CHAPTER 40

INSTRUMENTS AND TECHNIQUES USED IN EVALUATING THE PERFORMANCE OF AIR FLOW SYSTEMS

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INTRODUCTION

Objectives

It is the objective of this chapter to discuss the topic of evaluation of air flow systems as well as provide insight on practical approaches to system evaluation, utilizing up-to-date instrumentation and techniques. The material presented herein is directed to the student as well as the practicing industrial hygienist and will embrace instruments and techniques in evaluating both local exhaust and general ventilation systems.

This chapter will not delve deeply into the theory of air flow, but will require the reader to have a basic understanding of the general principles of ventilation such as the principles of air flow, pressure drops through ducts, and characteristics of blowing and exhausting. These subjects are discussed in some detail in Chapter 39, "Principles of Ventilation."

Bases for System Evaluation

To assure adequacy of design and performance. Independent of the type of system being evaluated, it should be constructed in accordance with a design basis be it a sophisticated engineering approach or the sketches of a sheet metal fabricator. Once a system is completely installed, various air flow measurements should be made before any aspect of the process or area to be controlled has an opportunity to affect the air flow characteristics of the system.

Sufficient input must go into the design basis to assure adequacy of system performance in the control of occupational hazards. Factors to be considered are toxic vapors, gases or dusts; nuisance materials or conditions; and explosive or flammability hazards. Assessment of the hazard in terms of environmental monitoring in conjunction with an evaluation of the air flow system immediately after start up is one sure way to test the adequacy of the design and installation.

To assure system performance is maintained. Since in many instances air flow systems are not an integral part of the process in terms of production or output, it is essential to run periodic checks on their performance. This is especially true for systems which have dampers, blast gates, etc., as well as those which may be affected by accumulations of the material they are conveying or controlling.

Maintenance of the entire air flow system from the entry to the exhaust stack cannot be overemphasized. Various air flow measurements discussed below will prove invaluable in determining the adequacy of, or the need for, maintenance.

To determine the feasibility for expanding (adding to) the system. The performance of many well designed and installed air flow systems is rendered inadequate by irrational expansion of the system. Various air flow measurements will provide input for judicious expansion while still maintaining the performance initially designed into the system. In many instances, relatively minor modifications may be indicated by such measurements.

To establish improved design parameters for new systems. The evaluation of existing systems may provide valuable input related to the specific operating conditions and characteristics of the hazards being controlled which may lead to improved design of new systems. For example, higher conveying velocities may be indicated to prevent ducts from becoming clogged, or turbulence and eddy currents at a hood entry resulting in contaminant escape, may require improved hood design.

To assure compliance with federal, state, or other regulations. Obviously, the purpose of any air flow system is either the control of hazardous chemical or thermal stresses, or providing a comfortable work environment. To assure that the former purpose is met, some regulations (laws) include air flow performance parameters which must be met. Chapter 1 includes a discussion of the 1970 Occupational Safety and Health Act. The initial package of standards embraced by this Act includes standards requiring certain minimum air flow requirements be maintained. It is not the purpose of this chapter to discuss paragraph 1910.-94 Ventilation[1] in detail, but merely to cite examples requiring minimum air flow parameters.

Minimum exhaust volumes for grinding wheels (Table G-4 of reference 1).

Minimum maintained velocities in spray booths (Table G-10 of reference 1).

Control velocities for undisturbed locations for open surface tanks (Table G-14 of reference 1).

Minimum ventilation rate for lateral exhaust of open surface tanks (Table G-15 of reference 1).

EVALUATING AIR FLOW SYSTEMS

Introduction

As there are numerous reasons for evaluating systems, there are degrees to which they may need to be evaluated. Instruments and techniques are

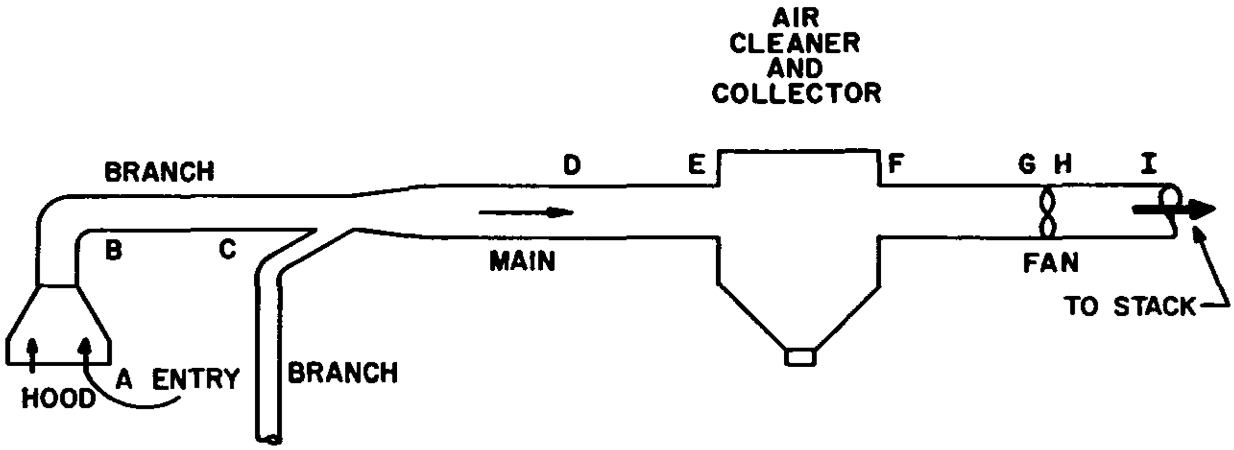
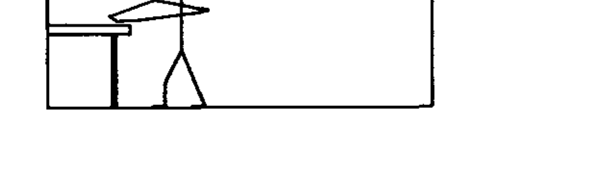


Figure 40-1. Schematic of a Local Exhaust System.

described below which may provide only a cursory evaluation of part of the system or an in-depth survey of the total system.

Figures 40-1 and 40-2 represent the two generic systems requiring air flow evaluation. Figure 40-1 is a schematic of a local exhaust system and Figure 40-2 is a schematic of a general room ventilation system[2] with the locations requiring evaluation identified by A, B, C, etc.

The instruments and techniques described in this chapter are in the order of increasing precision and accuracy. This order is reflected by the degree of interaction the instruments and techniques have with the system. The reader will note that visualization, the first approach discussed, barely interacts with the total system, whereas the final approach is actually titled "Measurements within the System." However, one should not lose sight of the fact that only by applying a combination of instruments and techniques can the total performance of any air flow system be evaluated.



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation Manual, 11th Edition. Lansing, Michigan, 1970.

Figure 40-2. Schematic of a General Room Ventilation System.

Visualization — A Cursory/Qualitative Estimate of Performance.

Purpose.

Visualization is an extremely important aspect of performance evaluation which heretofore has rarely been discussed in chapters or publications on air flow measurements. The primary application of visualization is as a cursory estimate of local exhaust system performance. Moreover, it provides an extremely effective technique for demonstrating the pluses of good design and the minuses of poor design to management and engineering personnel. Visualization techniques can also be used in training operating personnel in the proper use of the ventilation system.

