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Air velocity and flow measurement using a Pitot tube

Rex Klopfenstein Jr. *

King Industries Inc., 500 Lehman Avenue, Bowling Green, OH 43402, USA

Abstract

The accurate measurement of both air velocity and volumetric airflow can be accomplished using a Pitot tube, a differential pressure transducer, and a computer system which includes the necessary hardware and software to convert the raw transducer signals into the proper engineering units. The incorporation of sensors to measure the air temperature, barometric pressure, and relative humidity can further increase the accuracy of the velocity and flow measurements. The Pitot tube measures air velocity directly by means of a pressure transducer which generates an electrical signal which is proportional to the difference between the pressure generated by the total pressure and the still air (static pressure). The volumetric flow is then calculated by measuring the average velocity of an air stream passing through a passage of a known diameter. When measuring volumetric flow, the 'passage of a known diameter' must be designed to reduce air turbulence as the air mass flows over the Pitot tube. Also, the placement of the pitot tube in the passage will influence how accurately the measured flow tracks the actual flow through the passage. Calibrating the measurement system in a wind tunnel can further increase the accuracy of the velocity and the flow measurements. This objective of this paper is to provide the field engineer with single, concise source of information on flow measurement using a Pitot tube.

Keywords: Air flow measurement; Pitot tube

1. Introduction

A number of techniques are used to measure the velocity and flow rate of an air mass. These measurement techniques include plate orifices, nozzles, venturi tubes, Pitot tubes, vane anemometers, rate-of-cooling anemometer, etc.

This paper is designed to condense the information found in a number of references into a single document that will discuss the use of a Pitot tube to measure the velocity of an air stream.

The Pitot tube, along with a differential pressure measuring device, generates a signal which represents the difference between the total or Pitot pressure (caused by the moving air stream plus the static air column) and the static pressure (pressure acting at all points in stationary air). The resultant pressure magnitude (total pressure−static pressure = velocity pressure) represents the true pressure caused by the movement of the air mass. If the pitot tube is properly designed and the density of the air passing over the Pitot tube is known, the velocity of the air over the Pitot tube can be calculated using a standard formula [Eq. (1)] [1].

Volumetric airflow is determined by measuring the air velocity of an air mass as it moves through a passage of a known diameter. If the pitot tube is properly placed so that it measures the average air velocity of the air column through the 'known

* Tel.: +1-419-353-5311; fax: +1-419-352-1583; e-mail: rklopfen@wcnet.org

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passage', a standard formula can be used to calculate the flow [Eq. (7)] [1].

2. Pitot tube basics

The use of a Pitot tube permits the simultaneous measurement of pressures caused by the moving air molecules striking the tip of the Pitot tube and the static pressure of the stationary air mass. The difference between these pressure magnitudes represents the corrected magnitude of pressure caused by the movement of the air mass alone.

The basic Pitot tube is an L-shaped tube with two pressure ports located at the top of the tube assembly (Fig. 1). The bottom portion of the Pitot tube is where the sensing tip is located. The sensing tip is pointed into the moving air mass. The Pitot tube is usually constructed so that the static or reference pressure port can be used to aim the Pitot sensing tip [1,2].

The Pitot tube is constructed from co-axial tubing. The inner tube conducts the total pressure from the sensing tip to the total or Pitot pressure port whereas the outer tube provides a path from the static pressure tap to the static or reference pressure port.

Fig. 2 illustrates three common Pitot tube sensing tip designs [1,2]. These tip designs reflect various

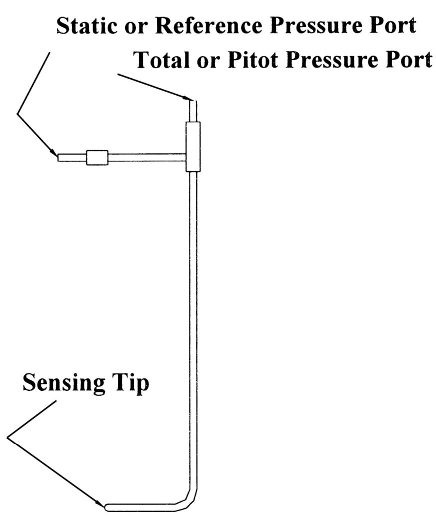

Fig. 1. Basic Pitot tube construction.

