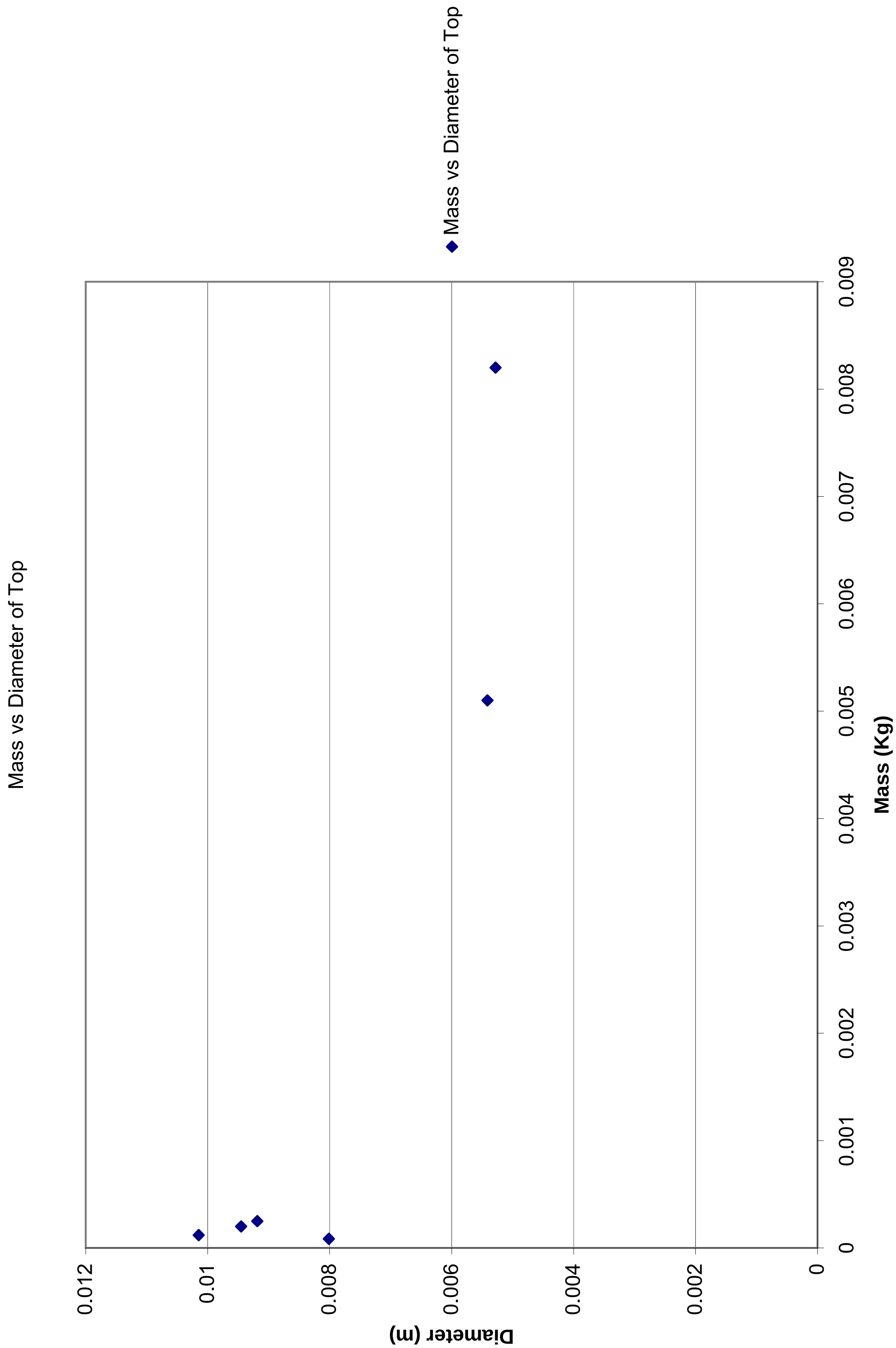
Unknowns relating to the ball

CT	Re	Ball Type	Db (m)	mb (Kg)	~~V~~b (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

D2>D1? (1 is good)	D2>Db? (1 is good)
1	1
1	1
1	1
1	1
1	1
1	1


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

Venturi

Variables:

- Discharge Coefficient: Calculated from a given a D_1 and Reynolds number using Venturi equation III and the given constants a, b and c (7).
- Expansibility Factor: Calculate from a given D_1 using Venturi equation II.
- R_e: Reynolds number calculated for a given D_1, viscosity, density and the determined Vin using Venturi 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 Venturi equations IV and V.

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

D_1(m)	D_2(m)	β	Discharge Coefficient C	Expansibility Factor ε	Reynolds Number R_e
0.000306	0.004763	0.064285714	0.544602674	1.00000854	321.404454
0.000612	0.004763	0.128571429	0.555743376	1.000136659	642.808909
0.000918	0.004763	0.192857143	0.562684658	1.000692411	964.213363
0.001225	0.004763	0.257142857	0.567789508	1.002193284	1285.61782
0.001531	0.004763	0.321428571	0.571848198	1.005380243	1607.02227
0.001837	0.004763	0.385714286	0.57522677	1.011254252	1928.42673
0.002143	0.004763	0.45	0.578126025	1.021156043	2249.83118
0.002449	0.004763	0.514285714	0.580668454	1.036926526	2571.23564
0.002755	0.004763	0.578571429	0.582934469	1.061223255	2892.64009
0.003062	0.004763	0.642857143	0.584979797	1.098164162	3214.04454
0.003368	0.004763	0.707142857	0.586844694	1.154739818	3535.449
0.003674	0.004763	0.771428571	0.588559216	1.244322548	3856.85345
0.0047	0.004763	0.98687664	0.593473314	4.407848454	4934.01297

Qmax(m^3/s)	Density O_2 (kg/m^3)	Density H_20(kg/m^3)	Hmax(m)	Hmax(cm)
0.00025	1.428	1000		
0.00025	1.428	1000	166.9957	16699.57
0.00025	1.428	1000	31.46691	3146.691
0.00025	1.428	1000	9.455922	945.5922
0.00025	1.428	1000	3.643079	364.3079
0.00025	1.428	1000	1.62919	162.919
0.00025	1.428	1000	0.79991	79.99095
0.00025	1.428	1000	0.415727	41.57267
0.00025	1.428	1000	0.222381	22.23805
0.00025	1.428	1000	0.119332	11.93321
0.00025	1.428	1000	0.062413	6.241255
0.00025	1.428	1000	0.030557	3.055666
0.00025	1.428	1000	5.76E-05	0.005758

Constants Used		a	0.49670179
Vin (m/s)	14.03395727	b	0.00873339
		c	-0.00044367

Appendix C: 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 O2, CO2, 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 4inX4inX1in, and the single readout flow meter should be no bigger than 1inX4inX1in.

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't be violated.

Appendix D: References

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