Chapter 3

This chapter will take approximately 2.5 hours to complete.

OBJECTIVES

Terminal Learning Objective

At the end of this chapter, the student will be able to identify, classify, and determine appropriate use of air measuring instruments.

Enabling Learning Objectives

3.1 Describe the relationship of air movers to other sampling system components and its classification.
3.2 Identify air mover selection criteria.
3.3 Define and classify pumps.
3.4 Describe the operation principle and driving force of ejectors.
3.5 Describe the principle of operation and sampling procedures of liquid displacers.
3.6 Describe the principle of operation and sampling procedures of air displacers.
3.7 Identify flow rate control.
3.8 Identify flow rate for sampling.
3.9 Identify air measuring instruments.
3.10 Identify the seven volume meters that are commonly used in air sampling and analysis.
3.11 Describe rate meters.
3.12 Identify and describe velocity meters and their standard procedures.
3.13 View sample problems.
3.14 Describe $PM_{2.5}$ flowmeters and devices.

Air Measuring Instruments

The ultimate goal of atmospheric sampling is to extract a sample, representative of a constituent of interest (pollutant) present in the environment, to determine its concentration. In order to determine a pollutant concentration, the mass of the pollutant and the volume of air sampled must be known.

The discussion in Chapter 3 is divided into two major sections: air movers and air measuring devices. Air movers are responsible for drawing the sample gas through the sampling train. Air measuring devices provide an accurate measure of the rate of gas flow (e.g., liters per minute, cubic feet per hour) or volume (e.g., liters, cubic feet) over a measured time period (e.g., minutes, hours) through the sampling train. The volume of air sampled, measured directly or indirectly, and the mass of pollutant collected (discussed in Chapters 4 and 5) are used to determine the concentration of the pollutant.

3.1 Introduction to Air Movers

The primary purpose of an air mover in the sampling process is to create a flow of air that will allow the contaminant in the air to be analyzed directly or to be captured by a collection device for subsequent analysis. Air movers include pumps, ejectors, and liquid and air displacement devices. Collection devices include filters, adsorbers, impingers, and impactors. Air movers range in capacity from a few cubic centimeters per minute (cm^3/min) of air up to tens of cubic meters per minute (m^3/min). In operational complexity, air movers range from a squeeze bulb to a multistage pump. Regardless of the type of air mover selected, they all move air through the sampling train by creating a pressure differential in the system. Air moves in a closed system, such as a sampling train or in the ambient air, only if there is a change in pressure from one location to another.

Relationship of Air Movers to Other Sampling System Components

Air movers are vital components of sampling trains used for the sampling and analysis of air for its pollutant content (see Figure 3-1). Several of the considerations governing the selection of an air mover for a particular application will be mentioned in this discussion.

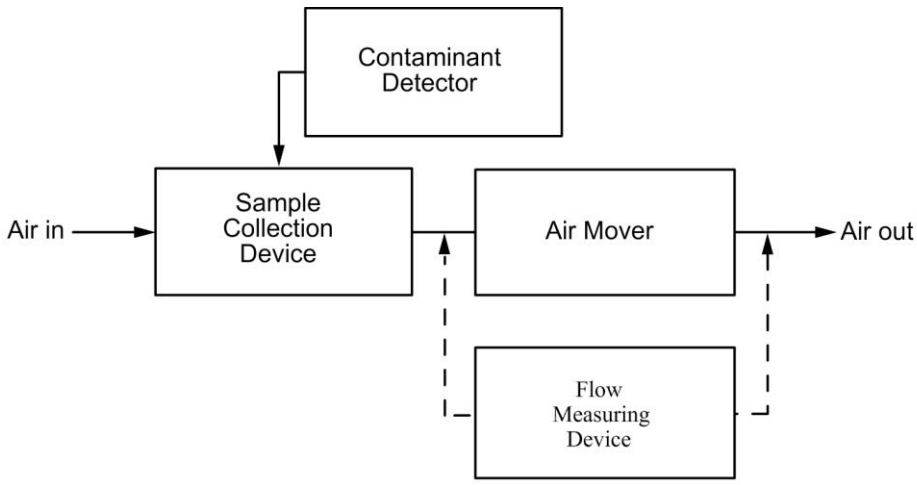

Figure 3-1. A sampling train.

Air Mover Classification

There are many parameters by which air movers can be evaluated and classified. Classification of air movers can be made according to their function, capacity, "driving" force, and principle of operation, among other parameters. The classification scheme often depends to a great extent on the classifier. The actual types of air movers to be discussed in this text are *pumps, ejectors, liquid displacers,* and *air displacers*.

3.2 Air Mover Selection Criteria

Since there is no one "typical" air sampling train, equipment selection is an important aspect of any airborne sampling scheme, meaning that air mover selection must be made along with the selection of other sampling train components. Here are some of the many factors to be considered before selection is discussed. The itemizing of the considerations is not necessarily in order of their importance.

Pollutant Concentration and Sampling Time

The required flow rate of the air mover is often determined by the sensitivity of the analysis method, which in turn sets the minimum quantity of the contaminant required for analysis. For example, if the analysis procedure required 10 μg of material to obtain the desired precision, and if the air contains 1 $\mu g/m^3$ of that material, a sample size of 10 m^3 would be required, assuming 100% collection efficiency. The required flow rate of the air mover can be calculated by determining the available sampling time and the sample volume required. For example, if the above-mentioned 10 m^3 of air had to be moved (sampled) in a period of 10 hours, an air mover of 1 m^3/hr capacity could be used. In many instances it is more feasible to sample for longer periods of time,

and sometimes at higher rates, than those required. As long as the sample size is greater than the minimum detectable and less than the concentration that theoretically saturates the collection medium, this may be of no consequence.

When whole air sampling is conducted, such as sampling into an inert bag or evacuated canister, the sampling flow rate determines the degree to which the sample represents the true concentration on a temporal basis. Therefore, it is important to understand the temporal variations associated with the constituent being sampled and to adjust the sampling time accordingly. These days, "whole air" sampling is often conducted in conjunction with sampling for air toxics.

Sampling Rate Required

In some instances it may be necessary to sample at some required flow rate to ensure efficient sample collection. An example is the collection of a sample by using a chemical reaction. The reaction kinetics may depend on the length of time the contaminant is in the presence of the reacting substance, and the length of contact time is dependent on the sampling rate. Another example would be the collection of particulate matter by using an impinger or impactor. For example, collection of a sample at a low flow rate should increase the time that the air is in contact with the reagent and may also decrease the size of the bubbles, thus increasing the surface area of air in contact with the reagent. The particle size collected will be dependent on the approach velocities, and these in turn are dependent on the sampling rates.

Physical and Chemical Nature of Air to be Sampled

The operation of the air mover selected must be compatible with the physical and chemical characteristics of the air and contaminant to be sampled. Air of a corrosive or abrasive nature can create problems with the air mover unless the internal parts are nonreactive with the sample air.

In instances where sampling is to be done in a potentially explosive environment, approved explosion-proof air movers or explosion-sealed air movers should be selected. A completely sealed electric motor for a pump, in conjunction with non-sparking metal parts, is an example of an explosion-sealed air mover.

Portability of Air Mover

Air sampling is often performed at temporary sampling sites. When sampling trains must be moved from location to location, it is important that each component be as portable and lightweight as possible. At permanent sampling locations, air mover portability is not such an important consideration.

The power source for the air mover may be the limiting factor in its portability, especially when the power source must be AC line voltage.

Air Mover Noise

Since air sampling may be required in areas having noise restrictions, the noise produced by an air mover must be considered. Also, the suppression of air mover noise has aesthetic value. Noise levels may be considered in relation to the length of the sampling period; that is, for short periods high noise levels *may* be

acceptable. Many commercially available air movers have special sound-adsorbing liners, vibration-reducing cushioning material, or mufflers as noise-reducing components of the mover itself.