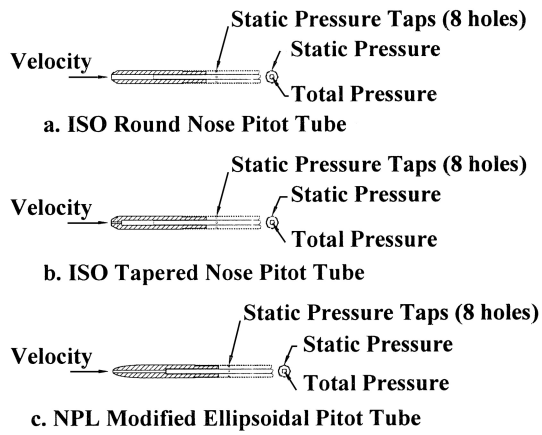

Fig. 2. Pitot tube sensing tip details.

attempts to correct errors in static pressure readings caused by pressure distributions along the Pitot tube as the air moves over the tube. The shape of the tip and the location of the static sense holes are designed so that the air stream moving over the tube has a minimal influence on the static pressure readings. Each of the tip designs shown in Fig. 2 have dimensional parameters based on the outside diameter of the Pitot tube. Refs. [1,2] contain a detailed description of these dimensional relationships.

The choice of tip design is based on a cost verse performance consideration. The ISO tapered nose design shown in Fig. 2b is the cheapest to manufacture but starts to lose some of its accuracy as the air velocity starts to increase. The ISO round nose design (Fig. 2a) maintains its accuracy at higher air velocities. The round nose design is less liable to physical damage than the tapered nose. The National Physics Laboratory (NPL) modified ellipsoidal nose design (Fig. 2c) provides the most accurate measurements at higher air velocities. This design does however increase the manufacturing costs of the Pitot tube.

3. Point velocity equations

The general relationship between the velocity of the air stream and the pressure caused by the air moving over the Pitot tube (total pressure minus static pressure) is given in Eq. (1).

$$V = 44.72136 \cdot K_{\mathrm{pitot}} \cdot \Gamma_{\mathrm{pitot}} \cdot \sqrt{\frac{h_{\mathrm{kPa}}}{d}} \tag{1}$$

where

- V air velocity (m/s)
- K_{pitot} Pitot tube constant
- Γ_{pitot} gas compression constant
- h_{kPa} [total pressure−static pressure] (kPa)
- d air density (kg/m^3)

If a standard Pitot tube (Fig. 2) is used, the Pitot tube constant (K_{pitot}) is 1. Also, if the velocity of the air stream over the Pitot tube is limited to subsonic velocities, the gas compression constant (Γ_{pitot}) is also 1. If these criteria are adhered to, the point velocity equation can be simplified [Eq. (2)].

$$V = 44.72136 \cdot \sqrt{\frac{h_{\mathrm{kPa}}}{d}} \tag{2}$$

The density of the air stream moving over the Pitot tube influences the velocity calculations. Two added parameters must be measured to calculated air density: barometric pressure and air temperature [1,3]. The air density is calculated as follows:

$$d = 3.4834 \cdot \frac{G}{Z} \cdot \frac{P_B}{T_K} \tag{3}$$

where

- d air density (kg/m^3)
- P_B barometric pressure (kPa)
- T_K absolute temperature (Kelvin)
- G ideal specific gravity [molecular wt of gas (kg/(kg·mol))/molecular wt of air (kg/(kg·mol))]
- Z compressibility factor of gas

The equation can be simplified when measuring the velocity of air. The compressibility factor and the ideal specific gravity are either equal to 1 or very close to 1 [1]. The simplified equation is:

$$d = 3.4834 \cdot \frac{P_B}{T_K} \tag{4}$$

Compensating the air density calculation for water vapor content further enhances the accuracy of the velocity calculation [3]. The measurement error introduced by omitting the water vapor compensation may be less than the uncertainty of measurement found in most commercial Pitot tubes.

This correction factor [Eq. (5)] requires a means of measuring the relative humidity of the air mass.

$$CF_d = 1 - \left[\frac{0.3783 \cdot \frac{RH}{100} \cdot P_S}{P_B}\right] \tag{5}$$

$$d_{\mathrm{COR}} = d \cdot CF_d \tag{6}$$

$$P_S = 1.7526 \times 10^8 \cdot \mathrm{e}^{(-5315.56/T_K)} \tag{7}$$

where

- CF_d density correction factor
- RH relative humidity (%)
- P_S partial pressure of water vapor at T_K (kPa)
- d_{COR} corrected air density (kg/m^3)

The corrected air density magnitude (d_{COR}) is used in the velocity equation [Eqs. (1) and (2)] to calculate velocity.

