CHARACTERIZING AIR FLOW IN VACUUM EXCAVATORS

BY

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A white paper

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Doug’s website is Leakflow.com

Glen Greager, Senior Mechanical Engineer, McCown Technology Corporation, provided the cognitive horsepower needed to contemplate Reynolds Numbers, and Terminal Fall Velocities of Gravel. When the water got deep, Glen came to the rescue.

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1. ABSTRACT

Vacuum excavators are widely used in the construction industry to provide a nearly harmless method of exposing underground utilities. However with the explosion of shallow trench fiber optic construction, the vacuum excavator has taken on another essential role. That of evacuating the spoils from micro trencher. The ability to remove the spoils is essential to maintaining high productivity and profitability.

Vacuum excavators wear over time and lose suction ability. There exists a need to measure that suction ability so that a user can judge the ability of any particular vacuum excavator to move material.

To date, the authors know of no commercially available test instrument that can measure the evacuating ability of a vacuum excavator. This paper investigates multiple methods of measuring the effectiveness of a vacuum excavator and ultimately identifies a method that is low cost to build and gives reliable measurements.

2. INTRODUCTION

2.1 A vacuum excavator

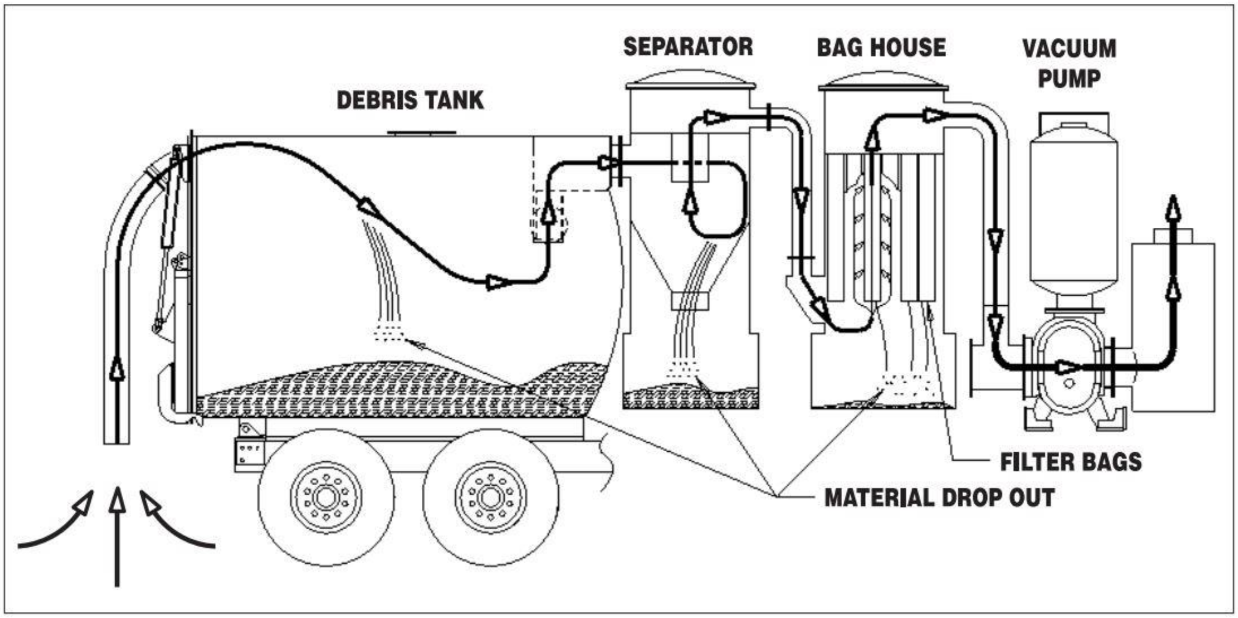
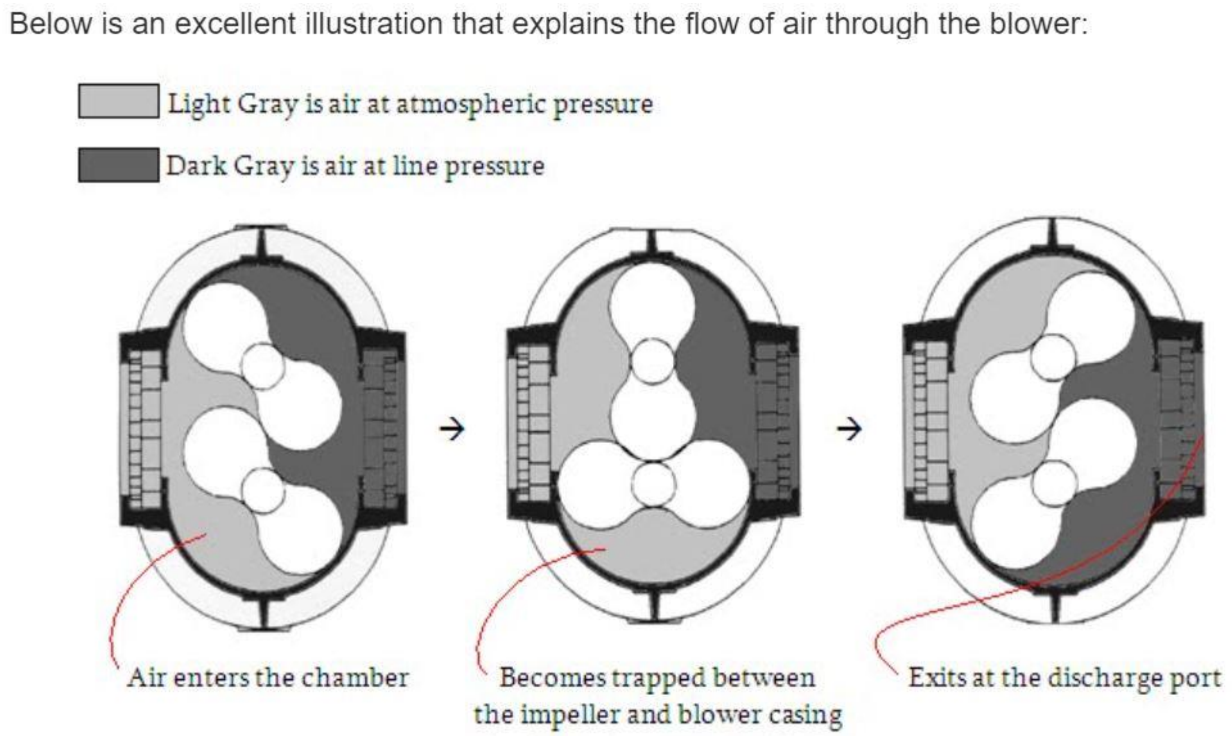


Figure 1 Generic Vacuum Excavator

Vacuum excavators all share the same overall design. There is a vacuum pump, more frequently called a "blower". The blower inlet is connected to various stages of filters and finally to a debris tank. The debris tank is where the material that is being suctioned up is deposited. The effectiveness of the suction is largely dependent on the capacity of the blower and the horsepower of the engine. As blowers wear, they have progressively less and less ability to maintain a pressure differential between the inlet and outlet. Since atmospheric pressure is present at the output, that is generally fixed. So what degrades is the low pressure or partial vacuum pressure developed at the inlet.

