Air-Flow

Venturi Meter, Orifice Meter, &
TSI Meter Calibration

Group 3

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Abstract

This experiment contains flow meter calibrations and characteristic analysis essential to the success of the upcoming air flow and particle removal studies to be conducted by Dr. Ranz. In these studies a rapid method of accurately determining the average air flow velocity will be vital. With this goal in mind, a TSI meter (hot wire anemometer) and three in-line flow meters, consisting of a Venturi meter (3.0”) and two Orifice meters (2.5” & 3.0”), were calibrated using a Pitot tube as the primary standard (See Figures V.2-3, 6, & 9).

Additionally, the flow characteristics of the in-line flow meters were also carefully examined. Both meter coefficients (“C”) and energy losses expressed as a pressure drop across the meter (“L”) were obtained for each in-line flow meter over a wide range of Reynold’s numbers (100,000-450,000). Typical values for the meter coefficient where 0.79 for the 3.0” Venturi meter, 0.67 for the 3.0” Orifice meter, and 0.66 for the 2.5” Orifice meter. Energy losses varied greatly depending upon the velocity of the stream (See Figure V.2-2, 5, & 8), however it was evident that the Venturi meter had the lowest energy loss followed by the 3.0” & 2.5” Orifice meters respectively.

Finally, a sample design problem (see Chapter VII) was undertaken to demonstrate the utility and importance of the data collected, along with its proper interpretation and limitations.

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I. Introduction

Experimental studies involving fluid dynamics require accurate and rapid methods of measuring fluid flow. Such measurements will be of vital importance to the upcoming air flow and particle removal studies to be conducted by Dr. Ranz. To choose the proper flow-measuring device both the strengths and weaknesses of a variety of meters must be analyzed. Point probes offer accurate velocity measurements but require a series of measurements to obtain an average. In-line flow meters provide the necessary convenience, but can cause large energy losses in the flowing fluid. Experimenters must therefore choose the measuring device with great care. To help future researchers confront these issues, this investigation analyses a series of flow meters with four primary objectives in mind;

1) Calibration of TSI Meter

The calibration of a hot wire anemometer, also known as a TSI meter, involves measuring air flow over a range of blower settings. At each setting a Pitot tube is used as a primary standard to determine the maximum velocity in the pipe. This is then graphically compared to the maximum velocity as measured by the TSI meter resulting in the appropriate calibration curve (see Figure V.1-1).

2) Calibration of In-line Flow Meters

The in-line flow meters under examination include a Venturi meter, 3” orifice meter, and 2.5” orifice meter. The calibration of these in-line flow meters involves taking measurements over a series of blower settings. At each the Pitot tube is used to obtain a velocity profile by traversing the duct. This can then be used to calculate the average velocity in the pipe. This is then graphically compared to the pressure drop measured at the constriction resulting in the appropriate calibration curves.

3) Analysis of Flow Meter Characteristics

Additional information such as meter coefficients and energy losses across the flow meter are vital parameters in any experimental design problems. For this reason, meter coefficients and energy losses for each in-line flow meter are presented over a wide range of Reynolds numbers (see Figure V.2-2, 3, 5, 6, 8, & 9).

4) Design Problem Illustrating Considerations in Meter Selection.

Finally, the principles in choosing an appropriate in-line flow meter are demonstrated with a hypothetical design problem. Given a flow rate, temperature, and pressure an appropriate duct diameter, flow meter, and blower type are selected. Pressure drops and energy losses across the meter are then calculated, while a flow diagram reveals the overall structure of the hypothetical apparatus (See Chapter VII).

These four objectives represent the guiding purpose of this experimental undertaking, and help provide a wealth of information vital to the success of future investigations involving air flow.

II. Theory and Technical Background

The air flow measurements, calibrations, and energy losses calculated in this experiment require a mathematical knowledge of fluid behavior. This chapter provides the mathematical theory and technical background necessary to undertake a quantitative analysis of fluid flow. This task is divided into five major sections consisting of information on; fluid statics, the Pitot tube, the TSI meter, in-line flow meters, and energy losses.