Instruments/Materials.

"Smoke tubes" is a descriptive term applied to a glass tube containing titanium tetrachloride adsorbed on a granular medium. When the ends of the glass tube are broken and air passed through the tube, the moisture in the air reacts with the $TiCl_4$ to generate hydrochloric acid "smoke."

CAUTION: Direct inhalation of this "smoke" will be irritating to the respiratory system and should be avoided.

A squeeze bulb, rubber tubing, and the tubes can be purchased from numerous suppliers (Table 40-1) and are relatively inexpensive.

Titanium tetrachloride is a chemical reagent available through standard chemical supply companies. It is also available in single use glass ampules (Table 40-1).

CAUTION: These fumes and the liquid are corrosive to the skin, and irritating to the eyes and respiratory system.

Because of the nature of this material, glass ampules are recommended.

Smoke candles are available in a range of sizes and a few colors. They can be purchased in terms of the cubic feet of smoke produced or the duration of smoke evolution (Table 40-1). *Other sources of visualization media.* There are numerous other means of generating visual clouds

TABLE 40-1
Instruments/Purposes/Suppliers

Instruments	Purposes	Suppliers*
Smoke Tubes Titanium Tetra-chloride Smoke Candles	Visualization of air flow in and around exhaust hoods. Quick indication of room pressure. Demonstrate general room air flow patterns.	E. Vernon Hill Co. Mine Safety Appliances Co. National Environmental System
Rotating Vane Anemometers	Measures air velocity.	Bendix Environmental Science Division E. Vernon Hill Co.
Vane Anemometers	Measures air velocity (some have attachments for static pressure).	Alnor Instrument Co. E. Vernon Hill Co. Bachrach Instrument Co.
Heated Thermocouple Anemometers	Measures air velocity (some are applicable for non-directional air velocity).	Hastings-Raydist Co. Alnor Instrument Co.
Heated Wire Anemometers	Measures air velocity, static pressure, temperature.	Anemostat Products
Pitot Tubes	Measures total, velocity, and static pressure.	Western Precision Co. Dwyer Instruments, Inc. Meriam Instrument Co. E. Vernon Hill Co. Ellison and Co.
Manometers	Measures total, velocity, and static pressure.	Dwyer Instruments, Inc. Meriam Instrument Co. E. Vernon Hill Co.
Aneroid Gauges (Magnehelic)	Measures total, velocity, and static pressure.	Dwyer Instruments, Inc.
Transducers	Used for remote readings and when rapid changes in pressure must be maintained.	Hastings-Raydist Co.

*This represents neither a complete list nor endorsement.

to follow air flow. A "heavier than air" cloud can be generated by simply placing dry ice in an alcohol bath. A "lighter than air" cloud can be generated by blowing air through a smoldering mixture of sawdust and oil[3].

Techniques. Visualization media are best suited for the evaluation of air flow patterns and velocities at exhaust entries and supply outlets.

1. Smoke tubes

Smoke tubes can be carried with the industrial hygienist on any of his surveys or inspections. They can be used best as an immediate survey type tool in assessing the ability of a local exhaust system to capture contaminants. Smoke should be administered close to the hood entry initially, and gradually the smoke source moved away from the entry to observe the sphere of containment the exhaust system produces. Larger quantities of smoke can be generated inside of the hood or enclosure to estimate rate of clearance as well as to check for eddy currents, reverse air flows, and escapement. Small amounts of smoke can be used to estimate the force and direction of air from outlets as well as a qualitative check of the performance of return air outlets.

2. Titanium tetrachloride

Titanium tetrachloride is used best by swabbing it along the periphery of hoods as a check for eddy currents, reverse air flow, and lack of control. Once swabbed inside of a hood, the smoke will persist for several seconds and thus provide an opportunity for prolonged observation or photographs.

3. Smoke candles

Smoke candles can be used to estimate clearance rates and containment of large hoods such as paint spray booths, laboratory hoods, or other high volume exhaust systems. Minimal performance of the system must be determined before igniting a smoke candle to assure reasonable removal of the smoke. Smoke candles can be held by forceps and moved across hood face openings to estimate the air distribution at the face. Colored smoke can be introduced in ventilation systems downstream from the fan to check for leaks.

Limitations. There are two significant limitations. First, visualization is strictly qualitative and does not provide any information in terms of design or performance specifications. Second, the materials used may be hazardous or at the very least — a nuisance; thus their use in occupied areas should be somewhat restricted.

Air Velocity and Flow — Exhaust and Supply Openings

Relationship of velocity to rate of flow. The velocity to rate of flow relationship is expressed in Equation 1.

Equation 1: $Q = AV$

Where: Q = Rate of flow in cfm
V = Average linear velocity in fpm
A = Cross-sectional area of the duct or hood in ft^2

From this equation it is possible to calculate air flow rate if the velocity (V) and cross-sectional area (A) are known.

The purpose of a local exhaust system is to capture and convey the contaminant from the source through an air cleaner to the atmosphere. Precise measurements of capture velocities as well as estimates of exhaust or supply volumes can be made at the point where the air flow system interacts with the work environment. These points are identified as "A" on Figure 40-1 and "M" and "O" on Figure 40-2.

Instruments/Techniques. In using the instruments described below, the need to take multiple measurements of a given slot, hood, or diffuser must be kept in mind. Only by making a uniform traverse of the opening being evaluated will one be able to arrive at a satisfactory average velocity to use in the calculation of air flow. The reader should review Pitot traverse techniques covered in this chapter, and in greater detail in reference 4, to develop an appreciation for multiple measurements in evaluating air flow.

TABLE 40-2.
Correction factors for rotating vane anemometers.

Opening	Correction Factor*
Pressure openings, more than 4 in. wide, up to 600 sq. in. area, with free opening 70% or more of gross area, no directional vanes.	1.03
Suction opening, more than 4 in. wide, up to 600 sq. in. area, with flange 2 in. wide, free-open area 60% or more of gross area	0.85

Volume: For suction openings, cfm = (factor) (velocity) (gross area)

For pressure openings, cfm = (factor) (velocity) $\left(\frac{\text{gross area} + \text{net area}}{2}\right)$

*If the opening is covered with a grille, the instrument should touch the grille face but should not be pushed in between the bars. For a free opening without a grille, the anemometer should be held in the plane of the entrance edges of the opening. The anemometer must always be held in such a manner that the air flow through the instrument is the same direction as was used for calibration (usually from the back toward the dial face).

From "Industrial Ventilation — A Manual of Recommended Practices", Committee on Industrial Ventilation, American Conference of Governmental Industrial Hygienists, Lansing, Mich 1970.

TABLE 40-3.
Correction factors for swinging vane anemometers.

Opening	Correction Factor
Pressure	
More than 4 in. wide and up to 600 sq. in. area, free opening 70% or more of gross area, no directional vanes. Use free-open area.	0.93
Suction	
Square punched grille (use free-open area)	0.88
Bar grille (use gross area)	0.78
Strip grille (use gross area)	0.73
Free open, no grille	1.00
Volume: cfm = (factor) (area) (velocity)	

From "Operating Instructions for the Alnor Series 6000-P Velometer" Alnor Instrument Company, Chicago, Ill., 1970.