2.2 Roots type blower



Below is an excellent illustration that explains the flow of air through the blower:

Figure 2 Roots Blower Drawing

A roots type blower is the most common type of blower found on vacuum excavators. It is simple and requires very little service. It is a positive displacement blower, which means a fixed amount of air is moved with each revolution. However, the absolute number of air molecules moved per revolution is a function of altitude. At higher altitudes the lower density of the air results with less motive force conveyed to the material being conveyed.

The filters preceding the blower in a vacuum excavator are critical in preventing wear to the blower lobes as well as to the overall pressure differential. Worn lobes create a blower that cannot create the difference in pressure needed to present a partial vacuum to the hose conveying the material. Clogged filters have their own pressure drop that is subtracted from the overall pressure differential. A clogged filter can cause a good blower to function like it is mostly worn out.

2.3 A microtrencher

Figure 3 Generic Micro Trenching Machine

Micro trenching is done by a rotary saw blade cutting a slot in the road. A vacuum line carries the spoils away to a vacuum excavator.

3. VACUUM CHARACTERIZATION

How does one measure how "hard a vacuum excavator is sucking"? First, to be technically accurate it is not sucking. You cannot pull air any more than you can push string. The atmosphere is blowing the air up the hose of a vacuum excavator. So the actual push provided by the air is limited by atmospheric pressure. Atmospheric pressure at sea level is around 14.7

PSI. However it is only 12.6 PSI at the altitude of Salt Lake City where our tests were conducted. So already we have lost over 2 pounds of force due to altitude.

The blower of the vacuum excavator mechanically bats air molecules up the discharge tube creating an area with fewer air molecules in the inlet side. This is a partial vacuum. The more rarified this partial vacuum is, the more pressure differential will be. The pressure differential is the force behind the airflow up the vacuum hose. The greater the differential, the greater the force. The greater the force the greater the volume of airflow and speed of the air stream in the tube.

Most vacuum excavators are rated by flow rates such as cubic feet per minute (CFM) however the CFM of the blower is with no plumbing restrictions and at sea level. An airflow in a device with plumbing and filters will never equal a bare blower under ideal lab conditions.

So the problem we tackled was as follows: **<u>How does one accurately measure the CFM of a vacuum excavator?</u>**

That should be simple, put a flow meter on it. Right?
But finding an inexpensive air flow meter capable of reading 0 – 1500 CFM in a 4 inch pipe is not readily available. Mass air flow sensors are used in most automobile engines but the range of CFM they measure is not high enough for our use.

CDI meters of Woburn, MA makes very nice mass air flow sensors. We used one of their products (5200 series) to build a flow meter to characterize the flow of large air compressors.

Their 5400 series will fit pipes up to 8” in diameter and indeed needs an 8” pipe to measure the flows we expect to measure due to an upper limit of air flow velocity. However they depend on a perfectly homogeneous and turbulent flow of air. Complex flow equalizers and straighteners area needed and the pipe needs to be quite long.   Layers/ stratification of the air as well as temperature changes cause the reading to wander. Not exactly a lab standard measurement.

They also they cost several thousand dollars. So we decided to build our own flowmeter. A pitot tube flow meter can be constructed for under $50. Should be simple, right?

3.1 Pitot Tube Flow meter

HVAC systems in large commercial buildings need to have air flows balanced in their larger air ducts. It is common to insert a pitot tube into a duct to measure the air velocity. CFM is derived by taking the cross sectional area of a duct multiplied by the velocity of the air in the duct. Aircraft use a device called a pitot tube to measure airspeed. It is a simple device that samples the pressure of oncoming air (pitot air source) and then compares that pressure against the air pressure in a zone that is shielded from the oncoming air (the static air source).

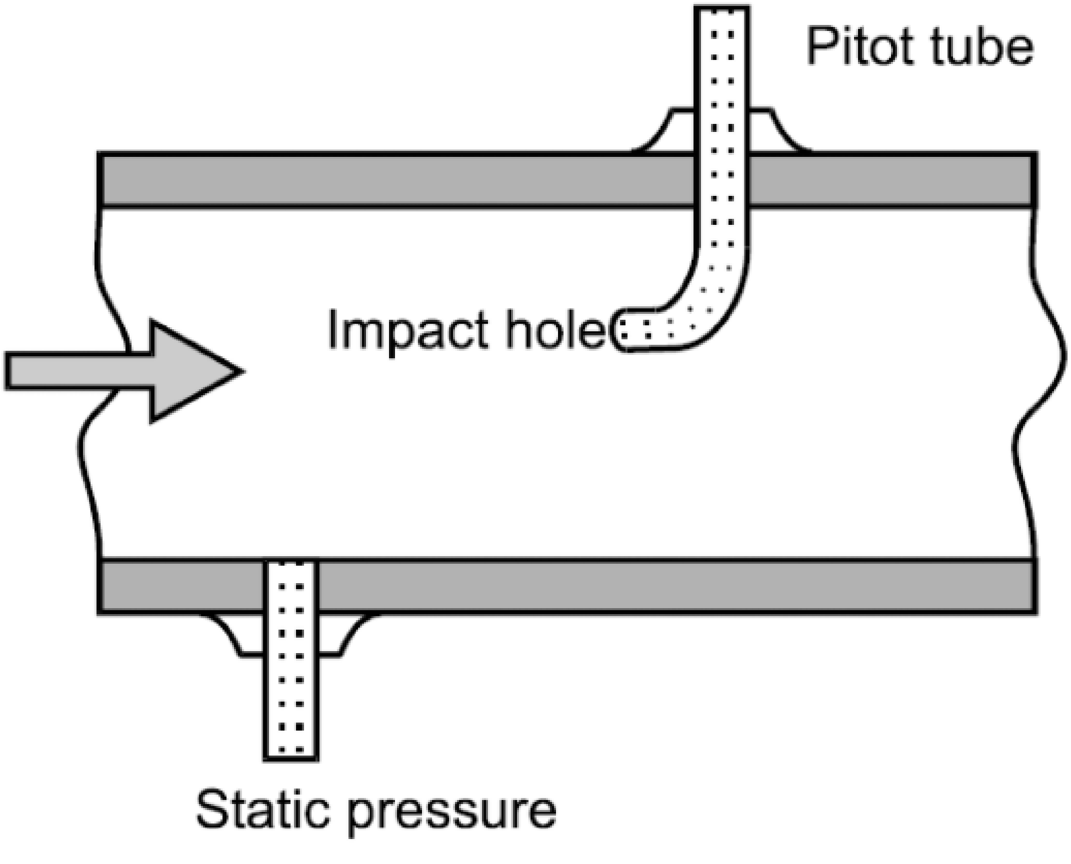


Figure 4 A basic Pitot Tube

Please see Appendix A for details of pitot tubes along with equations and application information.

3.2 Our First Method

These photos shows the first iteration of the flow meter.

Figure 5 Shop built Pitot Tube using 1/8” Copper Tubing

Figure 6 Flow straightener grid in inlet of Pitot Tube Flowmeter

Figure 7 Pitot Tube Flowmeter Assembly installed on a Vac Ex

The initial test of the flowmeter showed a 3.6” W.C. differential pressure WOT (wide open throttle). That would correspond with an altitude and temperature corrected flow of 472 CFM. That is somewhat believable for an older Ditch Witch FX 60 which, according to the spec sheet, should be up around 1000 CFM.