Air Mover Maintenance

Manmade equipment, whether air sampler components or computers, will not be maintenance-free. Maintenance considerations are of special importance for equipment to be used in the field, because valuable time can be lost in transit between the repair shop and the sampling location. There are three particular points to consider about air mover maintenance: (1) air mover parts that might need repairing should be easily accessible; (2) the complete repair should not be very time consuming; and (3) air mover parts should not be overly expensive. In general, increasing preventive maintenance activities decreases air mover malfunctions.

Resistance

Flow resistance considerations may dictate the selection of an air mover of a particular type (see Figure 3-2). The sample collection device will offer some resistance to the flow of air through it; therefore, the air mover must be able to overcome this resistance for efficient sample collection.

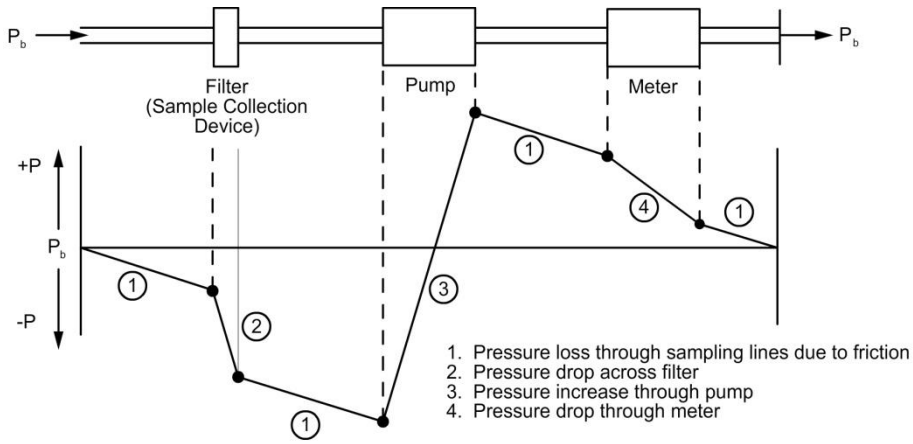

Figure 3-2. Pressure profile for basic sampling apparatus.

Constant Flow Rate

It is often desirable to collect a sample at a constant flow rate. Variation in sample conditions or other external influences can make this difficult. For example, the resistance of a filter can be expected to increase with sample "buildup," thereby decreasing the flow rate through the sample apparatus. Poor voltage regulation can result in variable motor speeds, leading to variable sampling rates. However, some commercially available air movers feature constant flow rates despite varying sampling conditions; others require flow regulation devices in order to have constant flow rates. Some flow regulation mechanisms will be discussed later in the chapter. Another factor of importance

in some applications is the ability to vary the flow rate of the air mover and then to maintain constancy at the selected rate. This topic will also be discussed in more detail later.

3.3 Pumps

Definition and Classification

Pumps have been defined as devices that raise or transfer fluids. Since air is a fluid, a pump that moves air either raises it to another level or transfers it to another location. In air sample collection, the air is transferred from one location through, or into, a sample collection device.

Classification of pumps is a difficult task because of the many variables. This section will discuss pumps in terms of two broad classes based on flow variation with pressure. These two major classes will be subdivided into categories according to specific principles of operation: (a) *positive displacement pumps* and (b) *centrifugal pumps*.

Positive Displacement Pumps

Positive displacement pumps are often characterized by a linear relationship between the suction pressure and pump capacity (see Figure 3-3). This indicates that $\Delta Q/\Delta p$ (ΔQ is the change in flow rate; Δ p is the pressure drop across the pump) is a constant value. Figures 3-3 and 3-5 are representative of characteristic curves of pumps to be discussed later.

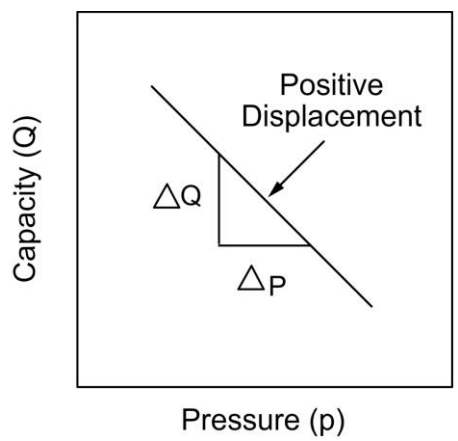

Figure 3-3. Positive displacement pump.

The name "positive displacement" arises from the fact that the inner parts of these pumps are movable and tight-fitting, and the air is displaced through them by the movement (displacement) of these tight parts. Figure 3-4 indicates a further subdivision of positive displacement pumps, this division being made according to the principle of operation. Reciprocating pumps are characterized by fixed casings containing movable pistons that work only forward-and-backward or up-and-down and by the pressure of suction and discharge valves.

Principle Operation	Type of Pump
Reciprocating	Piston Plunger Diaphragm
Rotary (not discussed in this manual)	Gear Lobe Vane Screw Rotary Plunger

Figure 3-4. Classification of positive displacement pumps.

Piston Pump (Reciprocating)

In a piston pump, air is drawn into a chamber or grinder on the suction stroke of a piston and is then pushed out on the discharge stroke, as illustrated in Figure 3-5. On the suction stroke, the suction valve is open, allowing air to flow in; on the discharge stroke, the suction valve closes and the discharge valve opens, allowing air to flow out. An internal combustion engine is an example of a piston pump. Piston pumps vary in complexity of operation from manually operated ones to models with many working parts.

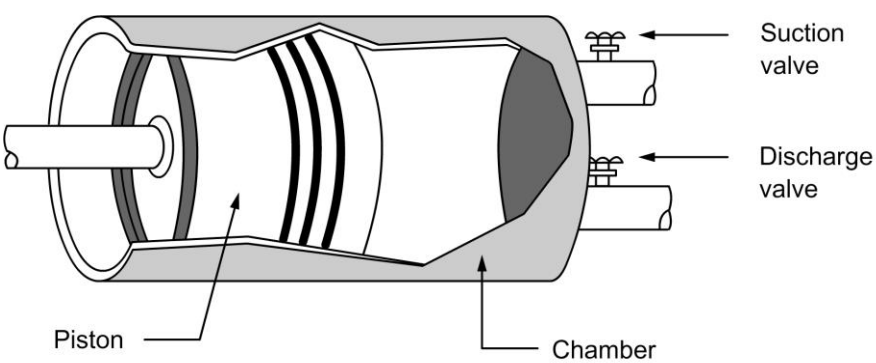

Figure 3-5. Piston pump.

Diaphragm Pumps (Reciprocating)

In principle, the operation of a diaphragm pump is very similar to a piston pump. The piston (plunger) in a diaphragm pump does not move in a tightly fitted chamber as in the piston pump, but is attached to the center of a circular diaphragm, the outer edge of which is bolted to a flange on the pump casing. The diaphragm may be made of metal or some soft material such as Teflon® or neoprene. The most important characteristics of the diaphragm material are its flexibility and resistance to reaction with the air being moved. The up-and-down motion of the plunger is permitted by diaphragm flexibility without the rubbing of one part on another (see Figure 3-6). On upward movement of the plunger, air flows into the pump through a suction valve. Downward movement of the plunger closes the suction valve and the air is forced through a discharge valve, perhaps located in the plunger itself. An automobile fuel pump is an example of a diaphragm pump.

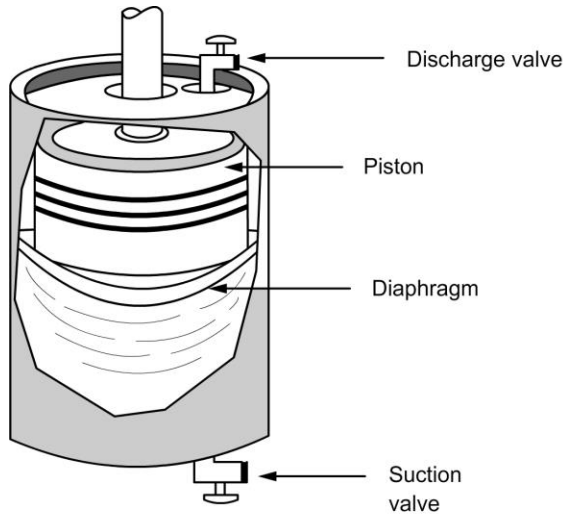

Figure 3-6. Diaphragm pump.