1. Rotating vane anemometers

The rotating vane anemometer is comprised of a vane or propeller on a shaft connected to gears. The air movement causes the vane to rotate. The revolutions of the vane turn the gears which register the revolutions on the dial of the instrument as linear feet. Readings are usually taken over one-minute periods, thus giving air velocity in linear feet per minute. These instruments are available in a number of sizes, however the most common vane sizes are 3, 4, and 6 inches in diameter (Table 40-1).

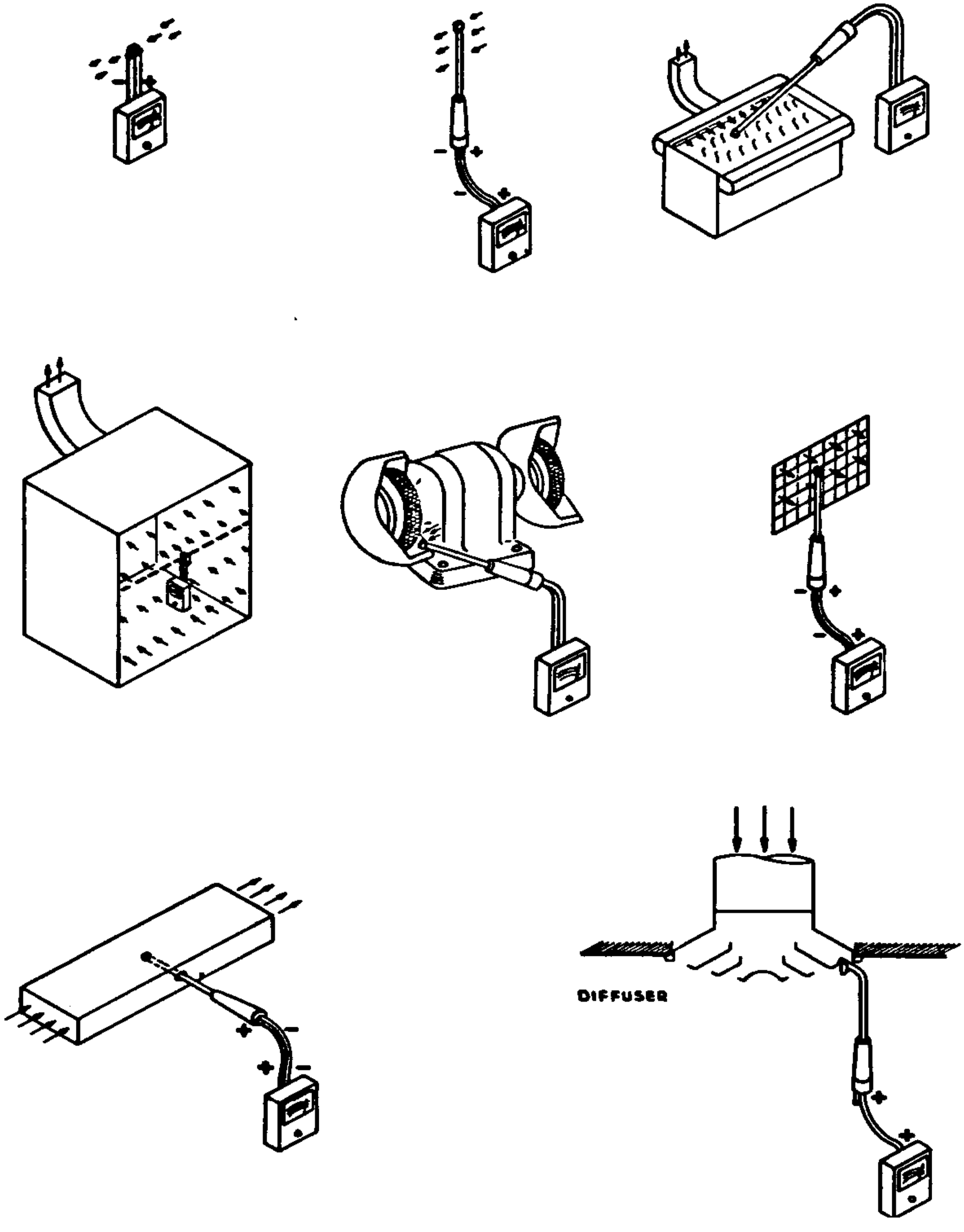
These instruments are best suited for determining air velocities and estimating air flow through large openings such as mine shafts and air supply and discharge grilles. Readings are generally obtained by traversing the opening at a uniform rate for a given period of time. Table 40-2 provides information on correction factors, techniques for taking measurements as well as the equations for calculating air flow rate.

The optimum range for these instruments is between 100 and 3000 fpm. They are best suited for use in relatively clean air and require the use of a timing device. They require frequent calibration and must be handled with care.

2. Swinging vane anemometer

The swinging vane anemometer indicates air velocity as a function of the pressure exerted by the air stream against a spring loaded swinging vane. They are quite portable and used extensively by industrial hygienists and ventilation engineers in the field (Table 40-1).

These instruments are used primarily for measuring velocities of exhaust or supply openings as shown in Figure 40-3. Fittings are available for some swinging vane devices which allow these to be used for a number of applications, such as measuring static pressures, as well as over a wide



Alnor Instrument Company, Chicago, Illinois.

Figure 40-3. Applications of a Commercially Available Swinging Vane Anemometer (Alnor Instrument Company).

range of velocities from 25 to 24,000 fpm. The optimum range of performance is 100 to 10,000 fpm.

Openings must be traversed with velocity measurements taken uniformly over the face of the the grille or hood being evaluated. Care must be taken to use probes for small openings (less than 3 ft²) since the size of the device could represent a significant portion of the area. It is important to follow the operating instructions provided with the instrument, otherwise significant errors can be introduced. Correction factors for supply (pressure) and exhaust openings and information on calculating air flow are shown in Table 40-3.

When air temperatures vary more than 30°F from 70°F and/or the altitude is greater than 1000 ft. above sea level, readings should be corrected in accordance with the following equations:

Equation 2: $$Vt = Vr\sqrt{\frac{460+t}{530}}$$

Where: Vt = true velocity
Vr = velocity read from meter
t = air stream temperature

Equation 3: $$Vt = Vr\sqrt{\frac{1}{d}}$$

Where: $$d = \left(\frac{530}{460+t}\right)\left(\frac{B}{29.92}\right)$$

B = barometric pressure in inches of Hg

Caution must be exercised in using these devices in a dusty, moist, or corrosive atmosphere, since it can affect the readings as well as impair the performance of the instrument. They require periodic calibration but are a good choice for general and field applications.

3. Heated thermocouple anemometers

The operating principle of the heated thermocouple anemometer instruments is simply that air moving past a heated object removes heat. The amount of heat removed is proportional to the quantity of air passing which is a function of velocity. These instruments have one or more thermocouples as sensing elements which are heated by either alternating or direct current. A change in air flow causes a change in temperature of the thermocouples, resulting in a change in the direct current output. Another unheated thermocouple is in the direct current circuit to a meter. As a result of the changes in temperature, a change in voltage is developed which is read as air velocity.