1) Fluid Statics, Manometer Readings, and Bernoulli's Equation

Fluid statics is primarily concerned with the pressure distribution within a fluid. For an incompressible fluid solely under the effect of a gravitational field, the pressure takes the following mathematical form (see Equation II-1).

$$\underbrace{P}_{\text{Static Pressure at Height (h). (Pa)}} = \underbrace{\rho}_{\text{Density of Fluid }(\mathrm{kg/m^3})} \cdot \underbrace{g}_{\text{Acceleration of Gravity }(9.807\ \mathrm{m/s^2})} \cdot \underbrace{h}_{\text{Depth of Fluid from the reference point. (m)}} + \underbrace{P_0}_{\text{Pressure at the reference point. (Pa)}}$$

Equation II-1 Static pressure in a fluid (G1, p34).

$$\left(\underbrace{P_2}_{\text{Pressure in Manometer Arm \#2 (Pa)}} - \underbrace{P_1}_{\text{Pressure in Manometer Arm \#1 (Pa)}}\right) = \left(\underbrace{\rho}_{\text{Density of Fluid in Manometer }(\mathrm{kg/m^3})} - \underbrace{\rho_{air}}_{\text{Density of Air, Often Neglected }(\mathrm{kg/m^3})}\right) \cdot \underbrace{g}_{\text{Acceleration of Gravity }(9.807\ \mathrm{m/s^2})} \cdot \underbrace{\Delta h}_{\text{Height Difference Between Manometer Fluid. (m)}}$$

Equation II-2 Pressure difference in a manometer (G1, p37).

For a fluid at rest the pressure is the same at all points having the same elevation. A manometer takes advantage of this principle to measure the pressure difference between two arms (see Equation II-2). A diagram of a manometer helps illustrate the physical significance of all pertinent variables (see Figure II-1).

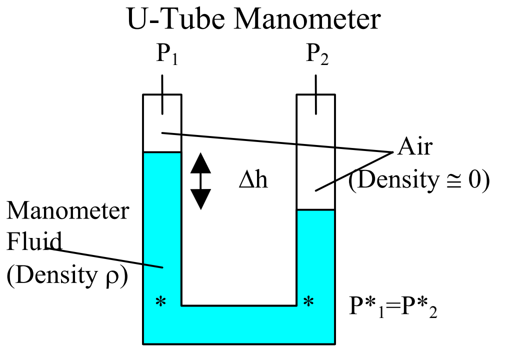

Figure II-1 Simple diagram showing important variables for a manometer.

When fluids are flowing, instead of static, the above equations will not fully describe the situation. Instead an energy balance involving potential energy, kinetic energy, and fluid pressure in a unit volume is necessary. An important form of this balance, which neglects friction, is called the Bernoulli equation (see Equation II-3).

Bernoulli's Equation

Velocity of Fluid at Point #1 (m/s)

Pressure of Fluid at Point #1 (Pa)

Velocity of Fluid at Point #2 (m/s)

Pressure of Fluid at Point #2 (Pa)

$$z_1 \cdot g + \frac{v_1^2}{2} + \frac{p_1}{\rho_1} = z_2 \cdot g + \frac{v_2^2}{2} + \frac{p_2}{\rho_2}$$

Density of Fluid at Point #2 (kg/m^3)

Height of Fluid at Point #1 (from the reference point) (m)

Density of Fluid at Point #1 (kg/m^3)

Height of Fluid at Point #2 (from the reference point) (m)

Acceleration of Gravity (9.807 m/s^2)

Acceleration of Gravity (9.807 m/s^2)

Equation II-3 Conservation of energy between points 1 & 2 (G1, p67).