Centrifugal Pumps

Centrifugal pumps are representative of pumps other than positive displacement pumps. Centrifugal pumps do not have a straight line relationship between suction pressure and capacity; thus, $\Delta Q/\Delta p$ is not constant (see Figure 3-7).

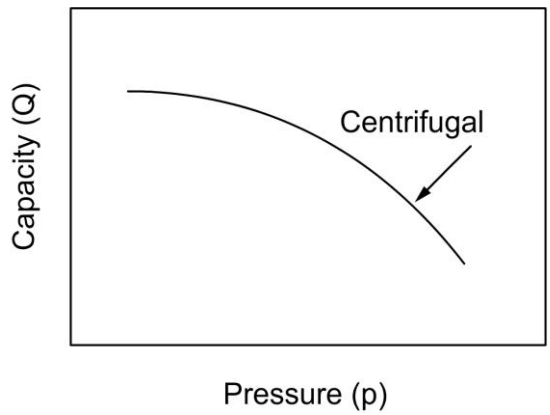

Figure 3-7. Centrifugal pump.

A centrifugal pump moves fluids by a centrifugal force created by a wheel, called an impeller, revolving in a tight casing. Some additional examples of pumps other than positive displacement pumps are: (a) turbine pumps, (b) propeller pumps, and (c) screw drag pumps. Each of these exhibits the same general pressure-capacity relationship as the centrifugal pump.

Centrifugal pumps (or fans) employ centrifugal force to move air. The simplest form of this type of pump consists of an impeller routing in a volute ("snail's shell") casing (see Figure 3-8). The rotation of the impeller creates a decreasing pressure at the impeller "eye," causing air to be drawn into the pump. Air drawn into the center of the impeller is "picked up" by the vanes and accelerated to a high velocity by rotation of the impeller. It is then discharged by centrifugal force into the casing and out the discharge nozzle.

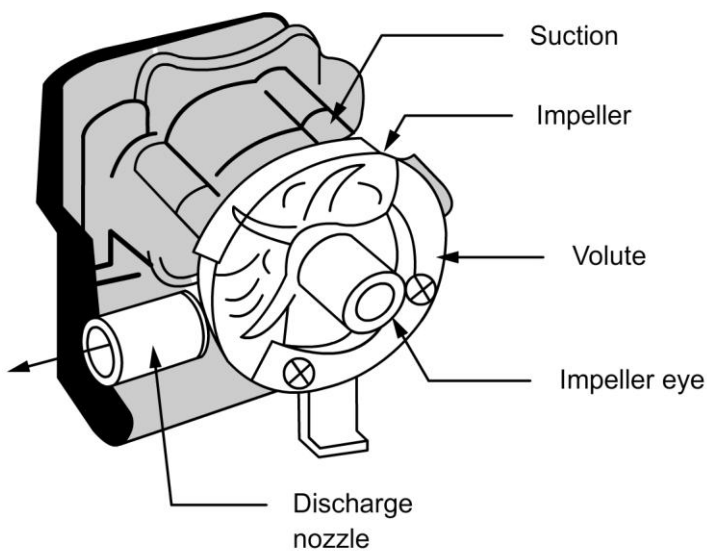

Figure 3-8. Centrifugal pump operation.

Centrifugal pumps encountered in air sampling can be divided primarily into three categories: (a) radial flow, (b) axial flow, and (c) mixed flow. Centrifugal pumps may also be classified into single-stage or multistage. Single-stage indicates a pump in which the total head is developed by one impeller; multistage indicates a pump having two or more impellers acting in series in one casing.

"Driving Forces" for Pumps

All pumps have at least one common characteristic - they have movable parts. The movement of the parts is the basis for the transfer of the particular fluid of interest. For the parts to move there must be a "driving force." Driving forces for pumps can be categorized as: (a) manual and (b) motors.

Some air movers in the general category of pumps can be operated manually. A hand-operated hypodermic syringe (piston pump), a hand-cranked pump (e.g., Drager Pump, MSA Midget Impinger Sampler), and a tire pump using a foot pedal are examples. These types of air movers are rarely used today. Electric motors operated by commercial power, motor-generation sets, or batteries are all used for driving air sampling pumps. When using batteries as the driving force, several factors should be considered, such as the motor power requirements and the required length of sampling. The length of the sample time is important in relation to the life of the battery.

In instances where constant flow is required, it is important that the driving force for the pump is constant and not be affected by environmental factors. If the driving force is variable, measures may have to be taken to try to regulate it. For example, a voltage regulator may be required in conjunction with an electric motor that is driving an air pump where variable voltage power sources are encountered.

Characteristic Curves

Pumps perform differently under different conditions; therefore, "characteristic curves," showing the relationships between the various conditions affecting their performance, are usually supplied by the manufacturer. The characteristic curves of most interest in air sampling are those indicating the pressure-flow relationship (see Figures 3-9 and 3-10).

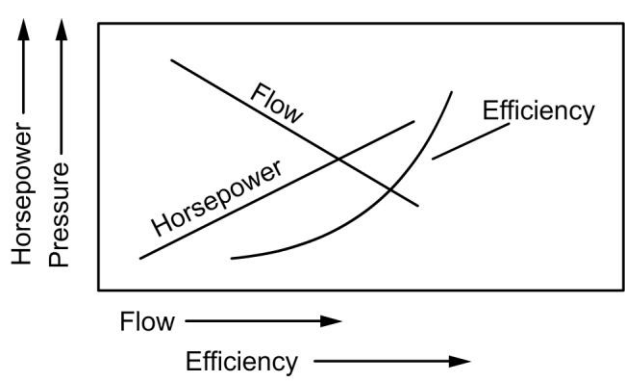

Figure 3-9. Characteristic curve for a positive displacement pump.

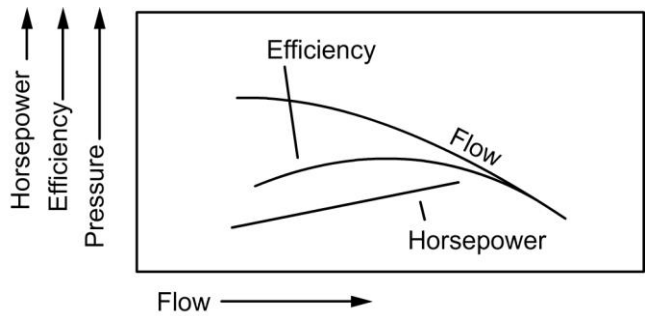

Figure 3-10. Characteristic curve for a centrifugal pump.

The quantity of flow is usually expressed in terms of a flow rate - e.g., cubic feet per minute (cfm), liters per minute (lpm), and cubic feet per hour (cfh). The pressure represents the amount of suction that must be available to overcome the resistance of the air to movement through the sampling train. Pressure can be expressed in pounds per square inch gauge (psig) or in inches of an equivalent height of a fluid. The suction pressure at which a pump is required to operate is often referred to as its head. The total head is equal to the total pressure drop between intake of the sample collection device and the pump intake. Other parameters such as efficiency, horsepower, and speed are indicated in the characteristic curves for certain pumps. Empirical equations relating various parameters are also available. It should be noted from Figures 3-9 and 3-10 that different types of pumps possess different characteristics. As flow increases for a rotary pump, the efficiency increases; as flow increases for a centrifugal pump, the efficiency increases and then decreases.

Selecting a Pump

When choosing a pump, the sampling rate required may limit the selection to certain categories of air movers. On the other hand, if flow rate is not critical, the wide variety of air movers available may require a more involved evaluation. A comparison of some of the advantages and disadvantages of certain types of pumps is found in Figure 3-11.