These instruments are usually comprised of a single probe connected to an operating unit housing the circuitry, meter, batteries, etc., and are about the size of a cigar box. They are quite portable and commercially available (Table 40-1). The units incorporate balancing circuits which render errors due to radiant heat and ambient temperature fluctuations negligible. Since these instruments are direct reading and have a short response time (less than one minute), they are applicable for field as well as laboratory use. Some of the instruments may be used in determining non-directional velocities such as general room air movement, depending upon the type of shielding around the sensors in the probe.

The limitations are related primarily to maintaining the integrity of the probe. Heavy dust loadings or corrosive materials as well as mechanical shock could damage the delicate wires in the probe. The range of air velocities is quite wide, with some instruments having advertised ranges from 10 to 10,000 fpm. A general rule of thumb is that velocities from 10 to 50 fpm may be estimated while velocities from 100 to 2000 fpm may be measured with some precision depending on the calibration of the unit. Periodic calibration is required.

These devices, as with any probe type velometer, can be used to measure entry or exit velocities of hoods, slots, grilles, etc., by placing the probe perpendicular to the direction of air flow and recording the measurements. The greater the number of measurements distributed uniformly across the opening being measured, the better the estimate of air velocity and flow rate will be.

4. Heated wire anemometers

The heated wire anemometer devices depend upon the change in resistance of a wire with a change in temperature. The degree of temperature change is proportional to the velocity of air passing the wire. Velocity is read directly on a meter which is actuated by a change in voltage from a Wheatstone bridge circuit.

Generally, the advantages and limitations are the same as those previously described for heated thermocouple anemometers.

There are some units available which can measure temperatures ranging up to 250°F and static pressures up to 10 inches of water. More precise hot wire anemometers measure velocity exclusively. Static pressure measurements will be discussed in more detail in the section titled "Measurements within the System."

5. Other thermal anemometers

a) Heated thermometer anemometer

The principle for the heated thermometer anemometer is the same as for heated thermocouple anemometers except that two thermometers are used instead of thermocouples. It is not amenable to field use because of the fragility of the thermometers and the amount of time required for the thermometers to reach equilibrium. Its primary use is that of a laboratory type device in the calibration of air samplers requiring negligible static pressure losses in the calibration train (e.g., electrostatic precipitators).

b) Kata thermometer[7]

The Kata thermometer is a special thermometer with a large bulb, containing alcohol, and a stem with marks at 95 to 100°F. It is heated above 100°F and the time required for it to cool from 100 to 95°F is a measure of the non-directional air velocity in the room. It was designed for comfort ventilation measurement, and its surface-to-volume ratio is similar to that of the human body. The useful velocity range is 25 to 500 fpm. It has the disadvantage of being fragile and having large radiation and convection areas. A silvered bulb is necessary to minimize the effect of thermal radiation. As expected, it has a slow response time. The disadvantages are sufficient to classify this device as a poor choice for the measurement of air velocity.

MEASUREMENTS WITHIN THE SYSTEM

Precise measurements which characterize the performance of air flow systems are made within the system. Instead of measuring the velocity of air going into exhaust hoods or coming from air outlets, measurements are made *inside* the ductwork leading to the point of entry or discharge. Such locations are depicted as B, C, D, E, F, G, H and I on Figure 40-1 and J, K and L on Figure 40-2. Measurements within the system are made to determine static pressure drops associated with hood entries, ducts, across air cleaners (e.g. filters and bag houses) as well as velocity pressures. Therefore, the instruments discussed will be primarily those used to measure pressure in terms of inches of water.

Some of the anemometers previously discussed, those with relatively narrow probes and fittings, can also be used to measure air velocities within the system. Independent of the measuring device, the accuracy in determining either duct velocities or flowrate is dependent upon the location and number of measurements taken in traversing the duct. Techniques discussed under "Pitot Traverse" below can be applied to the use of most measurements requiring multiple sensing points within an air flow system.

Relationship of Velocity to Pressure Measurements

The total pressure of a system is the algebraic sum of the static pressure plus the velocity pressure. Air velocity can be computed from the velocity pressure according to equation 4.

Equation 4: $$V = 1096\sqrt{\frac{VP}{0.075d}}$$

Where: V = velocity in fpm
VP = velocity pressure in inches of water
d = density factor equal to:

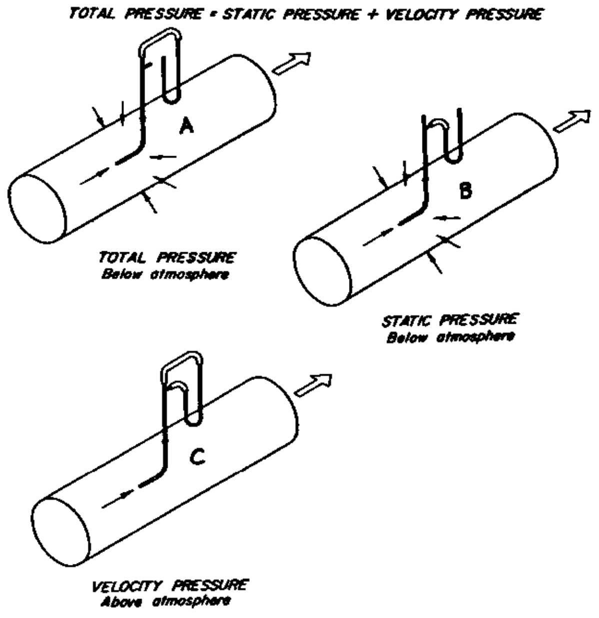
$$\frac{530}{460+t} + \frac{B}{29.92}$$

Where: B = barometric pressure in inches of mercury
t = air temperature in degrees F.

For air at standard conditions (70°F, 29.92" Hg), the density factor will equal unity. The equation then becomes:

Equation 5: $$V = 4005\sqrt{VP}$$

Table 1 of Chapter 39 can be used in converting velocity pressures at standard conditions to velocities in fpm. A "rule of thumb" in making corrections for density is that they should be made when the altitude is greater than 1000 ft. above sea level, the temperature of the air in the system is ± 30°F from standard, and the moisture content equal to or greater than 0.02 lb./lb. of dry air.



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation Manual, 11th Edition. Lansing, Michigan, 1970.