2) Pitot Tubes and the Traverse Method

Bernoulli's Equation can immediately be used to analysis the behavior of a Pitot tube (see Equation II-4). To develop such an equation air has been considered incompressible ($\rho_1 = \rho_2$), an assumption valid for air flows less than 60 m/s (P1, p5-10). Also a dimension-less meter coefficient, "C", which has a typical value of 0.98-1.00 for a Pitot Tube (P1, p5-10), has been added to compensate for any frictional losses. Finally, it should be noted that the difference between the static pressure and tip pressure is typically measured with a manometer (see Equation II-2).

$$V_{tip} = C \cdot \sqrt{2 \cdot \left(P_{tip} - P_{static} \right) / \rho_{static}}$$

Point Velocity at Tip of Pitot Tube

Static Density of Air (kg/m^3)

Pressure at Tip of Pitot Tube (Pa)

Static Pressure (Pa)

Meter Coefficient (Dimless) (Assumed 0.99)

Equation II-4 Point velocity relationship for a Pitot Tube (P1, p5-10).

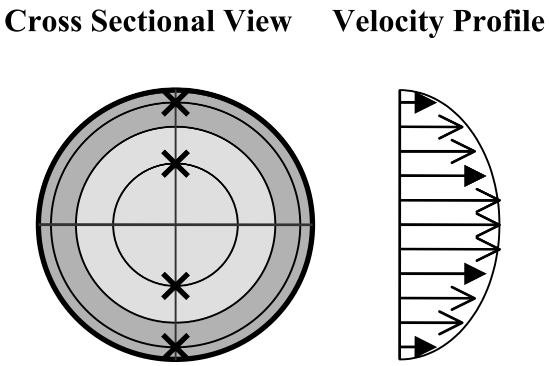

Figure II-2 Cross sectional view and velocity profile showing examples point velocity locations for a 4 point traverse (usually 8, 10, or 12). Each data point represents an equal area across the circular duct.

To obtain an average velocity for an air flow a velocity profile must be obtained by measuring the point velocity at a sufficient number of locations (usually 8, 10, or 12). Moreover, if these locations are carefully selected the individual point velocity data can simply be averaged to obtain the average air velocity. For this simplification to be valid, each data point must represent an equal cross sectional area of the duct (see Equation II-5 & Figure II-2). Also, data points are taken across the entire duct diameter (r_i at $\phi=0$ deg & 180 deg for all r_i). This duplication adds accuracy and also assures the flow is symmetric.

$$r_i = R \cdot \sqrt{(2i-1)/N}$$

Radius at which to measure point velocity (m)

Total Radius of Circular Duct (m)

Index i=1,2,...,N/2 (Dimless)

Total Number of Points for Traverse, Usually 8, 10, or 12 (Dimless)

Equation II-5 Traverse method for determining average air flow (P1, p5-11).

3) The TSI Meter (a Hot Wire Anemometer)

The hot wire anemometer is a point probe capable, with proper calibration, of accurately measuring gas velocities from 0.15 m/s to super-sonic speeds (P1, p5-11). It consists of a very fine wire along with appropriate electronics to accurately measure the resistance in that wire. As the velocity of air increases so will the rate of heat transfer from the wire. This will cause a temperature change in the wire which also effects the resistance in the wire. In this way a relationship between air velocity and resistance develops (Equation II-6). Finally, because the temperature of the air also effects the heat transfer rate, the anemometer can be used to measure temperature.

$$\sqrt{V} \propto I^2 \cdot R_w / \Delta t$$

Average Local Velocity (m/s)

hot-wire Current (Amps)

hot-wire Resistance (Ohms)

Difference in Temperature between the Wire and Air (Kelvin)

Equation II-6 Velocity relationship for a hot-wire anemometer (TSI Meter).

4) In-line Flow Meters (Venturi Meter & Orifice Meter)

The Bernoulli Equation (Equation II-3) in conjunction with the continuity equation (Equation II-7) allows the mathematical analysis of in-line flow meters such as the Venturi Meter or Orifice Meter (Equation II-8). To develop such equations air is at first considered incompressible ($\rho_1 = \rho_2$), however upon completion of the derivation a dimension-less expansion factor, "Y", is attached thereby taking compressibility into account. This expansion factor depends upon the ratio of pressure at the constriction to that upstream, and can be obtained from Geankoplis' Figure 3.2-3 (G1, p130). Also a dimension-less meter coefficient, "C", which has a typical value of 0.98-0.99 for a Venturi Meter & 0.61-80 for a Orifice Meter (G1, p131), has been added to compensate for any frictional losses. Finally, it should be noted that the difference in pressures is typically measured with a manometer (see Equation II-2).