Pump type	Advantages	Disadvantages
Piston pump (reciprocating)	1. Can operate at high suction pressure 2. Can be metered	1. Small capacity 2. Seal required between piston & piston chamber 3. Working parts such as check valves and piston rings may cause difficulties 4. Pulsating flow 5. Moderate maintenance
Diaphragm pump (reciprocating)	1. Wide range of capacities 2. No seal required 3. Good in continuous operation	1. Limited materials of construction 2. Operation at limited suction pressures 3. Pulsating flow 4. Periodic diaphragm replacement 5. Moderate maintenance
Centrifugal pump	1. Large range of capacities 2. No close clearance 3. Can obtain high suction heads by multistages 4. Light maintenance	1. No small capacities 2. Turbulence 3. Operational noise

Figure 3-11. Pump comparison.

Many features of commercially available pumps may or may not warrant consideration. Some features may have direct applicability for certain uses; others may provide flexibility, making the pumps more generally usable. In this discussion, only gauges and continuous operation capability will be considered.

Pump Gauges

Many pumps have inlet vacuum gauges and/or outlet pressure gauges. These gauges, upon proper calibration, can be used to determine the approximate flow rate through the pump. The flow rate can be determined by use of the pump's characteristic curve for the pressure-flow relationship (see Figure 3-12), or by direct reading if the gauge is calibrated in terms of cfm on its dial.

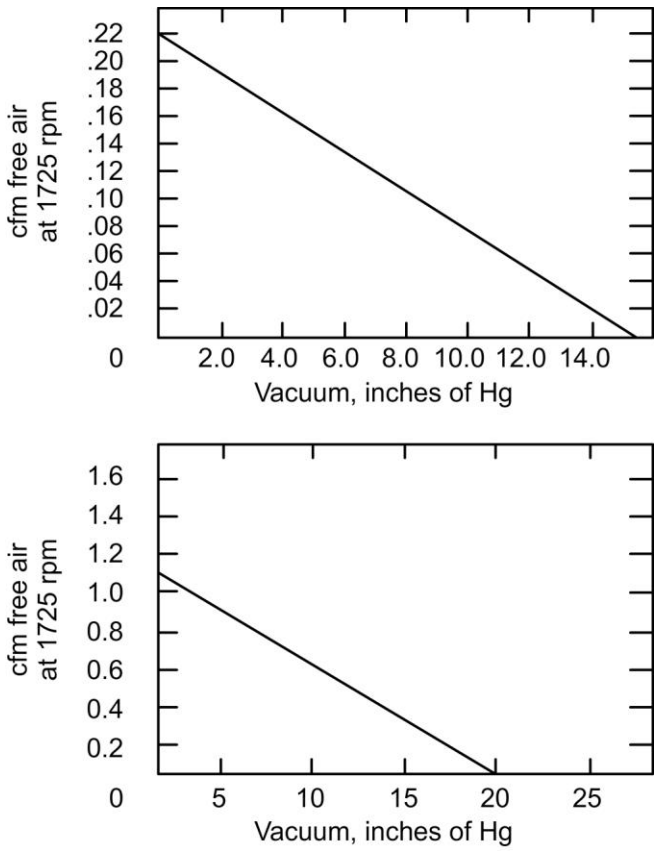

Figure 3-12. Pressure-flow relationship for metal bellows pumps for vacuum (continuous operation capability).

Pumps are often required to operate continuously for long periods of time (hours to days) at high vacuum. Some pumps such as rotary or diaphragm pumps used in ambient air monitors are capable of continuous operation at high vacuum, while others would tend to "burn" themselves out. The importance of this capability would be dependent on the sampling time required.

3.4 Ejectors

Principle of Operation

Another classification of air movers is the ejector, also known as an aspirator. As depicted in Figure 3-13, ejectors operate according to the jet principle. At the nozzle, the pressure head of the driving force is converted into a high velocity stream. The passage of the high velocity stream through the suction chamber creates a decreased pressure (vacuum), thus drawing air into the chamber itself. The incoming air is mixed with the high velocity driving force mixture and can be ejected against moderate pressure through the diffuser.

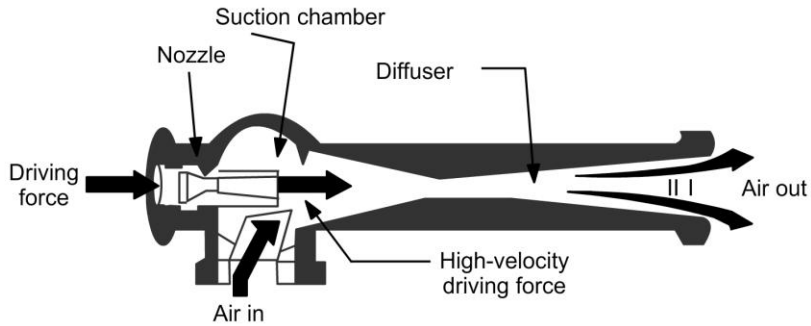

Figure 3-13. Ejector operation.

Driving Forces

The pressurized fluid that is converted into a high velocity jet stream in an ejector may be of several types. Some examples of fluids used are water, steam, compressed air or CO_2, and other gases such as Freon. Freon is no longer used since it has been classified as an ozone-depleting substance.

Sampling Use of Ejectors

Using ejectors as samplers, air moved is adequate for lower sampling rates. The sampling rates vary from a few liters per minute up to several cubic feet per minute. The flow rate through an ejector can be regulated to some extent by adjusting the nozzle opening. One limitation of using ejectors is that the pressurized driving force may have a time limit on its available effectiveness (i.e., if a pressurized gas cylinder is used, it may last only for a limited amount of time).

3.5 Liquid Displacers

Principle of Operation

Air movers that operate according to the principle of liquid displacement incorporate two sampling train components into one entity. In this case, the liquid displacement unit serves as both the sample collection device and the air move, or it may provide the air-moving capability for a second device which may act as the sample collection device.

Gravity flow of liquid from a container creates a vacuum within the container, thus drawing air into the container to fill the displaced volume (see Figure 3-14).

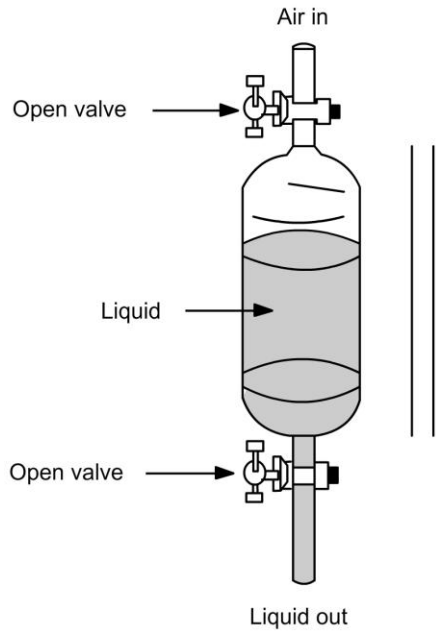

Figure 3-14. Liquid displacement.

Sampling by Use of Liquid Displacement

Liquid displacement is usually used only for grab sampling. The sample volume capacity is limited to the size of the liquid container. Some examples of liquids used are water, mercury (Hg), and organic solvents. These devices are generally no longer used as air sampling devices; however, they are used to calibrate volume air measuring devices, such as wet test meters. This technique is discussed in detail later in this chapter. In addition, students will calibrate a wet test meter using liquid displacement during the laboratory exercise portion of this course.

3.6 Air Displacers

Air displacement operates by the simple displacement of air or the creation of a vacuum in a closed container. Evacuated flasks and "plastic" bags are examples of air displacers.