So far, so good.

Then we tested a brand new HX75 which is factory rated at 1315 CFM. It have an altitude corrected differential pressure of 5.5” W.C. at idle and 12” W.C. WOT. Those would correspond to 576 and 851 CFM respectively.

So, we tested a brand new HX50, WOT it came in at 10” and 777 CFM. Factory rating on that unit is 1005 CFM

Unit Under Test	Diff Press In W.C.	Measured CFM	Factory CFM	Altitude Derating
New HX75 Idle	5.5	576.319627		
New HX75 WOT	12	851.280506	1315	1052
New HX50 WOT	10	777.109227	1005	804
Our FX60	3.7	472.697088	1027	821.6

Figure 8 Initial Results

This left us with some doubt as to the absolute accuracy of our flowmeter. It is good for comparison purposes, but how accurate is it.

We purchased a commercial pitot tube. It was a bit larger than the recommended 1/30 duct diameter. But it yielded results about 10% lower than our home made pitot tube. And since the flows were lower we chose to ignore those results versus saying Ditch Witch specs seem to not match observations. So let’s see if we can measure the velocity of the air using a different means.

Figure 9 Commercially Made Pitot Tube

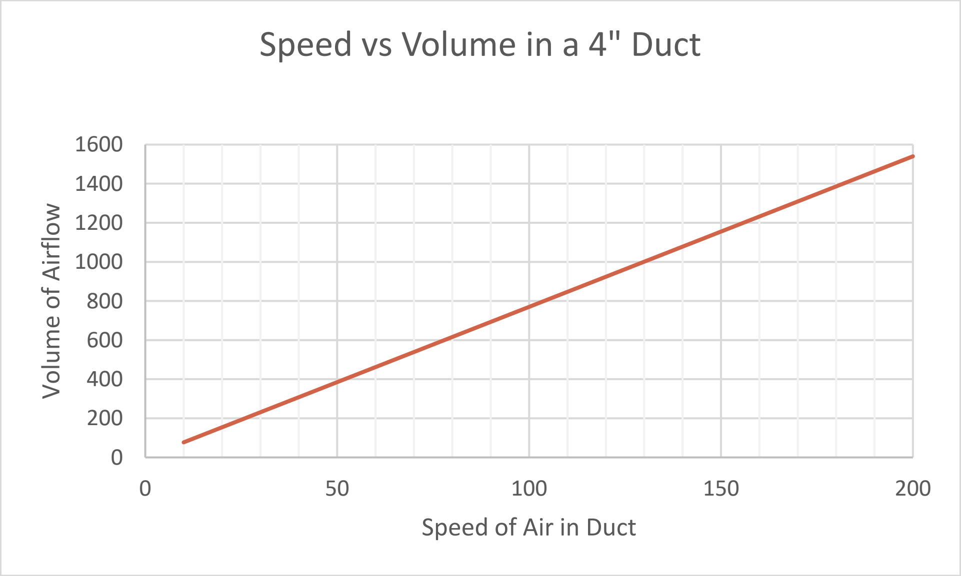


Figure 10 Speed of Air in a 4 Inch Duct

3.3 Our Second Method

These photos show our attempt at using a hot wire anemometer to measure the velocity of the air in the duct.

Figure 11 Hot Wire Anemometer

We discovered that our first anemometer had an upper limit of 60 mph. If you note Fig 7 above, the speeds of airflows in the duct we are measuring could be as high as 200 mph. This dictated upsizing the duct to 6 inches so that we would not exceed the limits of the sensor. Even then we were constrained. But we expected we could measure as high as 1000 CFM with a 6" duct (Fig 8 Below)

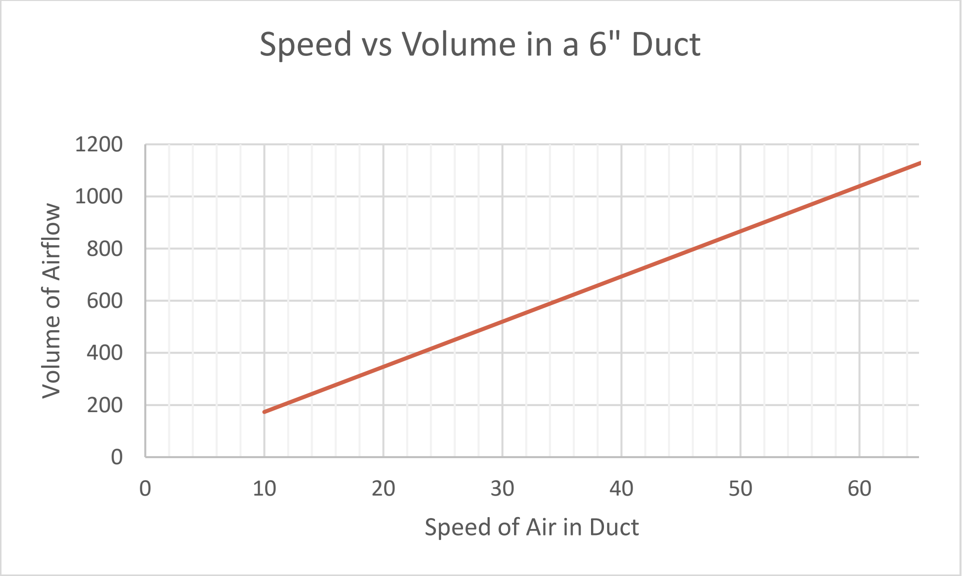


Figure 12 Speed vs Volume in a 6 Inch Duct

This first sensor actually has a nice phone app that allows one to enter duct size and it will give you a CFM reading directly. No need for math.

We quickly discovered proper orientation of the sensor in the air stream is critical. Even then you find different readings at different places in the cross section of the duct.

Figure 13 Crude Method of Checking Accuracy

Driving down the road with the units out the window, we measured the slipstream and found it somewhat accurate at lower speeds like 40 MPH but the higher we went the more sporadic it became. We purchased a second more expensive unit. The second unit needed an entry of the cross sectional area of the duct in square feet, no phone app. But it too gave a direct CFM readout on the instrument itself. It was more stable, but not rock solid like we were hoping. Again, on a calm day, at 30 MPH it would pretty much agree with the speedometer of the car. And it would not measure above 65 mph.

Second Set of Results

Measuring our worn out FX60

Pitot #1	472 CFM
Pitot #1	425 CFM
HWA #1	533 CFM
HWA #2	500 CFM

Small sample. Standard deviation is about 45 so they are clustered pretty good. The mean is 482.5. I think we can say that old unit is pretty worn out.
We need an accurate measurement method able to be stable up to 1500 CFM. In a 4 inch duct, the airspeed at that flow is 191.5 mph. Good work for pitot tubes. Clearly way above the limits of the hot wire anemometers.

We would have to size up the duct even more than the 6 inches we tried. That would require a duct approximately 8 inches in diameter so that the hot wire anemometers could be in their sweet spot. Getting the flow to be uniform across such a large diameter would take a long pipe and lots of internal structures to level out and straighten the flow. This involves things such as Reynolds Number calculations and verges on computational fluid dynamics to solve. These situations can quickly become a multivariate calculus situation. Not really the amount of work we were contemplating at the outset of this experiment. So, hot wire anemometers are out as a trusted lab standard. But they did give us results similar to the original pitot tube, so it was a valuable experiment as a sanity check.