4. Pressure sensing device

To measure the pressure generated by the air mass moving over the Pitot tube, some sort of pressure measurement device is required. Traditionally manometers have been used to measure the differential pressure between the total pressure and the static pressure sensing ports. At the relative low pressures encountered when measuring air flows with a Pitot tube (in the vicinity of 0.5 kPa), the manometers were usually filled with water. Also, the liquid columns are tilted at an angle to increase instrument sensitivity.

The techniques described in this paper are designed to be used on a computerized data acquisition system. To incorporate a Pitot tube velocity/flow device into the computerized data acquisition system requires a pressure sensor which can be interfaced to the computer. Several companies manufacture differential pressure sensors that exceed the performances of tube-type manometers at low pressure readings. These devices also have the advantage in that the optical reading errors are eliminated and it is not necessary to apply manometer correction factors to pressure readings. These sensors provide an electrical signal that is proportional to sensed pressure. The output of these pressure sensors is usually 0–5 volts D.C., 0–10 volts D.C., or 4–20 mA D.C. The 4–20 mA mode is selected when the sensor is located some distance (more than 4-6 m) from the signal conditioning equipment. Any of these types of transducer signals can be connected to most data acquisition systems. The 4–20 mA D.C. mode might require some auxiliary equipment to convert signals into a form compatible with the data acquisition system hardware. It will also be necessary to incorporate sensors to monitor air temperature, barometric pressure, and relative humidity into the computerized data acquisition system.

5. Air flow measurement

The volumetric airflow of an air mass can be determined by measuring the velocity of that air mass as it flows through a passage of a known diameter. When a Pitot tube is used to measure the air stream velocity, the air passage must be designed to reduce the air turbulence of the air stream as it passed through the passage or air horn.

The first parameter that must be specified during the air horn design process is the operating range (minimum and maximum) of the volumetric airflow measurement. The next parameter to be specified is the minimum air mass velocity flowing through the air horn. The minimum velocity should be high enough to provide a reliable reading from the pressure-sensing device at the minimum flow rate and low enough to maintain velocities in the subsonic range at the highest volumetric airflow rate.

Using the volumetric air flow equation and the minimum air mass velocity through the horn, the inside diameter of the air horn can be calculated [Eq. (8)].

$$Q = V_A \cdot A \tag{8}$$

where

Q	volumetric air flow (m^3/s)
V_A	average air stream velocity (m/h)
A	area of air horn passage (m^2)

Once the inside diameter is determined, the velocity produced at the maximum volumetric flow must be calculated. Using the inside horn diameter and the maximum airflow rate, the air mass velocity can be calculated. It should be verified that this velocity stays well below the speed of sound so that the gas compression constant of the Pitot tube remains very close to 1. Also, a calculation should be made to verify that the velocity pressure generated by the Pitot tube at the maximum flow rate does not exceed the maximum pressure rating of the pressure sensing device.

The accuracy of the Pitot tube velocity measurements is influenced by the maintenance of a laminar air flow over the Pitot tube sensing tip. Fig. 3 illustrates a ‘standard’ air horn inlet design that helps maintain laminar airflow as it enters the air horn [2]. All dimensions are based on the inside diameter of the air passage through air horn. It is

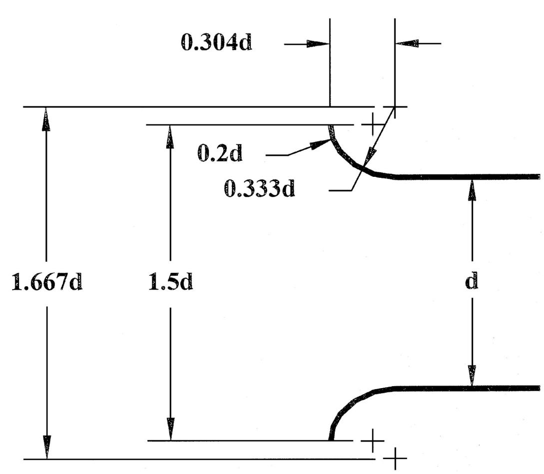

Fig. 3. Air horn inlet configuration.

also recommended that the sensing tip of the Pitot tube be located at least one diameter (d) from each end of the air horn.