Evacuated Flasks: Principle of Operation

A flask is evacuated by a vacuum pump to a very low pressure that must be determined. The flask is sealed and transported to the sampling location. When a valve is opened on the flask, the surrounding air moves into the flask because of the pressure differential. On closing the valve, the sample is confined for subsequent analysis. The rate at which sample air is permitted to enter the evacuated flask may be varied and is often prescribed by a sampling method designated for a particular constituent or classification of constitutents.

Sampling by Use of Evacuated Flasks

Evacuated flasks are usually used only for grab sampling; consequently, only relatively small sample volumes can be collected. Grab sampling is discussed in detail in Chapter 5.

Sampling methods for air toxics, such as TO-14A for the determination of volatile organic compounds (VOCs), specify the use of polished stainless steel canisters evacuated to a pressure less than 0.05 mm Hg, on an absolute basis. These canisters are often referred to as Summa canisters due to the "Summa" process used to passivate the internal surface to make it chemically inert. A Summa surface has the appearance of a mirror, bright and shiny. Summa canisters typically range in volume from 1 liter to 15 liters. Six-liter canisters are generally used for ambient air samples and for collecting samples over time.

The sample enters a canister through a high-temperature stainless steel bellows valve. A Summa canister will hold a high vacuum (>28" Hg) for up to 30 days. Beyond 30 days, low level concentrations of typical VOCs may be present, resulting in erroneous ambient air data.

Careful consideration should also be given to the possibility of flask "implosion" when glass containers are used, and appropriate protective means should be undertaken. However, glass flasks are seldom used today.

"Plastic" Bags: Principle of Operation

Air moving by use of a "plastic" bag (i.e., Tedlar, Mylar, Teflon, aluminized PVC) is another example of an air displacer. Since a plastic bag is non-rigid by design, either it is mounted within a rigid, airtight outer container and filled by creating a slight vacuum in the space around the bag, or, if there is no rigid outside container, air is pumped directly into the plastic bag. To be precise, the plastic bag is not responsible for the movement of the sample air flow as is the case with an evacuated flask; it merely serves as a collection device to hold the sample gas for subsequent analysis.

Sampling by Use of "Plastic" Bags

Plastic bags are usually used only for grab sampling; consequently, only relatively small sample volumes can be collected. Grab sampling with the use of a plastic bag is discussed in detail in Chapter 5.

3.7 Flow Rate Control

Control by Diversion

The principle of flow diversion is simply that the air moved by the air mover is not all passed through the sample collection device. As depicted in Figure 3-15, a "bleed" valve control, typically integral to the air mover (pump), allows the variation of the actual flow through the sample collection device. The position of the flow measuring device is such that it measures only the flow passing through the sample collection device.

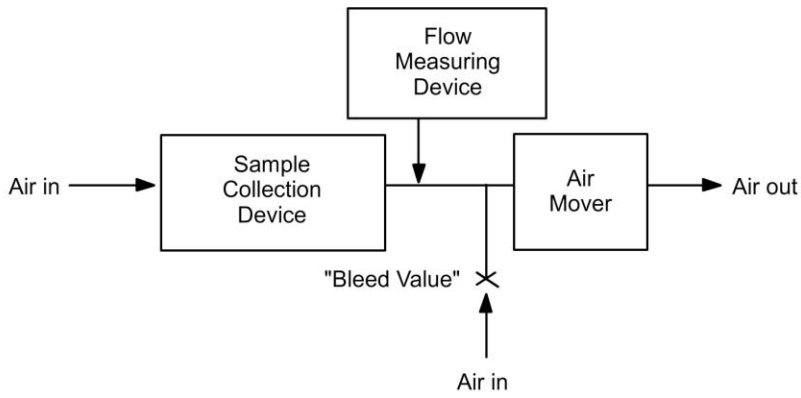

Figure 3-15. Flow rate control by diversion.

Resistance Control

In most air-moving devices, the flow rate decreases as the resistance it must overcome increases. Examples of this are depicted in Figures 3-9 and 3-10, which show sample characteristic curves for several pumps. The flow rate of the air mover can, therefore, be regulated by controlling the resistance it must overcome. A common method of control is to partially close a valve in the intake line, thus creating a greater resistance. Reproducible flow control can be accomplished by using needle valves with resettable marking.

Driving Force Control

It may be possible to control the air mover driving force, thereby controlling the rate of air flow. Adjustment of the nozzle opening on an ejector can be considered a driving force control because it affects the velocity of the pressurized gas stream. The velocity of the gas stream, in turn, affects the suction pressure.

Another example of driving force control is electric motor speed regulation. This can be accomplished on some pump motors by use of a variable transformer, which controls the amount of power sent to the motor. These variable transformers are known by several names, such as variacs and powerstats.

3.8 Flow Rate for Sampling

After a particular flow rate has been selected for sampling, and after it has been set for the sampling train, it is usually necessary to maintain the flow at exactly that rate.

Need for Control

A variation of the desired flow rate can be caused by a variation in the air mover driving force or a variation in the resistance to air flow. The resistance to air flow is equivalent to the suction head the pump must overcome. Some sampling conditions affecting flow variation have been mentioned above. Flow variation

during sampling may affect more than the determination of the volume of air sampled; it may also affect the performance of the sample collection device. For example, the absorption rate of a bubbler may be altered by a variation of the flow rate through it.

Control Mechanisms

Many flow rate control mechanisms operate by keeping at a constant value the effective resistance that the pump must overcome. In other words, as depicted in Figure 3-16, the pressure drop (Δp) from the environment being sampled to the pump intake is held constant.

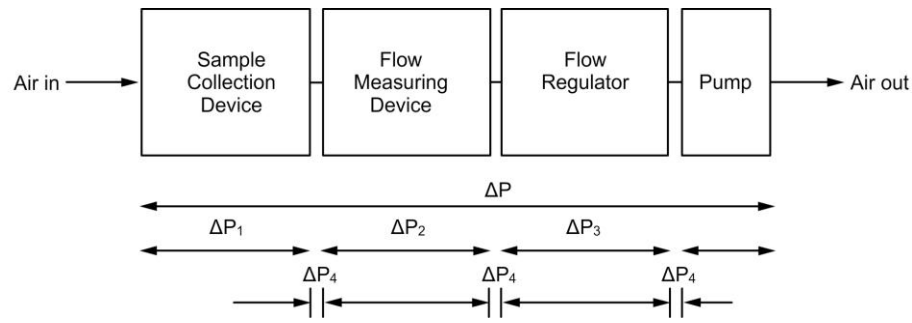

Figure 3-16. Flow rate control mechanism.

Sources of pressure drop in a system of this type include:

- the pressure drop across the sample collection device (Δp_1),
- the pressure drop across the flow measuring device (Δp_2),
- the pressure drop across the flow regulator (Δp_3), and
- the pressure drop due to friction in connecting lines (Δp_4).

Friction losses and flow measuring losses are usually considered as being constant. The resulting relationship can be shown in Equations 3-1, 3-2, 3-3, and 3-4.

(Eq. 3-1) $$\Delta p = \Delta p_1 + \Delta p_2 + \Delta p_3 + \Delta p_4$$

(Eq. 3-2) $$\Delta p_2 + \sum \Delta p_4 = constant$$

(Eq. 3-3) $$\Delta p - \Delta p_2 - \sum \Delta p_4 = \Delta p\ adjusted$$

(Eq. 3-4) $$\Delta p_1 + \Delta p_3$$

Initially in the sample collection (assume for this discussion the collection device is a filter for the collection of particles), the sample collection device resistance (Δp_1) is low; therefore, the regulator would have to offer a higher resistance (Δp_3). As sampling proceeds, the sample collector resistance (Δp_1) increases (as a "particle cake" builds up on the filter), thus automatically lowering

the flow regulator resistance (Δp_2) and keeping Δp_{adj} at a constant value. The regulator resistance control may be actuated by several mechanisms, usually a pressure drop directly related to time rate.

Another type of control mechanism accomplishes control by varying the pump motor speed. As the pressure drop across the sample collection device increases, a switching arrangement increases the pump motor speed - thus drawing a constant air flow.