3.4 Our Third method

Figure 14 Radar Speed Gun

So, how can we more accurately measure the speed of the air entering the vacuum excavator? Surely a radar speed gun would do the trick. They are used to show the speed of a pitched ball for baseball games. Our yard borders I-80, so we did a quick check of the traffic on the Eastbound Lanes. It would clock it at about 65 mph. However we were shooting at an angle. There is a cosine correction that must be applied whenever you using radar to measure something that is moving along a path that is not aligned with the boresight of the radar.

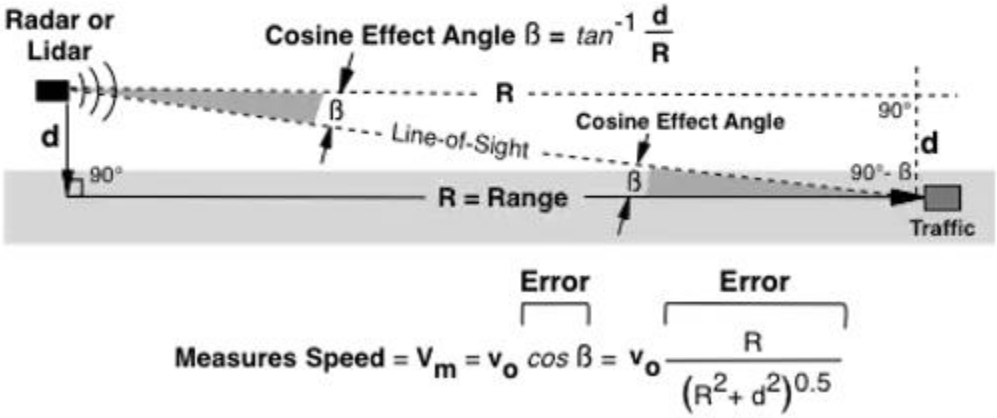


Figure 15 Slant Range Error Correction

We are at approximately 32 degrees to the freeway, which would be a correction of cos (32) or .848. 65 mph/.848 = 76 mph. That checks out to what we know the normal speeds are for that stretch of highway. Perhaps even a bit low. So, we have a standard that seems to be accurate.

Figure 16 A radar reflector

We needed something that would reliably return a reflection off of a presumably 10 GHz speed gun signal. The above photo is a ping pong ball with a strip of aluminum foil tape on it. We also put a small piece of aluminum foil on the inside of a shuttlecock.

Figure 17 The ball launcher

The method of inserting something into the air stream is shown above. 48” of 4” ABS tubing with a Y junction. The radar gun would side straight down the tube and balls and other test objects would be fed into the Y branch. We also tested outside the tube at an oblique angle. The signal seemed to be happy penetrating the tube without difficulty. The radar gun would see some reflections from the turbulent air if it was inserted in the tube without any targets in view.

Results?

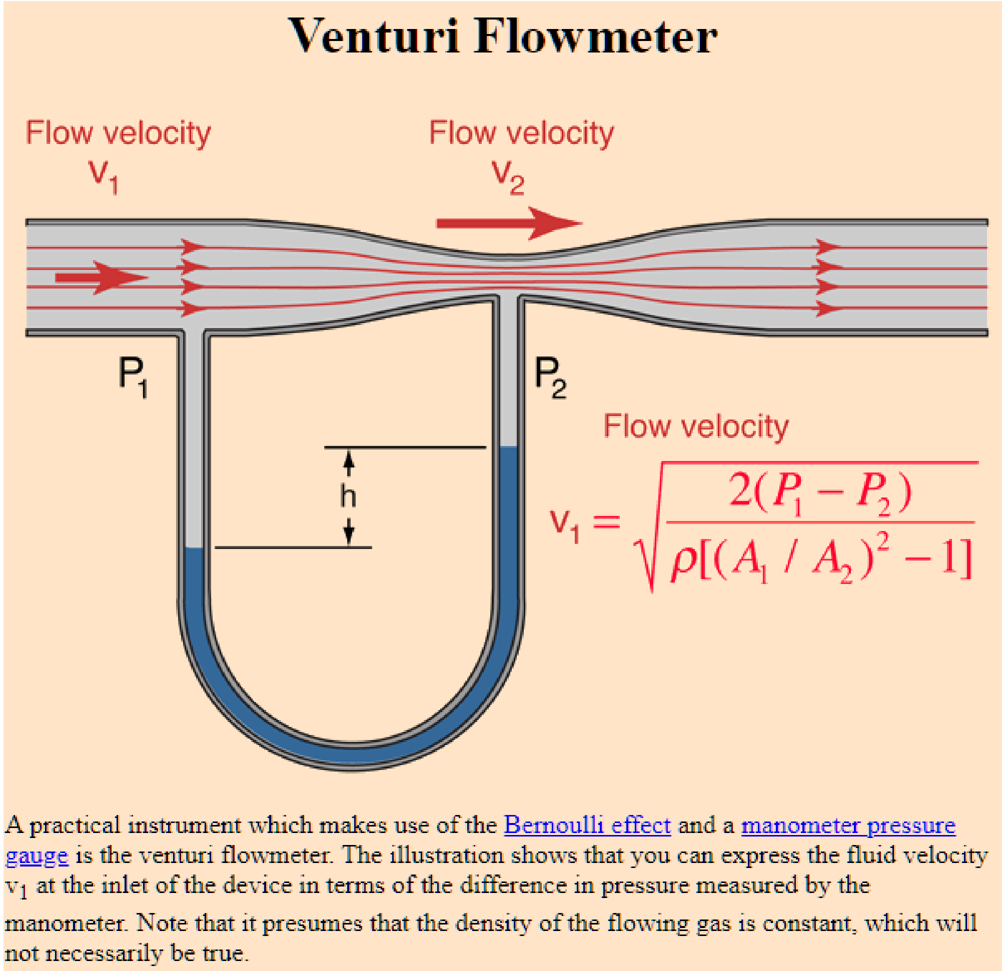
Very poor. The highest velocity recorded was 26 mph which would correspond to only 203 CFM. Obviously all of the other methods were way wrong or it just takes time for a ping pong ball to catch up to the velocity of the air in a duct. Pretty sure the latter is the explanation.

3.5 Fourth method

This was abandoned. It was a clear plastic 4" pipe that was going to be used with high speed photography to measure the velocity of small lightweight objects in the air stream. While waiting for delivery of the pipe, we built the venture flow meter and things suddenly got better.

3.6 Fifth method

There exists another design of flowmeter called a "Venturi Tube Flowmeter"



A practical instrument which makes use of the Bernoulli effect and a manometer pressure gauge is the venturi flowmeter. The illustration shows that you can express the fluid velocity v_1 at the inlet of the device in terms of the difference in pressure measured by the manometer. Note that it presumes that the density of the flowing gas is constant, which will not necessarily be true.

Figure 18 Venturi Tube Flowmeter[1]

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[1] http://hyperphysics.phy-astr.gsu.edu/hbase/Fluids/venturi.html

This designed proved to be easier, quicker and lower cost than any of the pitot tube or hot wire anemometer devices.