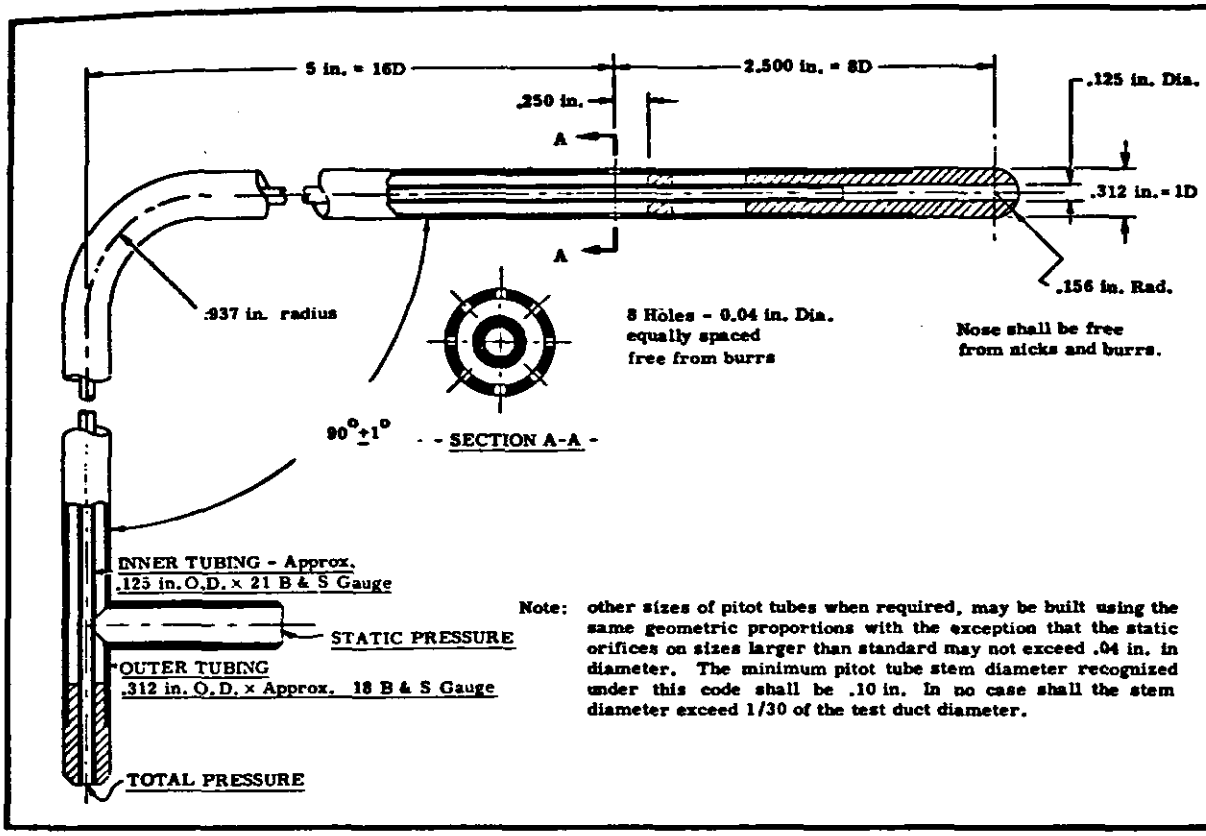
Figure 40-4. Relationship of Velocity Pressure to Static and Total Pressure for an Exhausting System.

Pitot Tube — Velocity Pressure

Equipment. The Pitot tube is the standard instrument for measuring the velocity of air in ducts. Figure 40-4 is a graphic representation showing the relationship of velocity pressure to static pressure and total pressure of an exhausting system.[4] The Pitot tube consists of two concentric tubes. The opening of the inner tube is axial to the flow and measures total pressure (A of Figure 40-4), while the larger tube with circumferential openings measures static pressure (B of Figure 40-4). The difference between the total pressure and static pressure is the velocity pressure (C of Figure 40-4).

Pitot tubes which are built to Air Moving and Conditioning Association[8] and ASHRAE[9] standards are considered primary standards and require no calibration. See Figure 40-5. Standard Pitot tubes fabricated from type 304 stainless steel are recommended because of their resistance to corrosion and use over wide temperature ranges up to 1000°F. Above this temperature, water-cooled Pitot tubes are required.

Pitot tubes are used to determine the velocity pressure contours inside of ducts. These measurements are obtained by connecting the static and total pressure taps to a manometer as shown in Figure 40-6. Inclined manometers (10:1) are normally used since they increase the accuracy and precision especially for velocities below 2000 fpm. A brief table appears in reference 4 which shows that the percent error using a carefully leveled



Air Moving & Conditioning Society: Standard 210. Arlington Heights, Illinois.

Figure 40-5. The Standard Pitot Tube. Note: Other sizes of Pitot tubes, when required, may be built using the same geometric proportions with the exception that the static orifices on sizes larger than standard may not exceed .04 in. in diameter. The minimum Pitot tube stem diameter recognized under this code shall be .10 in. In no case shall the stem diameter exceed 1/30 of the test duct diameter.

10:1 inclined manometer ranges from 0.25% at 4000 fpm to 4.0% at 1000 fpm, and up to 15% at 600 fpm. Thus, Pitot tubes used in the field are generally restricted to velocities above the 600-800 fpm range. Inclined manometers which read in fpm and inches of water are commercially available (Table 40-1). Conventional ranges are 400-12,600 fpm and 600-19,200 fpm. These manometers eliminate the need to convert VP to velocity as previously discussed.

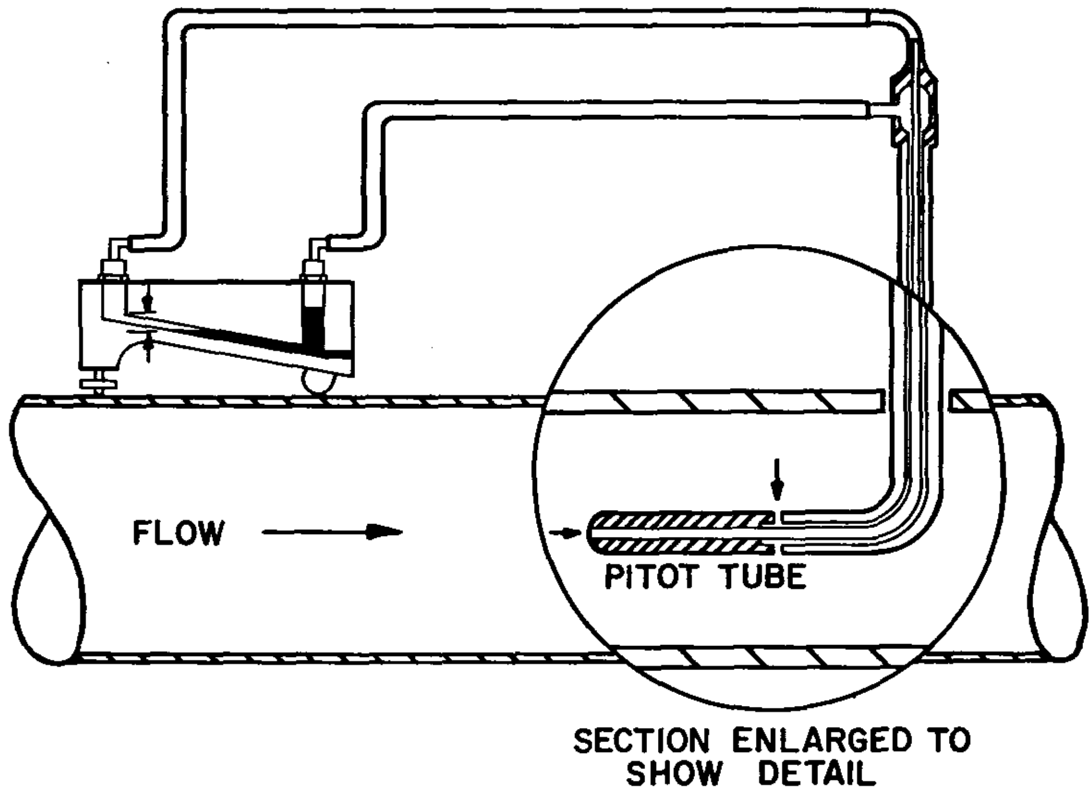
Pitot traverse. Aside from instrument error, the most significant requirement in making valid velocity or air flow measurements is the location selected for the measurements and the traverse of that location. The reason for these requirements is that air flow is not uniform in the cross section of a duct. This is especially true near such interferences as elbows, entries, etc. Therefore, for greatest accuracy, measurements should be taken at least 8.5 diameters of straight run downstream or 1.5 diameters upstream from interferences. Once the location is selected, a Pitot traverse can be conducted. Figure 40-7 shows a cutaway of both a round and rectangular duct, exemplifying the principle of measuring the VP of equal areas. Note that for round ducts it is advisable to traverse in two planes perpendicular to each other. The optimum number of measurements per plane for ducts of stated diameters is suggested below:

Duct Diameter, Inches	Number of Measurements
3-6	6
5-48	10
44 and greater	20

Reference 4 includes tables giving distances from the duct walls for the diameters stated above.

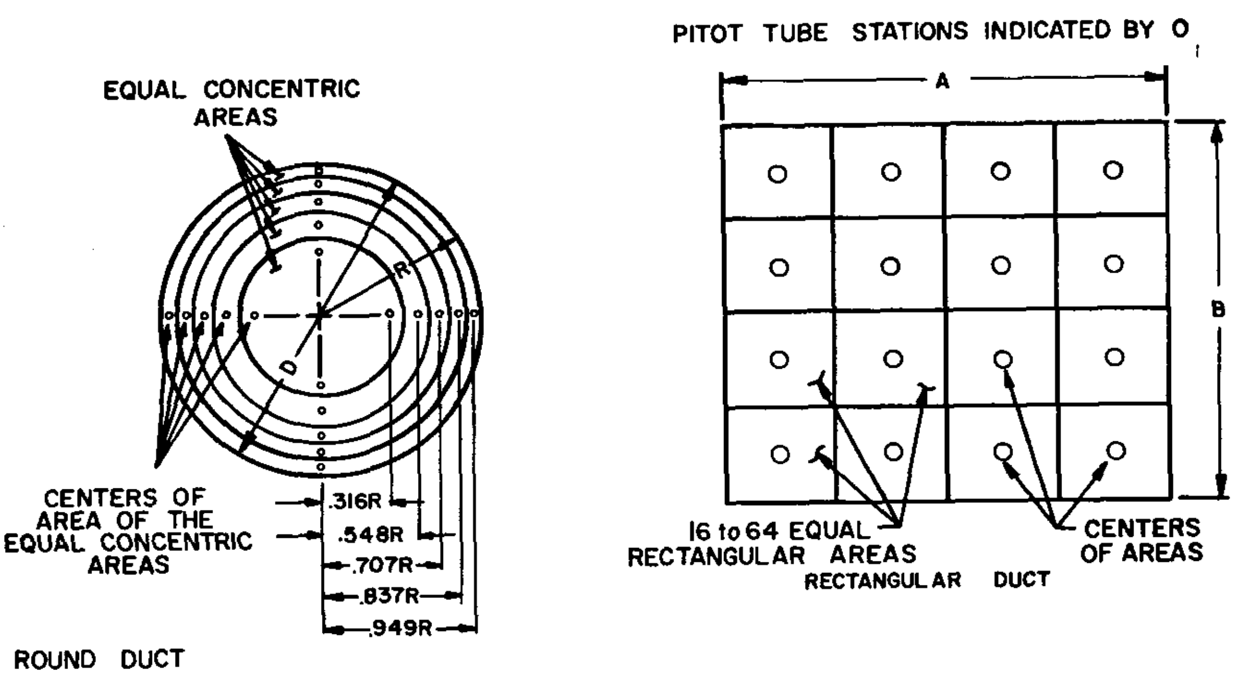
Like round ducts, rectangular ducts are traversed in terms of equal area segments. Rectangular ducts should be divided in a minimum of 16 to a maximum of 64 equal area rectangles with readings taken in the center of each rectangle as shown in Figure 40-7.

Once the readings as VP are taken and tabulated, the average velocity, in fpm, should be calculated. *Do not average the VP;* however the $\sqrt{VP}$ may be averaged and converted to velocity. From the velocity in fpm (V) and the area of the duct in ft² (A), flowrate (Q) can be calculated according to Equation 1.



Dwyer Instruments, Inc.: Bulletin No. H-100. Michigan City, Indiana, p. 3.

Figure 40-6. The Pitot Tube Connected to an Inclined Manometer.



Dwyer Instruments, Inc.: Bulletin No. H-100. Michigan City, Indiana, p. 3.

Figure 40-7. Traverse of a Round and Rectangular Duct Area.

In cases when accuracy is not a prime consideration, a single centerline reading can be taken at least 10 diameters of straight duct downstream from the nearest interference. This VP should be adjusted by multiplying by 0.81, or the velocity should be multiplied by 0.90.

When it is not possible to find undisturbed traverse locations 8.5 to 10 diameters downstream, alternate locations should be selected on the basis of a 5:1 ratio between downstream and upstream interferences. Depending on the situation and need for accuracy, multiple points for traverse can be selected and those points within 10% agreement averaged and used to determine velocity and air flow.

Limitations. There are fewer limitations for Pitot tubes than for other air velocity measuring devices. Whereas they can be used in corrosive or variable temperature conditions, the impact and static openings can become clogged with particulate matter. Also, as with the other instruments discussed, corrections should be made if the temperature is ± 30°F from standard, the altitude is greater than 1000 ft., and the moisture content is 0.02 lb./lb. or greater. They cannot be used to measure low velocities (less than 600 fpm) and require an inclined manometer which must be level and free from vibration. They are not applicable for use in small diameter ducts (less than 3 inches) or in orifice type openings.

Aneroid Gauges

The most common and best known of the aneroid gauges is the magnehelic gauge. Aneroid gauges can be used for total, static, and, in conjunction with a Pitot tube, velocity pressure measurements. They are small, extremely portable, and not as sensitive to vibration and leveling as liquid filled manometers. Since the inches of water pressure is a function of the location of an indicating needle on a dial, they are extremely easy to read. Magnehelic gauges are commercially available in ranges from 0 to 0.5″ WG. (500-2800 fpm) to 0 to 150″ WG. (2000-125,000 fpm) (Table 40-1).

The principal limitations are accuracy and calibration. Accuracy is usually below ± 2% full scale. Since they are mechanical, there is a need to calibrate these devices periodically.

Manometers

Manometers range from the simple U-tube to inclined manometers already mentioned. A range of sizes and varieties of U-tube manometers are available and they may be filled with a variety of media ranging from alcohol to mercury. Readings can be converted to inches of water simply by correcting for differences in density (e.g., 1 inch of mercury is equal to 13.61 inches of water).

When extreme accuracy is not essential or in high pressure systems, U-tube manometers will suffice. However, for accuracy and in low pressure systems, inclined manometers are required.