3.9 Air Measuring Instruments

Introduction

The accuracy and precision of a given method for the determination of the concentration of an air pollutant are based on two factors:

- the accuracy and precision of the sampling method, and
- the accuracy and precision of the analytical method.

Examine the following term:

(Eq. 3-5)

$$\frac{\mu g}{M^3}\left(\frac{\text{Mass of pollutant}}{\text{Volume of air sampled}}\right)$$

You can see that the μg (*mass of pollutant*) term is a result of the analytical process, while the M^3 (*volume of air sampled*) term is a result of the sampling process. Not only is the mass of pollutant important in the final calculation of $\mu g/M^3$, but the volume of air sampled is also important. We will concentrate in this section on the measurement of the volume of air sampled.

The accuracy and precision of the sampling method depend on these factors:

- the environmental conditions during sampling,
- the collection efficiency of the sampling method,
- the accuracy and precision of the flow rate measurement, and
- any interferences.

The determination of the volume of air sampled, V (e.g., liters), generally involves a measurement of flow rate, Q (e.g. liters/minute), and sampling time, t (e.g. minutes).

(Eq. 3-6)

$$V = Q \times t$$

Types of Air Measuring Devices

The flow rate during atmospheric sampling can be measured by a variety of air measuring devices. Air measuring devices can be broadly classified into three categories: *volume meters, rate meters,* and *velocity meters*.

Volume meters measure the total volume, *V,* of gas passed through the meter over some specified time period. If the time period, *t,* is measured with a timing device, flow rate can be calculated by:

(Eq. 3-7) $$Q = \frac{V}{t}$$

Rate meters measure the time rate of flow through them. Flow rate is measured through some property of the gas.

Velocity meters measure the linear velocity, *v,* of a gas in a duct. Volumetric flow rate can then be calculated by measuring the cross-sectional area, A, of the duct through which the gas is flowing, by:

(Eq. 3-8) $$Q = A \times \bar{u}$$

Calibration

Air that is to be sampled often is moved at a known rate over a known time period. The determinative process used to establish this known flow rate and known time period is a form of calibration. Remember that $V = Q \times t$, or that volume sampled, *V,* is the product of flow rate *Q* and time *t*. The calibration process applied to both the flow rate and time allows the accurate determination of volume.

In precise terms, calibration is the comparison of an output value with a known input value. It is typical to "challenge" an instrument under calibration with a series of values (e.g. concentrations, temperatures, pressures) for a given operating range. The difference between the input and output may be accounted for by making an adjustment to the device being calibrated. This is typical in modern instruments or devices. Alternatively, a calibration curve is developed to represent the difference by plotting the "known input value" versus the "instrument response value." If this approach is used, all subsequent data from that instrument will need to be adjusted based on the calibration curve.

The frequency with which calibration occurs depends on a number of conditions. Some of these are:

- instrument use (What are the conditions under which the instrument is used?),
- instrument users (How many different people use the instrument? What are their qualifications?),
- instrument characteristics (How often does the instrument require calibration under controlled laboratory conditions? How sensitive is the instrument?), and
- regulatory requirements as to how frequently the instrument or device must be calibrated.

The basic equipment required for calibrating air flow measuring instruments

includes a standard meter, an air mover, and often a source of constant power.

Standard meters are of three types: primary standards, intermediate standards, and secondary standards. *Primary standards* are those whose volumes can be determined by measurement of internal physical dimensions alone. The measured internal dimensions are regular, and accuracies better than ± 0.30% can be achieved. *Intermediate standards* are devices which have an accuracy only marginally less than that of primary standards at ≤ 2%, but whose internal dimensions are not easily measured. *Secondary standards* are those calibrated against primary or intermediate standards under known conditions of gas type, temperature, and pressure. Accuracies less than 5% are generally achievable.

3.10 Volume Meters

Volume meters measure the volume of gas passing through the meter. When coupled with a timing device (like a calibrated stopwatch), flow rate (volume/time) can be calculated. There are seven volume meters commonly used in air sampling and analysis.

The Spirometer (or "Bell Prover") – Primary Standard

The spirometer consists of a cylinder of known volume, closed at one end, with the open end submerged in a circular tank of fluid (Figure 3-17). The cylinder can be opened or closed to the atmosphere by a valve. As the cylinder is lowered into the water, and the water displaces the air and causes it to be discharged from the cylinder, the rate of discharge can be regulated.

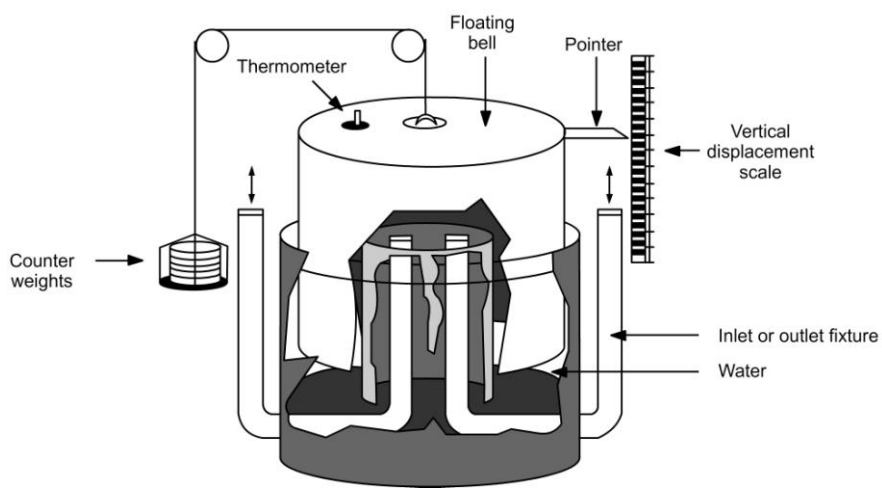

Figure 3-17. Spirometer.

The volume of the cylinder is determined from its dimensions. A counterweight and cycloid counterpoise allow pressure differentials across the spirometer as low as 0.02 inches of water (Figure 3-18).

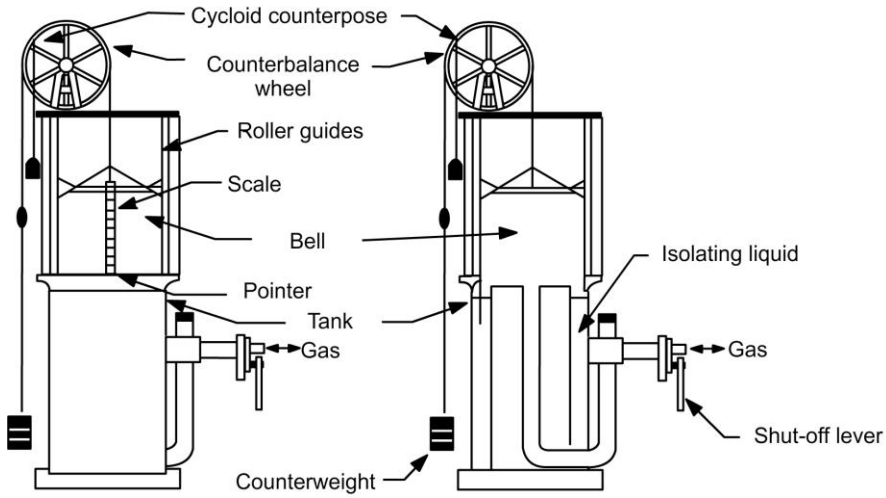

Figure 3-18. Orthographic and cross-sectional views of a 5-ft³ spirometer.