Average Mass Flow Rate across Section #1 (kg/s)

Average Mass Flow Rate across Section #2 (kg/s)

$$m_1 = m_2$$

$$\rho_1 v_1 A_1 = \rho_2 v_2 A_2$$

Density of Fluid at Section #1 (kg/m^3)

Average Velocity of Fluid at Section #1 (m/s)

Cross Sectional Area at Section #1 (m^2)

Density of Fluid at Section #1 (kg/m^3)

Average Velocity of Fluid at Section #2 (m/s)

Cross Sectional Area at Section #2 (m^2)

Equation II-7 Continuity equation for flow in a pipe. Can be interpreted as a statement of conservation of flowing mass across two sections spanning the pipe.

Average Mass Flow Rate (kg/s)

Meter Coefficient (Dimless)

Area at Constriction (m^2)

Expansion Factor (Dimless)

$$m = \frac{C \cdot A_c \cdot Y}{\sqrt{1 - (D_c / D_u)^4}} \sqrt{2 \cdot (P_u - P_l) \cdot \rho_u}$$

Diameter at Constriction (m)

Diameter Upstream (m)

Pressure Upstream (Pa)

Low Pressure
1) Venturi: at Constriction
2) Orifice: at 0.3-0.8 Diameters Downstream
(Pa)

Density of Air Upstream (kg/m^3)

Equation II-8 Flow equation for a in-line flow meter (Venturi Meter or Orifice Meter).

5) Permanent Energy Losses

Energy loss is an important consideration for choosing any in-line flow meters. As a fluid is irreversible compressed and expanded, or opposing frictional forces take there toil, a permanent loss of energy develops. Because the continuity equation (see Equation II-7) assures the mass flow rate cannot decrease from one section to another, this energy loss is instead manifest as a pressure drop. Therefore, the energy loss can simply be expressed as a pressure drop across the in-line flow meter in question (see Equation II-9). This new term can be added to Bernoulli's Equation, after first dividing by the density of the fluid, to obtain an energy balance that also accounts for energy losses (see Equation II-3).

$$\underbrace{L}_{\text{Energy Losses Expressed as a Pressure Drop (Pa)}} = (\underbrace{P_u}_{\text{Pressure Upstream (Pa)}} - \underbrace{P_d}_{\text{Pressure Downstream (Pa)}})$$

Equation II-9 Energy losses as expressed as a pressure drop across an in-line flow meter.

VII. Design Problem

This example design problem illustrates the issues involved in flow meter selection, and demonstrates the utility of the data collected in this experiment. These goals are accomplished in four steps; the desired flow parameters are first specified, followed by selection of an appropriate flow meter and duct diameter, next the predicted results of these choices in terms of energy losses are presented, and finally a flow diagram of the proposed system is shown.

1) Specified Flow Parameters and Initial Assumptions.

The desired parameters for the air flow stream are; a temperature of 120 ^{o}F, a pressure of 30 psig, and a flow rate of 5,000 lb_m/hr. In SI units these quantities correspond to a temperature of 322 ^{o}K, pressure of 308200 Pa, and flow rate of 0.630 kg/s. Additionally, specifying these characteristics for air fixes most of its physical quantities. Those quantities of interest are; density of 3.339 kg/m^3, and viscosity of 1.98 x 10^{-5} kg/m/s (P1, p.3-162). This leaves only the duct diameter to determine the Reynold's number for the flow.

Along with the above quantities some additional assumptions help make reasonable choices in the design.

1) The energy costs incurred by energy losses will outweigh any modest expenses for the initial design. We are therefore designing for efficiency.

2) The flow parameters are expected to deviate only slightly from those listed above. Therefor, operation over a wide range of conditions is not required.

2) Flow Meter and Duct Diameter Selection.