Figure 19 Venturi Tube Flowmeter

$$\boxed{Q = CA_2 \sqrt{\frac{2\,(P_1 - P_2)}{\rho\,(1 - \beta^4)}}}$$

Figure 20 Venturi Tube Formula

- Q is the flow rate through the pipe and through the meter (cfs – U.S. or m^3/s – S.I.)
- C is the discharge coefficient, which is dimensionless
- A_2 is the constricted area perpendicular to flow (calculated from the venturi throat diameter) (ft^2 – U.S. or m^2 – S.I.)

- P_1 is the undisturbed upstream pressure in the pipe (lb/ft^2 – U.S. or N/m^2 – S.I.)
- P_2 is the pressure in the pipe at the constricted area, A_o (lb/ft^2 – U.S. or N/m^2 – S.I.)
- $\beta = d/D$ = (diam. at A_2/pipe diam.), which is dimensionless
- ρ is the fluid density (slugs/ft^3 – U.S. or kg/m^3 – S.I.)

This device consisted of a 4” male camlock pressed into a 12” section of 4” ABS pipe. Then a 4” to 3” ABS bell reducer. 12” of 3” ABS pipe. Another bell reducer. Followed by 24” of 4” ABS pipe. The manometer low pressure port was achieved by tapping a ¼” NPT port in the center of the 3” section and another 2” past the bell reducer towards the open end. Brass barbed fittings were threaded into the holes and the manometer tubing pressed onto the barbed brass fittings. Except for the digital manometer, all fittings were found at Home Depot for approximately $50. None of the ABS fittings were glued.

Results: 6” W.C. on one of our FX60s (the one used in previous tests) and 6.5” W.C. on a different FX60 that happened to be in the shop for repair. Unsure as to the condition of the filters.
This corresponds to 478 CFM and 497 CFM respectively when the pressure differentials were entered into an online calculator:
https://www.efunda.com/formulae/fluids/venturi_flowmeter.cfm#calc

However another online calculator allows you to enter the density of the air. At our altitude it is approx. 1.09 kg/m3, but other sources cite it as substantially lower
https://www.ajdesigner.com/venturi/venturiflow.php#ajscroll

After finding more reliable density vs altitude sources, I took the originally Bernoulli’s formula and entered it into a spreadsheet and made a graph for the various altitudes.

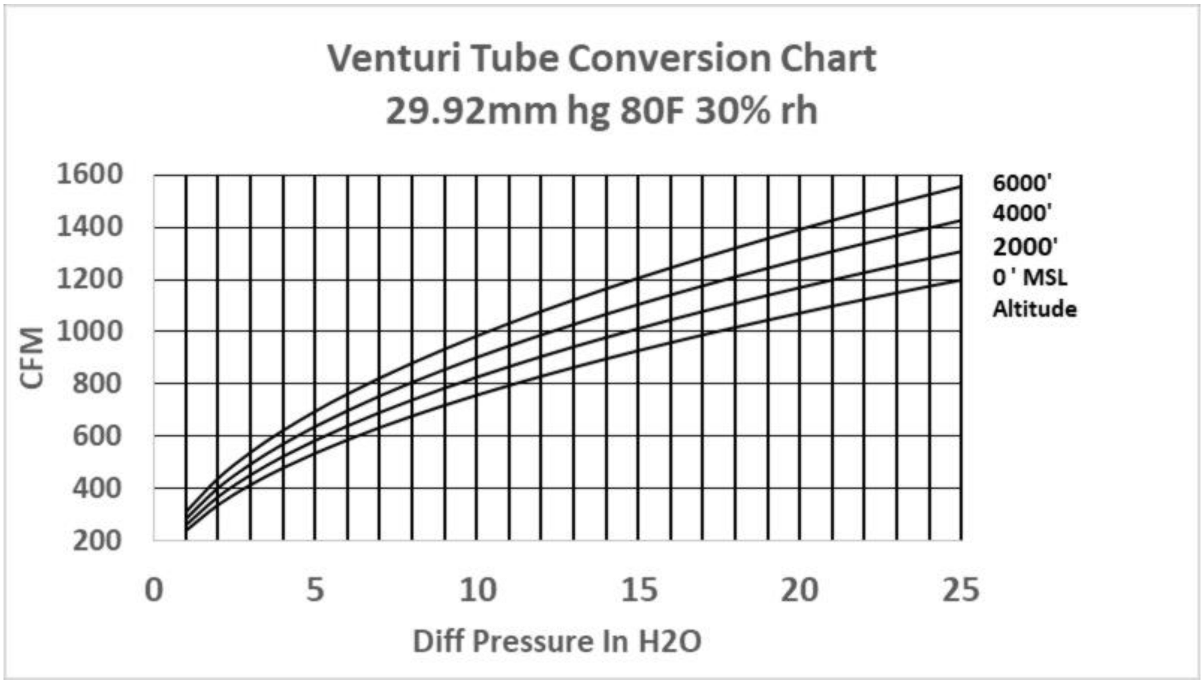

Figure 21 Venturi Tube Conversion Chart

This corresponds with all of our other tests nicely. Rugged, cheap and easy for the DIY crowd. You can replace the digital manometer with 24” section ¼” of transparent tubing. Put tape around it so that it is in a U shape. Add colored water in the tube, just enough to fill it part way and watch the levels of the water in each leg start out level with each other with no air flow. Once you start the machine, the water in tube connected to the 3” section of the venturi will rise, the water in the other side of the U tube will fall. The measured distance between the levels is the pressure difference measured in inches of water column. (W.C).

Here are some other measurements using the approx. altitude of Salt Lake City:

	Delta P (in W.C.)	CFM	Factory Spec
New HX30	2.76	473	512
New HX30	3.15	506	512
Old FX 60	6	698	1027
Older FX60	6.5	698	1027
New HX50	13.2	1036	1005
New HX75	18	1210	1315

Figure 22 Altitude Corrected - Actual Measurements

These figures are much closer to the factory specs for these units.   We presume the manufacturer will agree that we are in the ballpark with our accuracies.   The “new” HX30s tested were not factory fresh. They had been rented out a few times and the condition of the filter was unknown.

Interesting to note, that a brand new HX50**, at idle**, has the same delta P and flow as our old FX60s at wide open throttle. This matches our experience in the field where an HX50 at idle was picking up as many spoils from a micro trencher as our older FX60s wide open. It was initially hard to believe, but gravel in the trench (or not in the trench) is hard to argue with.

At this point we would suggest that you want a delta P of above 10” W.C. as measured with this particular design vortex tube for effective micro trench evacuation.

4.   HOW HARD MUST ONE SUCK?

This answer really depends on what you hope to pick up. Light powders do not take much airflow to move, but to lift a chunk of 3” cobble, and move it up a tube, the terminal velocity of the particle is half the problem. The other half is the velocity of the airflow.

Figure 23 The Enemy

Terminal velocities or more properly the “settling velocity of a solid particle in a liquid” can become quite complex. The simple equation is Gravity Force – Buoyancy Force = Drag Force. We are going to ignore Buoyancy Forces as a stone is much more dense than the air, so the buoyant forces on the stone are very small compared to the drag force that actually pushes the stone up the tube.

One must also consider that the density of air in Salt Lake City is .058 lbs per cubic foot where it is .066 lbs at sea level.