6. Pitot tube placement

When measuring the velocity of an air stream, the Pitot tube is placed into the air stream so that the sensing tip points directly into the moving air stream. To obtain the most accurate readings, the sensing tip of the Pitot tube must be parallel to the direction of flow of the moving air stream.

When the Pitot tube is used in conjunction with a passage of a know diameter to measure volumetric flow, the radial placement of the Pitot tube influences the accuracy of the flow calculations. As the air mass flows through a closed pipe (air horn), friction is generated where the air mass contacts the pipe wall. This frictional drag reduces the velocity of the air stream near the pipe wall. The velocity of the air stream increases as the centerline of the air horn is approached (Fig. 4). The profile shown in Fig. 4 will be maintained as long as the flow of the air stream remains laminar; that is, the velocity remains below the magnitude where turbulence is generated at the air–wall interface.

Since the volumetric flow calculations [Eq. (8)] are based on the average airflow velocities, the ideal radial placement of the Pitot tube is at the average velocity point in the velocity profile (Fig. 4). With the Pitot tube located at the average velocity point in the air stream, the calculated air flow magnitude [Eqs. (2) and (8)] will approximate the actual volume of air flowing through the air horn.

7. Calibration techniques

If the airflow rates measured by the air horn/ Pitot tube unit must be traceable to NIST standards, the air flow unit (air horn and Pitot tube) can be calibrated using a wind tunnel whose instrumentation is calibrated and traceable to the NIST. The horn/Pitot tube unit is mounted onto the wind tunnel so that all air flowing through the wind tunnel flows through the unit being calibrated. The wind tunnel calibration procedure produces a calibration curve that plots the pressure drop across the total and static ports of the Pitot tube against the flow rate which generated that pressure drop. The calibration curve should be generated with a minimum of 10 points. The more calibration points, the closer the calibration curve fits the actual flow response curve. The calibration curve should also include the barometric pressure, temperature, and relative humidity of the air mass used to calibrate the air horn unit.

8. Software implementation

If the air horn/Pitot tube assembly is not calibrated and the sensing tip of the Pitot tube is located at the average velocity point in the air horn, the computer system reads the various physical parameters and then calculates the air flow through the air horn using Eqs. (2)–(8). It will be necessary for the computer system to monitor the parameters representing the air temperature, relative humidity, barometric pressure, and the pressure drop across the total and static ports of the

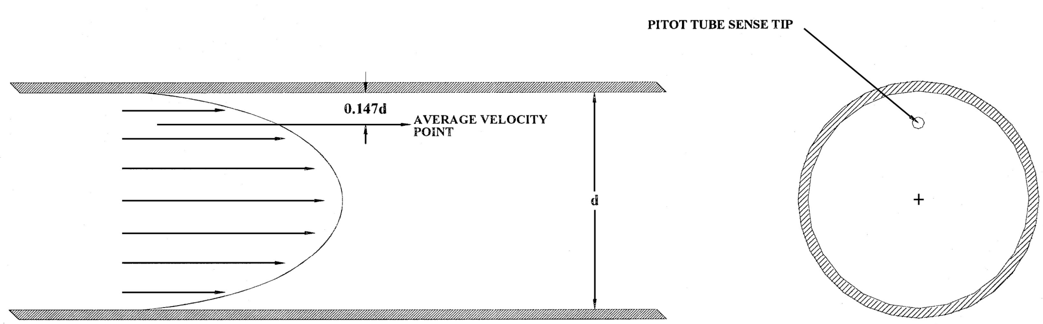

Fig. 4. Airflow through pipe.

Pitot tube. The cross-sectional area of the air horn is entered as a constant.

The incorporation of calibration information into the flow rate calculations is not straightforward. The calibration factors can not be applied directly to the airflow calculation because of the non-linear relationship between the velocity pressure and the air flow rate.

One technique that will overcome this non-linear relationship problem uses a look-up table which contains correction factors that compensate for deviations from the ideal air horn construction and Pitot tube placement within the air horn. A horn factor is generated for each velocity pressure (flow rate) point recorded during calibration. The linearization software reads the velocity pressure from the air horn and uses that value as an index into the horn factor lookup table to retrieve the proper horn factor. The linearization software has provisions to interpolate (straight line) between discrete velocity pressure calibration points.