Selecting the correct flow meter for a job is not an easy task. Experts claim that 75 percent of the in-line flow meters in industry are performing below satisfactory levels, and that improper selection accounts for 90 percent of these deficiencies (F1, p.z-15). Much of this may be due to the large number of flow meters to choose from. For example, Omega's 1992 catalog lists 18 different varieties of flow meter to chose from, each with their own set strengths and weaknesses (F1, p.z-10). However, for our purposes the selection options will be limited to either a Venturi meter or a Orifice meter.

The Venturi meter, as compared to the Orifice meter, offers very low permanent energy losses and has a meter coefficient very close to one. The Orifice meter would provide more flexibility should flow parameters become altered, however based upon the assumptions listed above the correct choice is the Venturi meter

Next the duct diameter must be selected. To aid in this choice a spreadsheet has been utilized to rapidly determine the consequences of different duct diameter selections (See Figure VII-1 on next page).

Table VII-1 Predicted Physical Behavior for the Venturi Meter Design Problem.

	Given				Immediatly Sets	
Temperature	Pressure	Mass Flow Rate			Density	Viscosity
(deg K)	(Pa)	(kg/s)	Pipe Length =	10 (m)	(kg/m3)	(kg/m/s)
(Given)	*(Given)*	*(Given)*	Pipe Friction		*(P1, p3-162)*	*(P1, p3-162)*
322	308168	0.630	Factor =	0.013	3.339	0.0000198

Select				Calculated		
	Venturi	Average	Reynolds	Energy Loss	Energy Loss	Minimum Power
Duct Diameter	Constriction	Velocity	Number	From Meter	From Pipe	Required
(inches)	(inches)	(m/s)	(Dimless)	(J/kg)	(J/kg)	(W)
(Parameter)	*(Parameter)*	*(Calculated)*	*(Calculated)*	*(Calculated)*	*(Calculated)*	*(Calculated)*
1	0.5	372.416	797484	4647.01	354925.47	226530.66
1.5	0.75	165.518	531656	1791.76	46739.16	30574.48
2	**1**	**93.104**	**398742**	**911.21**	**11091.42**	**7561.66**
3	**1.5**	**41.380**	**265828**	**351.34**	**1460.60**	**1141.52**
4	**2**	**23.276**	**199371**	**178.67**	**346.61**	**330.93**
5	**2.5**	**14.897**	**159497**	**105.75**	**113.58**	**138.18**
6	3	10.345	132914	68.89	45.64	72.16
7	3.5	7.600	113926	47.95	21.12	43.51
8	4	5.819	99685	35.04	10.83	28.90
10	5	3.724	79748	20.74	3.55	15.30
12	6	2.586	66457	13.51	1.43	9.41
24	12	0.647	33228	2.65	0.04	1.70
36	18	0.287	22152	1.02	0.01	0.65

The Venturi meter has been chosen with a constriction always half the total diameter. Additionally, the systems has been assumed to have a total duct length of 10 meters. With these two assumptions, the only variable is the duct diameter. This table illustrates how drastically different duct diameters affect the system.

At this stage the selection boils down to choosing a duct diameter that can be purchased easily, has a low energy loss, is not too fast, yet not too slow, and also is within the range of Reynold's numbers examined in this experiment. This limits the selection to one of four possibilities (highlighted in bold), with the duct diameter of 5" probably the best due to its low total energy loss.

3) Predicted System Performance and Pump Selection.

The total energy loss and minimum work required to overcome that energy loss can be seen in Table VII-1. It should be pointed out that at small duct diameters energy losses due to the pipe far outweigh those incurred at the flow meter. This situation is reversed for slow flow rates.

For the chosen duct diameter of 5", the total energy loss is 114 J/kg, while the work required to overcome this loss is 138 Watts. This is only 0.19 horsepower, however additional power would be necessary to get the stream up to speed. A 5 HP turboblower would most likely be sufficient for this apparatus.

4) Flow Diagram.