Simply put ” A balance of the gravitational, buoyancy and drag forces on the submerged solid body determines a settling velocity of the body.”[2]

But this water can get deep quickly. Stokes, Budryck and Rittinger equations.

Grace’s method of determining shape factors. Can’t we just find the answer somewhere?

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[2] (http://www.dredgingengineering.com/dredging/media%5CLectureNotes%5CMatousek%5CC._oe4625_IntermezzoI.pdf)

https://www.gigacalculator.com/calculators/terminal-velocity-calculator.php

Using a mass of 250 g, Cross section area of 7 square inches, Drag Coefficient of .294, Air density of 1.225 kg/m3, Gravity of 1 we get a result of 123 mph. I realize I am mixing metric and imperial units, but it was just easier that way.

Referring back to the velocity of air in a 4" duct, you need close to 900 CFM to levitate a chunk of 3" cobble.

The (guesstimate) Answer (at the moment):

900 CFM

At the altitude of Salt Lake City, on an 80 degree F day, 900 CFM is moving 52 pounds of air per minute or .87 pound or 395 grams of air per second. About the same mass as that chunk of 3 inch cobble we are trying to move up the tube. One would imagine the force of the air must exceed the weight of the object being moved. This all seems to fit rather well.

We don't have a good figure for the drag coefficient and the shape of every rock is different, but the answer passes the sanity check. It might be a bit high, but experience shows a new vac ex proves more than capable of the task while worn units give dismal results. Clean filters also make a striking difference.

5. OTHER PERFORMANCE ENHANCERS

Obviously detecting and correcting any leaks in the vac goes a long way to improving performance. We increased our flow by detecting a bad gasket and loose door on a cyclone separator by over 100 CFM. The best way to detect a vacuum leak is a smoker used on bee hives.

We plan another paper on the effect dirty filters have on the system as well as the best methods to wash filters. We have made a filter washing machine and have several methods of testing pressure drop over the filter elements. But there is probably enough meat there to make another paper rather than add on to this one.

Figure 24 Beehive Smoker Leak Detector

6. APPENDIX A

The following is from Dwyer Instruments, manufacturers of pitot tubes and manometers. No copyright was evident. This was used as our guidelines for our first pitot tube measurements.

Air Velocity Measurement

Fig. 1-B 1

Introduction

In air conditioning, heating and ventilating work, it is helpful to understand the techniques used to determine air velocity. In this field, *air velocity* (distance traveled per unit of time) is usually expressed in feet per minute (FPM). By multiplying air velocity by the cross section area of a duct, you can determine the air volume flowing past a point in the duct per unit of time. *Volume flow* is usually measured in cubic feet per minute (CFM).
Velocity or volume measurements can often be used with engineering handbook or design information to reveal proper or improper performance of an airflow system. The same principles used to determine velocity are also valuable in working with pneumatic conveying, flue gas flow and process gas systems. However, in these fields the common units of velocity and volume are sometimes different from those used in air conditioning work.

To move air, fans or blowers are usually used. They work by imparting motion and pressure to the air with either a screw propeller or paddle wheel action. When force or pressure from the fan blades causes the air to move, the moving air acquires a force or pressure component in its direction or motion due to its weight and inertia. Because of this, a flag or streamer will stand out in the air stream. This force is called *velocity pressure*. It is measured in inches of water column (w.c.) or water gage (w.g.). In operating duct systems, a second pressure is always present. It s independent of air velocity or movement. Known as *static pressure*, it act equally in all directions. In air conditioning work, this pressure is also measured in inches w.c.

In pressure or supply systems, static pressure will be positive on the discharge side of the fan. In exhaust systems, a negative static pressure will exit on the inlet side of the fan. When a fan is installed midway between the inlet and discharge of a duct system, it is normal to have a negative static pressure at the fan inlet and positive static pressure at its discharge.

Total pressure is the combination of static and velocity pressures, and is expressed in the same units. It is an important and useful concept to us because it is easy to determine and, although velocity pressure is not easy to measure directly, it can be determined easily by subtracting static pressure from total pressure. This subtraction need not be done mathematically. It can be done automatically with the instrument hook-up.

Sensing Static Pressure

For most industrial and scientific applications, the only air measurements needed are those of static pressure, total pressure and temperature. With these, air velocity and volume can be quickly calculated.

To sense static pressure, five types of devices are commonly used. These are connected with tubing to a pressure indicating instrument. Fig. 1-A shows a simple thru-wall static pressure tap. This is a sharp, burr free opening through a duct wall provided with a tubing connection of some sort on the outside. The axis of the tap or opening must be perpendicular to the direction of flow. This type of tap or sensor is used where air flow is relatively slow, smooth and without turbulence. If turbulence exists, impingement, aspiration or unequaled distribution of moving air at the opening can reduce the accuracy of readings significantly.

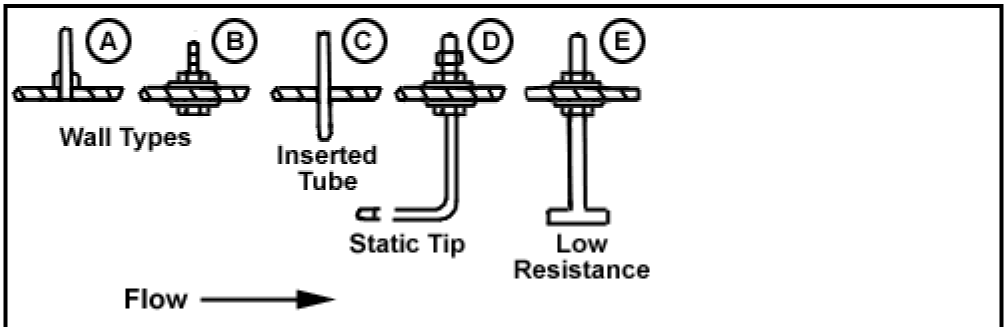


Fig. 1 - Types of Static Pressure Sensing Devices

Fig. 1-B shows the Dwyer No. A-308 Static Pressure Fitting. Designed for simplified installation, it is easy to install, inexpensive, and provides accurate static pressure sensing in smooth air at velocities up to 1500 FPM.

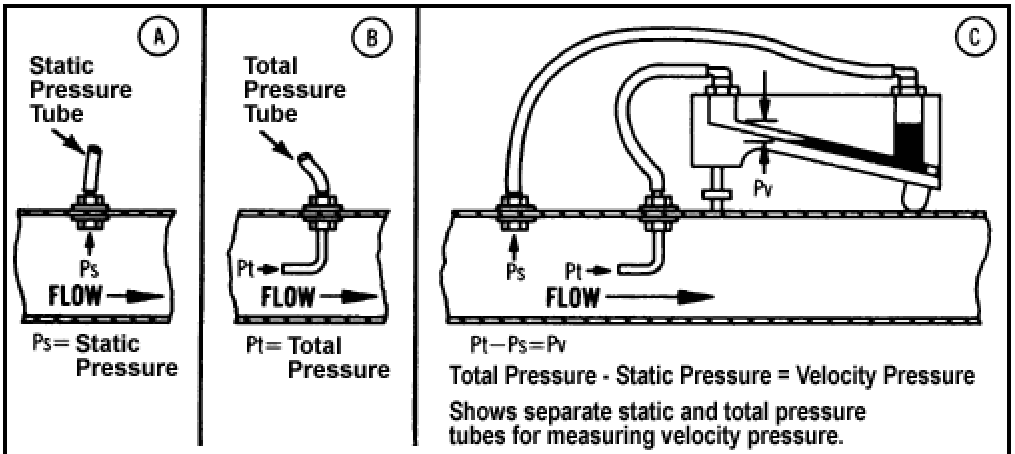
Fig. 1-C shows a simple tube through the wall. Limitations of this type are similar to wall type 1-A.