The volume of air passed through a spirometer is given by the following formula:

(Eq. 3-9)

$$V = \frac{\pi d_2 h}{4}$$

Where: V = *volume of air passed through spirometer*
π = *a constant = 3.14*
d = *diameter of bell*
h = *vertical displacement of bell*

The fluid in the spirometer should be at the same temperature as the room. This is to ensure that the fluid and the air will be in thermal equilibrium and thereby minimize spirometer fluid evaporating into the air. This thermal equilibrium also simplifies volume corrections since temperature is constant during the calibration procedure. This is true for water, but some spirometers use oil. The real importance of thermal equilibrium is that the air displaced from the bell must be at the same temperature as the room for volume calculations. The pressure inside the bell is also brought into equilibrium with room conditions.

Once the volume of air is determined using room conditions, a conversion to standard conditions must be made to determine the true volume of air that has passed through the spirometer. EPA standard conditions for temperature and pressure (STP) generally applicable to atmospheric sampling and ambient monitoring are 25 degrees Celsius (298 K on an absolute basis) and 760 mm Hg, also on an absolute basis. This conversion to standard conditions is made using the following formula (see Equation 2-7):

(Eq. 3-10)

$$V_2 = V_1\left(\frac{P_1}{760\,\text{mm Hg}}\right)\left(\frac{298\,\text{K}}{T_1}\right)$$

Where:

V_2 = *volume of gas at 2nd conditions or at* P_2 *and* T_2
V_1 = *a volume of gas at 1st conditions of* P_1 *and* T_1
T_1 = *initial temperature of gas, K*
T_2 = *final temperature of gas (in this case, 298 K)*
P_1 = *initial pressure of gas, mm Hg*
P_2 = *final pressure of gas (in this case, 760 mm Hg)*

The spirometer is calibrated by the manufacturer against a National Institute of Standards and Technology (NIST) "cubic-foot" bottle. If a spirometer is suspected to be in error, its calibration can be checked with an NIST-certified "cubic-foot" bottle or by a "strapping" procedure.

The strapping procedure involves the measurement of the dimensions of the bell with a steel tape and subsequent calculation of the volume. Experienced personnel routinely obtain accuracies of ± 0.2% when calibrating a spirometer by the strapping procedure. Nelson (1972) gives a very detailed procedure for performing the strapping procedure. Manufacturers of spirometers include example calculations in the literature accompanying their instruments.

Flow rates can be measured by timing the volume of air passing to or from the spirometer and determining the rate of flow. The spirometer is simple, inexpensive, dependable, and is used almost solely as a primary standard for calibration of other types of flow- and volume-measuring devices. Because the spirometer can be produced in large sizes, it has typically been used to calibrate Roots meters, which are positive displacement meters.

Displacement Bottle Technique - Primary Standard

The displacement bottle consists of a bottle filled with water (or some other liquid) and a tube through which air can enter the bottle (Figure 3-19). As the liquid in the bottle is drained or siphoned out, air is drawn in to take the place of the volume of liquid lost. The volume of gas sampled is equal to the volume of liquid displaced.

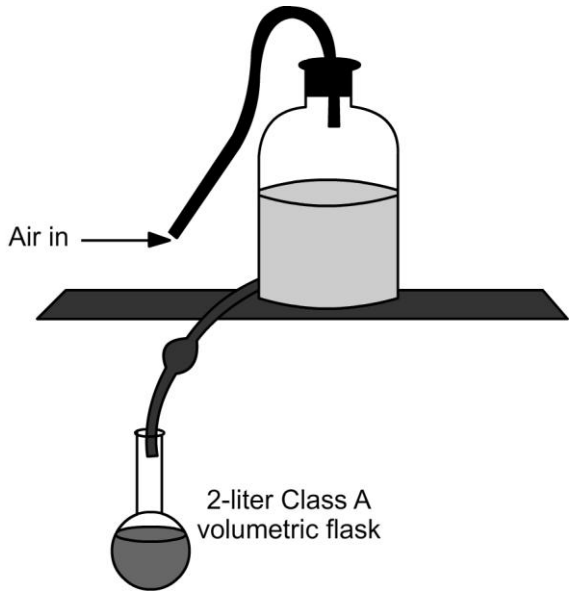

Figure 3-19. Displacement bottle technique.

The fluid in the displacement bottle should be in thermal equilibrium with the room temperature. This equilibrium will ensure no liquid evaporation from the bottle water to the air, and will simplify volume corrections for *T* and *P*. The volume of displaced liquid can be measured with a graduated cylinder or Class A volumetric flask, depending on how accurately the volume needs to be measured. Accuracy can range from 1 to 5%, depending on what measuring device is used. A NIST-traceable volumetric flask (e.g., Class A designation) must be used for this method to be considered as a primary standard. The displacement bottle as used in this technique simply serves as the air mover.

Again, once the volume of air has been determined at room conditions, it should be converted to the volume at standard conditions. This conversion uses the relationship previously stated in Equation 3-10.

Frictionless Pistons - Primary Standard

The soap-bubble meter and the mercury-sealed piston are two frictionless pistons. Mercury-sealed piston meters are no longer available; however, some remain in use. Accurate and convenient measurement of flows between 1 and 1000 mL/min can be made with a soap-bubble meter. Some mercury-sealed pistons can accurately measure flows from 100 cm^3/min to 24,000 cm^3/min.

Moving-Bubble Meter

A bubble meter consists simply of a cylindrical glass tube with graduated markings, usually in milliliters. Inverted burets are often used as soap-bubble meters (Figure 3-20); however, burets cannot be used with anything other than a vacuum source. Simple bubble meters (Figure 3-21) can be purchased, although the basic design can be made conveniently by a competent glass blower.

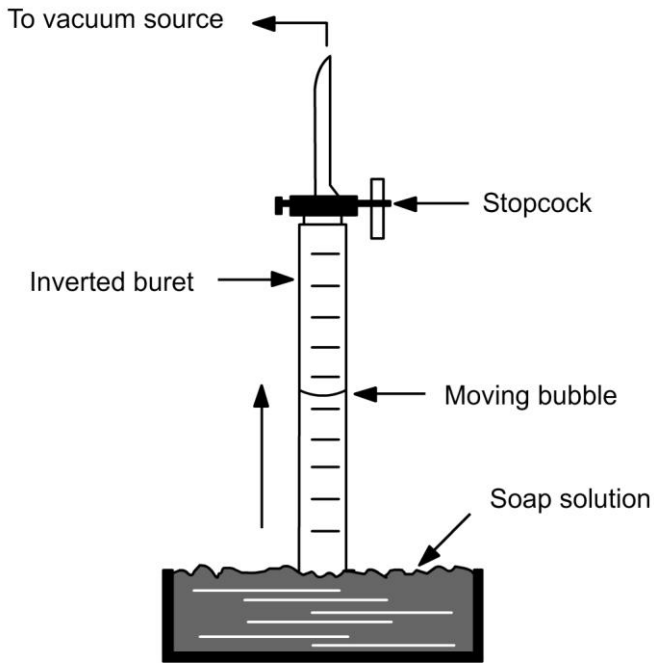

Figure 3-20. Moving-bubble meter.

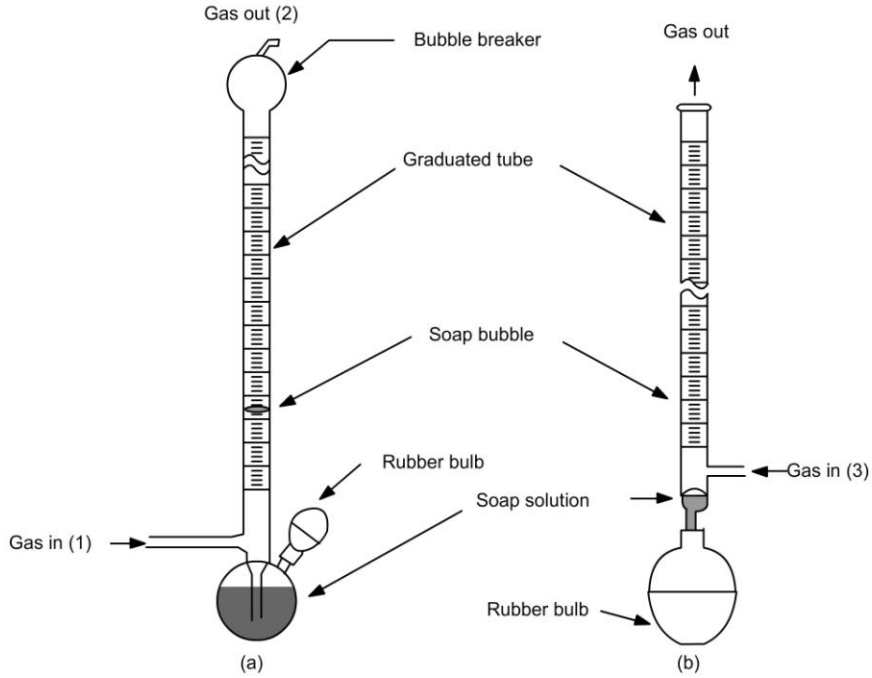

Figure 3-21. Moving-bubble meters: (a) one with bubble breaker and capability of handling vacuum at (2) or pressure at (1); (b) one capable of handling only pressure at (3).