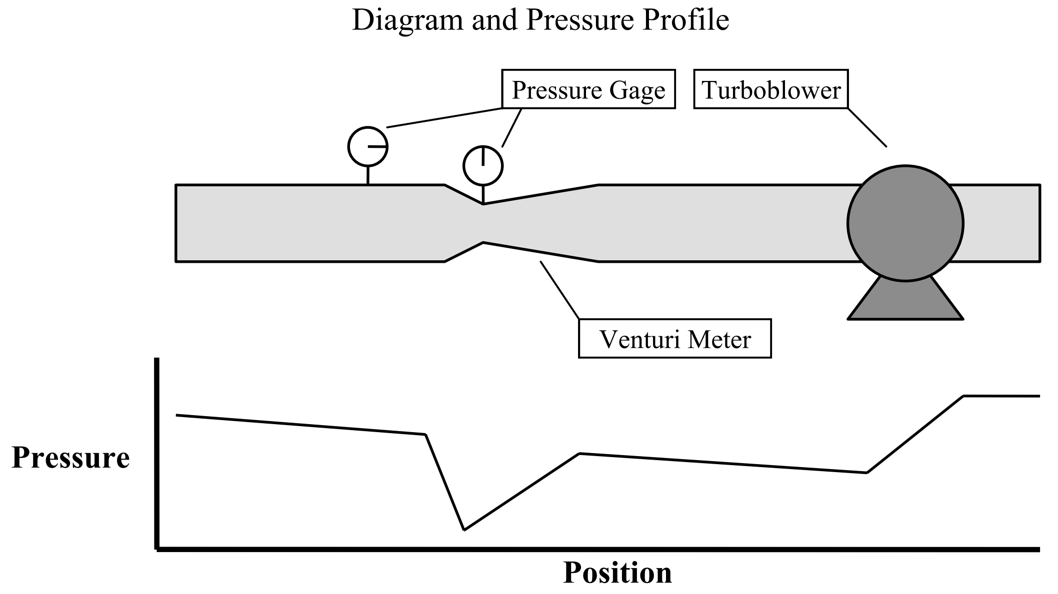

Figure VII-2 Diagram of a Venturi Meter and Turboblower. Below, the pressure is plotted verses position in the system. Notice the pressure loss due to friction in the pipes. Also, the pressure drop incurred in the Venturi meter is almost completely recovered, as it would be if it produced no energy losses. Finally, the Turboblower increases the air flow pressure thereby driving the air around the system.

IX. Nomenclature

Symbol	**Physical Meaning**	**SI Units**
A_1	Cross sectional area at section #1.	m^2
A_2	Cross sectional area at section #2.	m^2
A_c	Cross sectional area at constriction.	m^2
C	Meter coefficient.	Dimless
D_c	Diameter at constriction.	m
D_u	Diameter upstream.	m
g	Acceleration of gravity.	9.807 m/s2
h	Depth of fluid from reference point.	m
Δh	height difference between manometer fluid.	m
i	Index.	Dimless
I	Hot-wire current.	Amps
L	Energy loss expressed as a pressure drop.	Pa
m_1	Mass flow rate across section #1.	kg/s
m_2	Mass flow rate across section #2.	kg/s
N	Total number of points for duct traverse.	Dimless
P	Static pressure at height (h).	Pa
P_0	Pressure at reference point (h=0).	Pa
P_1	Pressure in manometer arm #1.	Pa
P_2	Pressure in manometer arm #2.	Pa
P_d	Pressure downstream.	Pa
P_l	Low pressure.	Pa
P_{static}	Static pressure.	Pa
P_{tip}	Pressure at tip of Pitot tube.	Pa
P_u	Pressure upstream.	Pa
r_i	Radius at which to measure point velocity.	m
R	Total radius of duct.	m
R_w	Hot-wire Resistance.	Ohms
Δt	Temperature difference between wire and air.	deg Kelvin
v_1	Average velocity of fluid at section #1.	m/s
v_2	Average velocity of fluid at section #2.	m/s
V	Average local velocity.	m/s
V_{tip}	Velocity at tip of Pitot tube.	m/s
Y	Expansion factor.	Dimless
ρ	Density of fluid.	kg/m^3
ρ_1	Density of fluid at point #1.	kg/m^3
ρ_2	Density of fluid at point #2.	kg/m^3
ρair	Density of air.	kg/m^3
ρstatic	Static density of air.	kg/m^3

X. References

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