Fig. 1-D shows a static pressure tip which is ideal for applications such as sensing the static pressure drip across industrial air filters and refrigerant coils. Here the probability of air turbulence requires that the pressure sensing openings be located away from the duct walls to minimize impingement and aspiration and thus insure accurate readings. For a permanent installation of this type, the Dwyer No. A-301 or A-302 Static Pressure Tip is used. It senses static pressure through radially-drilled holes near the tip and can be used in air flow velocities up to 12,000 FPM.

Fig. 1-E shows a Dwyer No. A-305 low resistance Static Pressure Tip. It is designed for use in dust-laden air and for rapid response applications. It is recommended where a very low actuation pressure is required for a pressure switch or indicating gage - or where response time is critical.

Measuring Total Pressure and Velocity Pressure

In sensing static pressure we make every effort to eliminate the effect of air movement. To determine velocity pressure, it is necessary to determine these effects fully and accurately. This is usually done with an impact tube which faces directly into the air stream. This type of sensor is frequently called a "total pressure pick-up" since it receives the effects of both static pressure and velocity pressure.



Total Pressure - Static Pressure = Velocity Pressure

Shows separate static and total pressure tubes for measuring velocity pressure.

Fig. 2 -- Types of Pressure Measurements

In Fig. 2, note that separate static connections (A) and total pressure connections (B) can be connected simultaneously across a manometer (C). Since the static pressure is applied to both sides of the manometer, its effect is canceled out and the manometer indicates only the velocity pressure.

To translate velocity pressure into actual velocity requires either mathematical calculation, reference to charts or curves, or prior calibration of the manometer to directly show velocity. In practice this type of measurement is usually made with a Pitot tube which incorporates both static and total pressure sensors in a single unit.

Essentially, a Pitot tube consists of an impact tube (which receives total pressure input) fastened concentrically inside a second tube of slightly larger diameter which receives static pressure input from radial sensing holes around the tip. The air space between inner and outer tubes permits transfer of pressure from the sensing holes to the static pressure connection at the opposite end of the Pitot tube and then, through connecting tubing, to the low or negative pressure side of a manometer. When the total pressure tube is connected to the high pressure side of the manometer, velocity pressure is indicated directly. See Fig. 3.

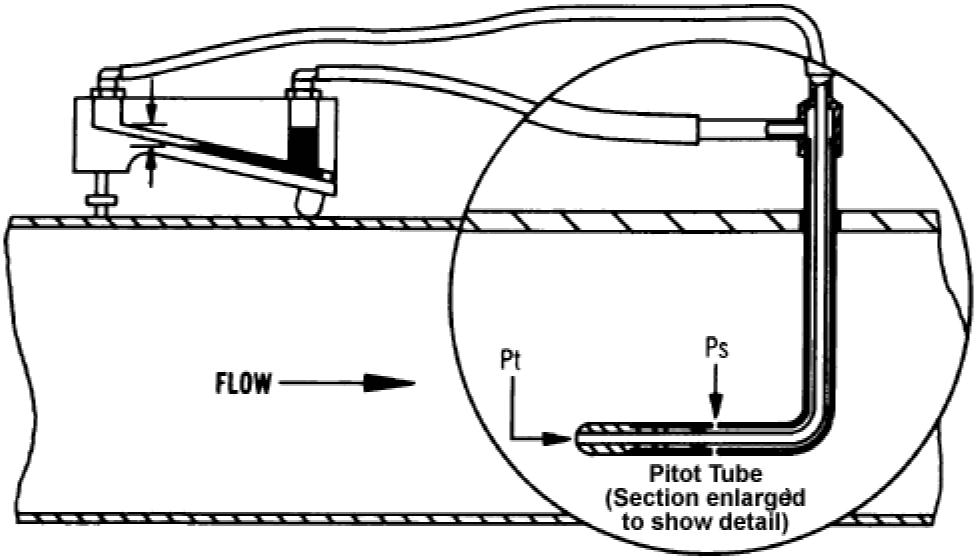


Fig.3 – Pitot Tube senses total and static pressure.
Manometer measures velocity pressure –
(Difference between total and static pressures).

Since the Pitot tube is a primary standard device used to calibrate all other air velocity measuring devices, it is important that great care be taken in its design and fabrication. In modern Pitot tubes, proper nose or tip design - along with sufficient distance between nose, static pressure taps and stem - will minimize turbulence and interference. This allows use without correction or calibration factors. All Dwyer Pitot tubes are built to AMCA and ASHRAE standards and have unity calibration factors to assure accuracy.

To insure accurate velocity pressure readings, the Pitot tube tip must be pointed directly into (parallel with) the air stream. As the Pitot tube tip is parallel with the static pressure outlet tube, the latter can be used as a pointer to align the tip properly. When the Pitot tube is correctly aligned, the pressure indication will be maximum.

Because accurate readings cannot be taken in a turbulent air stream, the Pitot tube should be inserted at least 8-1/2 duct diameters downstream from elbows, bends or other obstructions which cause turbulence. To insure the most precise measurements, straightening vanes should be located 5 duct diameters upstream from the Pitot tube.

How to Take Traverse Readings

In practical situations, the velocity of the air stream is not uniform across the cross section of a duct. Friction slows the air moving close to the walls, so the velocity is greater in the center of the duct.

To obtain the average total velocity in ducts of 4" diameter or larger, a series of velocity pressure readings must be taken at points of equal area. A formal pattern of sensing points across the duct cross section is recommended. These are known as traverse readings. Fig. 4 shows recommended Pitot tube locations for traversing round and rectangular ducts.

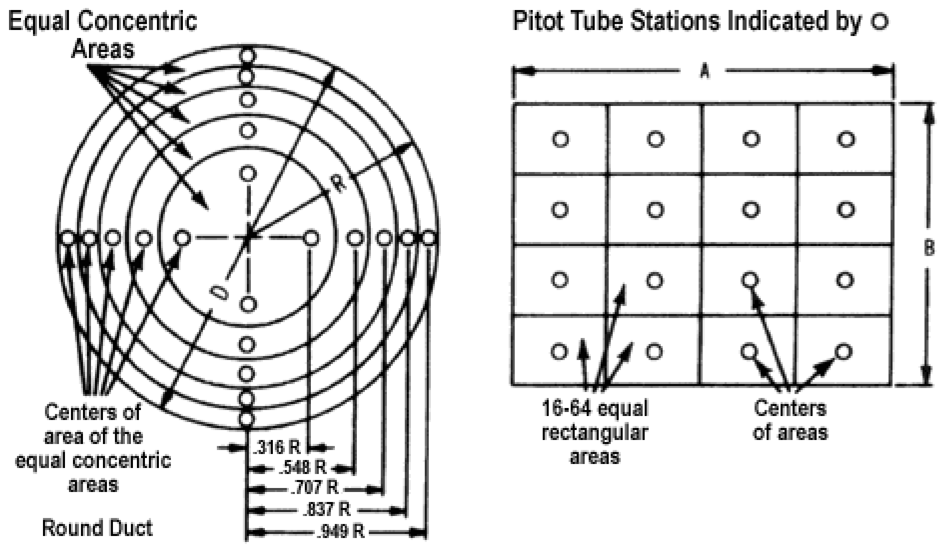


Fig. 4 – Traverse on round and square duct areas

In round ducts, velocity pressure readings should be taken at centers of equal concentric areas. At least 20 readings should be taken along two diameters. In rectangular ducts, a minimum of 16 and a maximum of 64 readings are taken at centers of equal rectangular areas. Actual velocities for each area are calculated from individual velocity pressure readings. This allow the readings and velocities to be inspected for errors or inconsistencies. The velocities are then averaged.