Static Pressure Measurements

Instrumentation and taps. Instruments used in measuring static pressure include the static leg of the pitot tube as well as any pressure measuring device connected to a hole in the side of a duct. U-tube manometers and Magnehelic gauges are quite acceptable. Whereas the exact location of the hole is not extremely critical, the type of hole is. Generally, the holes should not be located in points where there is some basis for turbulence or non-linear flow such as the heel of an elbow. Holes should be flush with the inside of the duct with no projections or burrs. Thus, holes should be drilled and not punched. The location of holes 90° apart will allow for the averaging of multiple readings to provide an improved estimate of static pressure.

Taps can range in complexity from a simple soft rubber hose held tightly against a 1/16 inch hole, to soldered pet cocks for use in high pressure applications.

Applications. Static pressure measurements at strategic points in a system provide invaluable information as to the performance. These measurements are neither difficult to obtain nor do they require expensive or delicate instrumentation.

Estimation of air flow by the throat suction method[6] provides a fairly accurate estimation of flowrate of an exhaust opening if the coefficient of entry can be determined. Coefficient of entries for various hoods are given on Figure 2 of Chapter 42. Measurements are made between one and three diameters of straight duct from the throat of the exhaust inlet (point where the hood is connected to the branch duct). It is advisable to take multiple readings 90° apart. The flowrate in cfm can then be determined according to equation 6:

Equation 6: $Q = 4005\ CeA\sqrt{SP_h}$

Where:
- Q = Rate of flow in cfm
- Ce = Ratio of actual flow to theoretical flow (Figure 2 of Chapter 42) (Entry loss in ″ WG)
- A = Cross-sectional area of duct in ft^2
- SP_h = Average static pressure reading in inches of water

Static pressure comparisons provide a means of either continuously or periodically monitoring the performance of a system. Additional information may be required, but strategically located static pressure taps can flag malfunctioning equipment, clogged ducts, dirty or broken filters, dented exhaust hoods, and changes in fan static pressure.

The permanent installation of manometers immediately downstream from exhaust hoods controlling a hazardous material or critical process is advisable, as is the placement of such devices across a filter to determine the need for shaking, cleaning, or maintenance.

Other Measuring Devices

There are a number of other devices for measuring fluid flow, but their application is restricted to either laboratory use or the calibration of air sampling devices. Some are discussed briefly below:

Orifice meter[7]. An orifice meter is simply a restriction in a pipe between two pressure taps. There are several types of orifice meters used, but the simplest and most common is the square edged orifice. If it is properly constructed, the orifice plate will be at right angles to the flow, and the surface will be carefully smoothed to remove burrs and other irregularities. Orifice meters are seldom used as permanent flow meters in ventilation systems because of their high permanent pressure loss. They are more typically used in the ventilation laboratory for calibration purposes. Permanent head loss will vary from 40 to 90 percent of the static pressure drop across the orifice as the ratio of orifice diameter to pipe diameter varies from 0.8 to 0.3. Detailed discussions of orifices and orifice equations can be found in reference 11.

Venturi meters[7]. A Venturi meter consists of a 25° contraction to a throat, and a 7° re-expansion to the original size. This differs from the orifice meter where the changes in cross section are abrupt. The advantage of the Venturi over the standard orifice is that the permanent reduction in static pressure is small, because the velocity head in the throat is largely reconverted to static pressure by the gradual enlargement. A well designed and constructed Venturi will have a permanent static pressure loss of only 0.1 to 0.2 inches of H_2O as compared to 0.4 to 0.9 for the orifice plate. Venturi meters are used in conjunction with a manometer as an in-line flow measuring device. A more detailed explanation of the Venturi is offered in reference 11.

CALIBRATION OF INSTRUMENTATION

All too often the need for calibration is not applied to devices for measuring air flow and velocity, yet as a group, with the exception of the Pitot tube, they require periodic calibration. Generally, air flow measuring instrumentation is based on electrical or mechanical systems which are sensitive to shock. In addition, use of these instruments in corrosive or dusty atmosphere affects their reliability.

A calibration wind tunnel as shown in Figure 40-8 represents the method of choice for calibrating the devices described in this section. Reference 12 is an excellent treatment of the design and use of the calibration wind tunnel. A well designed wind tunnel must have the following components[12]:

1. *A satisfactory test section.* Since this is the location of the probe or sensing element of the device being calibrated, the gas flow must be uniform, both perpendicular and axial to the plane of flow. Streamlined entries and straight runs of duct are essential to eliminate pronounced vena contracta and turbulence.
2. *A satisfactory means of precisely metering air flow.* A meter with adequate scale graduations to give readings of $\pm$ 1% is required. A Venturi or orifice meter represent optimum choices since they require only a single reading.
3. *A means of regulating air flow.* A wide range of flows are required. A suggested range is from 50 to 10,000 fpm. Therefore, the fan must have sufficient capacity to overcome the static pressure of the entire system at the maximum velocity required. A variable drive provides for a means of easily and precisely attaining a desired velocity.

Meters must be calibrated in a manner similar to how they are used in the field. Vane actuated devices should be set on a bracket inside a large test section with a streamlined entrance. Low velocity probe type devices may be tested through appropriate openings in the same type of tunnel. High velocity ranges of probe type devices and impact devices should be tested through appropriate openings in a circular duct at least 8.5 diameters downstream from any interference. Straighteners as shown in Figure 40-8 will reduce this requirement to 7 diameters.

NOTE: Devices must be calibrated at multiple velocities throughout their operating range.