Tables 1 and 2 illustrates the technique used to generate the air horn correction factors. The upper portion of the table contains data which describes the environment in which the air horn was calibrated (atmospheric pressure, air temperature, and relative humidity

The next grouping of data contains air density corrections for air velocity calculations. These values are calculated using Eqs. (3)–(7). The final data items describe the cross-sectional area of the air horn.

The airflow data provided by the calibration laboratory is listed in the first two columns. Each calibration point represents the velocity pressure generated by the calibrated wind tunnel flow rate. The third column contains the calculated air velocity using the velocity pressure from column 2 and calibration site environmental information from upper portion of table. The fourth column contains the calculated flow rate using column 3 air velocities and the cross-sectional area of the air horn. Finally, an air horn correction factor is generated for each test point by dividing the calibrated flow rate in column 1 by the calculated flow rate in column 4. The air horn correction factor is used during flow rate calculations to compensate for deviations from the standard air horn/Pitot tube construction. The airflow factor is multiplied by the calculated airflow to generate compensated airflow.

Table 1
41 mm diameter horn factor calculations

Atm (kPa):	98.2	(Calibration site)		
Temp. (°C):	18.7	(Calibration site)		
Temp. (K):	291.9	(Calibration site)		
Relative humidity (%):	44.0	(Calibration site)		
Density (kg/m^3):	1.172			
Vapor pressure—H_2O (kPa):	2.156			
Corrected density (kg/m^3):	1.168			
Air horn diameter (m):	0.0414			
Air horn area (m^2):	0.0013			
Flow (m^3/s) (calib. sheet)	Total pressure (kPa) (calib. sheet)	Air velocity (m/s) (corr. for calib. site)	Air flow (m^3/s) (calculated)	Horn factor
0.00472	0.008	3.69	0.00497	0.950
0.00755	0.020	5.84	0.00786	0.961
0.01038	0.038	8.02	0.01079	0.962
0.01321	0.060	10.11	0.01361	0.971
0.01605	0.088	12.24	0.01648	0.974
0.01888	0.120	14.34	0.01931	0.978
0.02171	0.1158	16.43	0.02212	0.982
0.02454	0.200	18.50	0.02491	0.985
0.02737	0.247	20.58	0.02771	0.988
0.03020	0.299	22.63	0.03047	0.991

Table 2
145 mm diameter horn factor calculations

Atm. (kPa):	98.2	(Calibration site)		
Temp. (°C):	21.2	(Calibration site)		
Temp. (K):	294.4	(Calibration site)		
Relative humidity (%):	44.0	(Calibration site)		
Density (kg/m^3):	1.162			
Vapor pressure—H_2O (kPa):	2.517			
Corrected density (kg/m^3):	1.157			
Air horn diameter (m):	0.14453			
Air horn area	0.0164			
Flow (m^3/s) (calib. sheet)	Total pressure (kPa) (calib. sheet)	Air velocity (m/s) (corr. for calib. site)	Air flow (m^3/s) (calculated)	Horn factor
0.16046	0.081	11.85	0.19448	0.825
0.16754	0.086	12.19	0.20005	0.837
0.17462	0.096	12.90	0.21158	0.825
0.18170	0.104	13.40	0.21989	0.826
0.18878	0.112	13.94	0.22865	0.826
0.19586	0.121	14.47	0.23734	0.825
0.20294	0.130	14.99	0.24596	0.825
0.21002	0.138	15.46	0.25360	0.828
0.21710	0.148	15.98	0.26212	0.828
0.22418	0.158	16.53	0.27123	0.827

The differences in the horn factor (calibration factor) between the 41 mm (Table 1) and the 145 mm (Table 2) air horns illustrate the effects of non-ideal placement of the Pitot tube. The air horns are calibrated with the Pitot tubes placed on the centerline of the air horn bores. The centerline location of the Pitot tube simplifies the verification of the Pitot tube placement. The centerline of the smaller air horn is closer to the average velocity point (Fig. 3) that that of the larger air horns. Because the location of the Pitot tube in the smaller air horn is closer to the average velocity point, its horn factor is closer to 1.

9. Conclusions

There are many methods to measure the velocity and flow rates of an air stream. It is the author's opinion that the use of an appropriately designed air horn is the best way to measure relative small air flow (m^3/h). This method is enhanced with the use of a computerized data acquisition system that has access to the air temperature, barometric pressure, and the relative humidity. The computer system also makes it easy to use table look up and interpretation techniques to apply the calibration data.

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