By taking Pitot tube readings with extreme care, air velocity can be determined within an accuracy of ±2%. For maximum accuracy, the following precautions should be observed:

1. Duct diameter should be at least 30 times the diameter of the Pitot tube.
2. Located the Pitot tube section providing 8-1/2 or more duct diameters upstream and 1-1/2 or more diameters down stream of Pitot tube free of elbows, size changes or obstructions.
3. Provide an egg-crate type of flow straightener 5 duct diameters upstream of Pitot tube.
4. Make a complete, accurate traverse.

In small ducts or where traverse operations are otherwise impossible, an accuracy of ±5% can frequently be achieved by placing Pitot tube in center of duct. Determine velocity from the reading, then multiply by 0.9 for an approximate average.

Calculating Air Velocity from Velocity Pressure

Manometers for use with a Pitot tube are offered in a choice of two scale types. Some are made specifically for air velocity measurement and are calibrated directly in feet per minute. They are correct for standard air conditions, i.e., air density of .075 lbs. per cubic foot which corresponds to dry air at 70°F, barometric pressure of 29.92 inches Hg. To correct the velocity reading for other than standard air conditions, the actual air density must be known. It may be calculated if relative humidity, temperature and barometric pressure are known.

Most manometer scales are calibrated in inches of water. Using readings from such an instrument, the air velocity may be calculated using the basic formula:

$$V=1096.7\sqrt{\frac{h_V}{d}}\;\begin{cases}=4004.4\sqrt{h_V}\ \text{for .075 lb/ft}^3\ \text{dry air}\\ @70^\circ\text{F, 29.92 in. Hg Baro.}\end{cases}$$

Where: V = Velocity in *feet per minute.*
h_V = Velocity pressure in *inches of water.*
d = Density of air in *pounds per cubic foot.*

To determine dry air density, use the formula:

$$d=1.325\,\frac{P_B}{T}$$

Where: d = Density of air in *pounds per cubic foot.*
P_B = {Barometric (or absolute) static pressure in *inches of mercury.*}
T = Absolute temperature (indicated temperature in °F plus 460°).

With dry air at 29.9 inches mercury, air velocity can be read directly from the **Air Velocity Flow Charts**. For partially or fully saturated air a further correction is required. To save time when converting velocity pressure into air velocity, the Dwyer Air Velocity Calculator may be used. A simple slide rule, it provides for all the factors needed to calculate air velocity quickly and accurately. It is included as an accessory with each Dwyer Pitot tube.

To use the Dwyer Calculator:

1. Set relative humidity on scale provided. On scale opposite known dry bulb temperature, read correction factor.
2. Set temperature under barometric pressure scale. Read density of air over correction factor established in #1.
3. On the other side of calculator, set air density reading just obtained on the scale provided.
4. Under Pitot tube reading (velocity pressure, inches of water) read air velocity, feet per minute.

Determining Volume Flow

Once the average air velocity is know, the air flow rate in cubic feet per minute is easily computed using the formula:

$Q = AV$
Where: Q = Quantity of flow in *cubic feet per minute*.

A = Cross sectional area of duct in *square feet*.
V = Average velocity in *feet per minute*.

Determining Air Volume by Calibrated Resistance

Manufacturers of air filters, cooling and condenser coils and similar equipment often publish data from which approximate air flow can be determined. It is characteristic of such equipment to cause a pressure drop which varies proportionately to the square of the flow rate. Fig. 5 shows a typical filter and a curve for air flow versus resistance. Since it is plotted on logarithmic paper, it appears as a straight line. On this curve, a clean filter which causes a pressure drop of .50" w.c. would indicate a flow of 2,000 CFM.

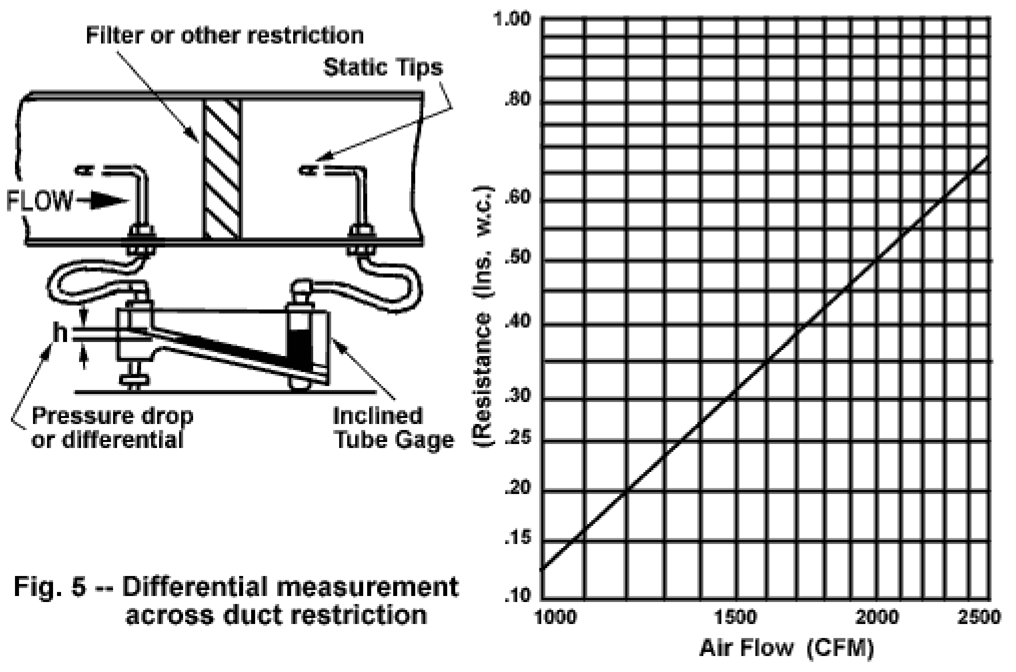


Fig. 5 -- Differential measurement across duct restriction

For example, assuming manufacturer's specification for a filter, coil, etc.:

Given Flow Q (ft^3/min.) = at differential "h" (inches w.c.)

To determine flow at other differentials, the formula is:

$$Q_n \text{ (other flows)} = Q\sqrt{\frac{h_n}{h}}$$

Where:

Q = Quantity of flow in *cubic feet per minute*
h = differential in *inches water column*
h_n = differential (other flow conditions)