AIR FLOW SYSTEM SURVEYS

System Start-up vs. Design Basis

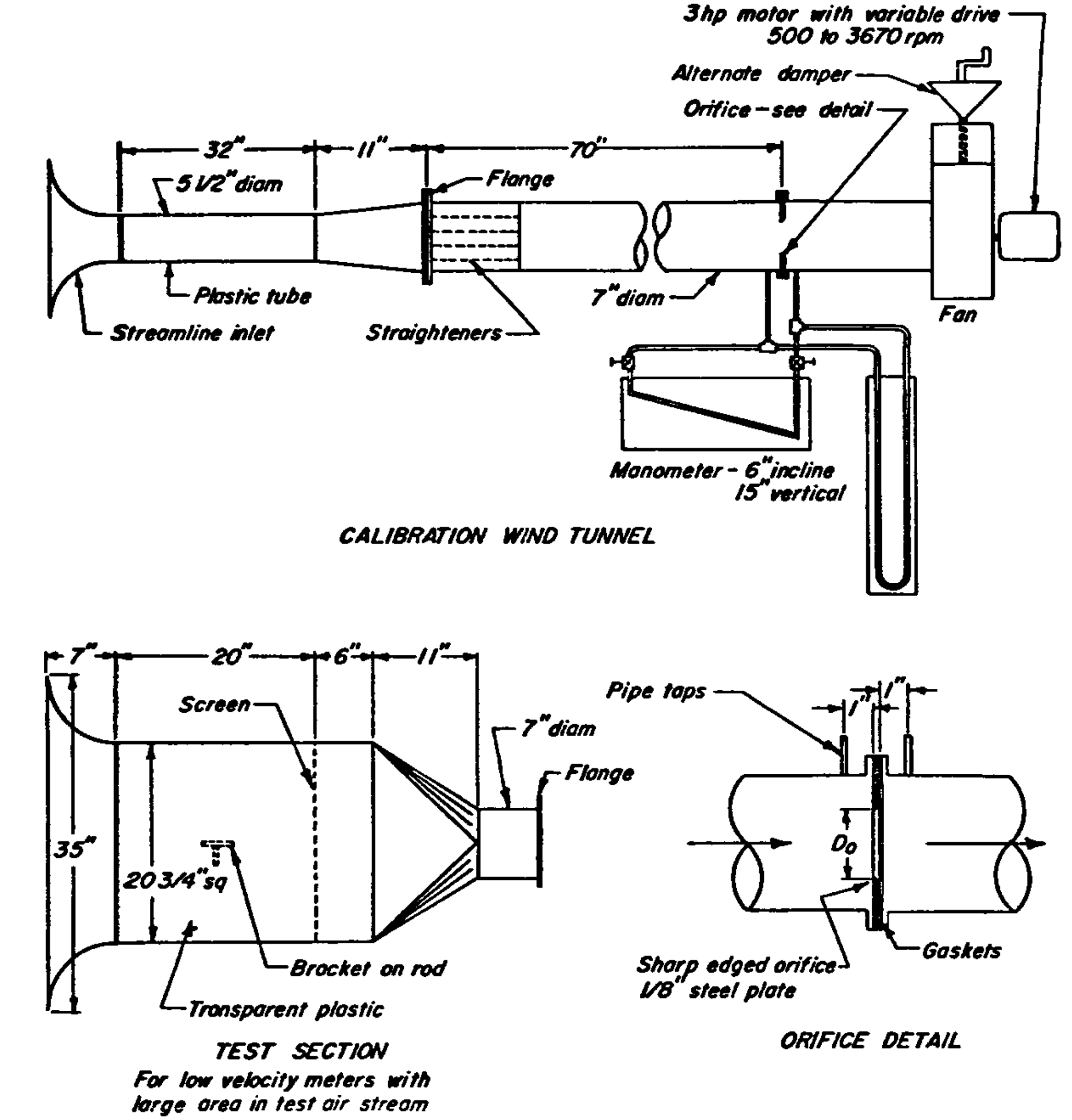
Any ventilation system, be it local exhaust for contaminant control or general for comfort, is designed in terms of removing or distributing a specified quantity of air at a specified velocity at a total system pressure which is the sum of the parts. An initial survey of the system is the only time a valid comparison can be made between the design basis and optimum system performance.

Sketch of the system. A sketch not necessarily to scale but representative of dimensions should be drawn noting such items as hoods, elbows, branchings, air cleaner, fan and stack. Supply ducts, plenums, and diffusers should be shown for general systems. Figure 40-1 and 40-2 represent gross simplifications of this concept.

The sketch should be considered as part of the permanent record on which future changes in the systems may be recorded.

Specific air flow measurements. Measurements in terms of air flow, velocity, and static pressure must be made to determine that the system is adequately balanced and performing according to the design basis. These measurements include:

1. Static pressure measurements at:
   a) hoods
   b) up and downstream of the air cleaner
   c) up and downstream of the fan
2. Air flow in cfm at:
   a) hoods (throat suction method)
   b) branches and mains (Pitot tube)
   c) up and downstream of fan (Pitot tube)
3. Supply, capture, and conveying velocities at:
   a) diffuser outlets (supply velocity)
   b) face or opening of hood (capture velocity)
   c) branches and mains (conveying velocity)
4. Fan performance
   a) fan speed in rpm
   b) horsepower (BHP) calculated using cfm (Q), total pressure (TP), and mechanical efficiency (ME) of fan.



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation Manual, 11th Edition. Lansing, Michigan, 1970.

Figure 40-8. The Calibration Wind Tunnel.

Equation 7: $$BHP = \frac{(Q)\ (TP)}{6356 \times ME}$$

The locations of the measurements must be identified on the sketch and a record kept for future comparisons. A sample form can be found in reference 4.

The measurements obtained should agree within 10% of the design basis. If not, system modification should be made until such agreement is obtained.

Other Checks. Local exhaust systems are installed for the singular purpose of removing some contaminant from the work environment. Visualization techniques using smoke tubes or candles can be most helpful in verifying the system exerts a sphere of control over a sufficient area to prevent excessive exposures to operating personnel. Air evaluation for specific contaminants is also recommended to verify the system will control contaminants to levels known to be safe. Air samples taken in the breathing zone of operating personnel will be most helpful in assessing the adequacy of contaminant control.

As with the previous measurements, photographic records of smoke tests and the results of air evaluation tests should be maintained for future reference.

System Operation vs. System Start-up

Once systems are started up and determined to perform satisfactorily, the degree of evaluation *can be reduced as long as good records of start-up or initial conditions have been made.* Experience with air flow systems clearly indicates periodic surveys are required to assure system performance is adequate. Operating personnel cannot be relied upon as an "indicator" of system performance. Also, ventilation systems are rarely an integral part of the operation in terms of quality and production, and all too often receive inadequate maintenance.

For most systems simple velocity measurements at exhaust hoods and supply ducts will provide a crude indication of system performance when compared with start-up evaluations. For local exhaust systems, the throat suction method applied to exhaust hoods and static pressure differentials for air cleaners and fans will suffice in confirming the system is performing satisfactorily.

The throat suction method will provide valid information unless:

1. The hood entry has been modified/damaged;
2. There are obstructions ahead of the point of measurement; or
3. The system has been modified.

However, a reduction in throat suction can provide valuable information, such as an indication that there has been:

1. Accumulations of material in an elbow, branch, or main, thus clogging or restricting air flow. Build-up in the elbows result from impaction, while build-ups in straight runs result from insufficient conveying velocity or overloading the system.
2. A change in blast gate setting if the system is balanced using blast gates.
3. Additional branches and hoods added to the system. "Adding on" to a system is a real temptation. It is not sound economics when it renders the entire system deficient.
4. Excessive build-up on the filter. It is best to monitor filter build-up by attaching a static pressure measuring device across the filter.
5. Reduced fan output resulting from belt slippage, damaged or worn rotor, or build-up on the fan blades.

Data Handling and Recording

The sketch of the system made at start-up or for the initial air evaluation survey and the results of the ensuing air flow survey must be recorded and filed in such a manner that future air flow surveys can be conducted in a similar manner. The periodicity of air flow surveys can only be determined by such conditions as:

1. Nature of the materials being controlled. The more hazardous the materials, the more frequently the system should be checked.
2. Nature of the system. A blast gate system will require more frequent checks than other systems.
3. The degree of maintenance. Air flow surveys can be used to indicate the need for more frequent and improved maintenance.

Reference 4 provides a sample of a diagram, check list and additional information regarding checking and testing systems.

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12. HAMA, G. "A Calibration Wind Tunnel for Air Measuring Instruments." *Air Engineering*, 9:18, Detroit, Michigan, 1967.

Preferred Reading

In addition to References 2, 4, 6, 9, 10, 11, and 12, the following represent selected sources which can contribute to the reader's knowledge of the subject title.

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