The moving-bubble meter is one of the simplest of primary standards. The inside walls of the tube are wetted with a soap solution. A bubble is formed by touching the tip of the buret to the soap solution, as in Figure 3-20, or by squeezing the rubber bulb until the soap solution is raised above the gas inlet (Figure 3-21).

Either a vacuum at the top or slight positive pressure at the bottom of the tube moves the bubble (a frictionless piston) up the tube. By timing this movement and noting the volume traversed by the bubble over the measured time span, volumetric flow rate can be calculated.

The volume measured by a moving-bubble meter must be corrected for two conditions. First, if the room temperature and pressure are different from standard atmospheric conditions, the volume must be corrected by the relationship previously stated (Equation 3-10):

(Eq. 3-11)

$$V_2 = V_1\left(\frac{P_1}{760\,\text{mm Hg}}\right)\left(\frac{298\text{K}}{T_1}\right)$$

Where:

V_2 = *volume of gas at 2nd conditions or at* P_2 *and* T_2
V_1 = *a volume of gas at 1st conditions of* P_1 *and* T_1
T_1 = *initial temperature of gas, K*
T_2 = *final temperature of gas (in this case, 298 K)*
P_1 = *initial pressure of gas, mm Hg*
P_2 = *final pressure of gas (in this case, 760 mm Hg)*

Second, the measured volume can be slightly larger than the standardized volume because water from the bubble evaporates into the gas behind the bubble. If the gas behind the bubble has a relative humidity greater than 50%, the error is small. If the gas is dry, the error can be large and must be corrected by the following formula:

(Eq. 3-12)

$$V_c = V_{meas}\left(\frac{P_b - P_w}{P_b}\right)$$

Where:

V_c = *corrected volume*
V_{meas} = *measured volume*
P_b = *atmospheric pressure, mm Hg*
P_w = *vapor pressure of water at the room temperature, mm Hg.*

Note that P_b and P_W must have the same units (Torr and mm Hg are equivalent).

Table 3-1. Vapor pressure table.[1]

TEMPERATURE (C°)	VAPOR PRESSURE (TORR)
15° C	12.8
16° C	13.6
17° C	14.5
18° C	15.5
19° C	16.5
20° C	17.6
21° C	18.7
22° C	19.8
23° C	21.1
24° C	22.4
25° C	23.8
26° C	25.2
27° C	26.8
28° C	28.4
29° C	30.1
30° C	31.9

Moving-bubble meters can be calibrated by measuring the dimensions of the tube; however, poor control on glass dimensions in manufacturing make this inaccurate. The bubble meter is usually calibrated by filling the tube with a liquid (water or mercury, for example), then draining the liquid from the top graduation to the bottom graduation. The volume or weight of the collected liquid can be measured. Since water is susceptible to thermal expansion and contraction, proper corrections for temperature must be made if this calibration is to be accurate. The moving-bubble meter should only be used to measure volumes between graduations that have been calibrated.

The bubble meter is used almost exclusively in laboratory situations for calibration of other air-measuring instruments. In average laboratory conditions, the moving-bubble meter is accurate to about ± 1%, depending on how accurately it is calibrated. Accuracy decreases for flows below 1 mL/min and above 1 L/min mainly because of gas permeation through the bubble. A detailed description of the calibration and use of bubble meters has been published by Levy (1964). Increased accuracies have been reported for bubble meters fitted with automatic sensing devices that start and stop a timer.

Mercury-Sealed Piston

An electronically-actuated mercury-sealed piston is no longer commercially available and is rarely encountered today due to the health and environmental

[1] A more detailed saturation water vapor table can be found in the appendix.

issues associated with mercury. In its day, the mercury-sealed piston was considered expensive; however, its accuracy (± 0.2% for time intervals greater than 30 seconds) and simple operation make it an extremely useful tool.

The mercury-sealed piston consists of a precision-bored, borosilicate glass cylinder with a close-fitting polyvinyl chloride piston (Figure 3-22). The piston and cylinder wall are sealed with a ring of mercury that stays in place because of its high viscosity and the closeness of the fit between the cylinder and piston. Gas entering the solenoid valve is vented until the measurement cycle is actuated. When the measurement cycle is started, the solenoid valve closes the vent, allowing gas to enter the cylinder.

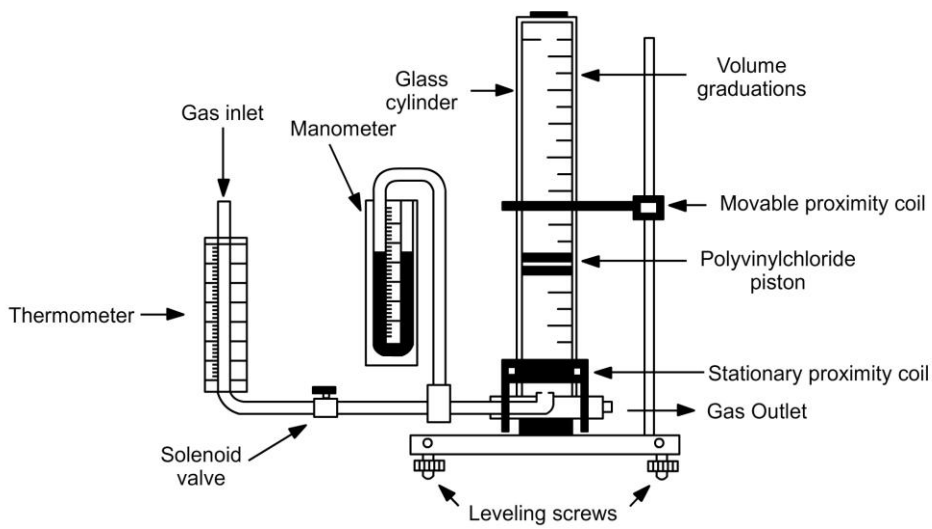

Figure 3-22. Mercury-sealed piston volume meter.

A timer is started and stopped as the mercury seal passes the lower and upper proximity coils (metal detectors). The volume displaced can be set by adjusting the upper proximity coil. The volume is corrected to standard conditions using the pressure drop across the piston (usually < 3 inches of water). The measured time and the corrected volume can be used to calculate volumetric flow.

Calibration of the mercury-sealed piston volume meter is usually performed by the manufacturer. The borosilicate glass cylinder is bored to a precise diameter. The inside diameter is air-gauged at least every inch to check for consistency. Before the instrument is sent out it is compared to a standard-mercury-sealed piston volume meter that is traceable to NIST.

Although mercury-sealed piston meters are no longer available, similar devices such as automated soap-bubble meters and automated non-mercury based piston meters (i.e. dry-piston meters) are commercially available and in widespread use today.

Automated Bubble Flowmeters

A semiautomatic bubble flowmeter instrument is easier to use than the manual version and is likely to provide more uniform and accurate flow rate

measurements, particularly at relatively high flow rates. An electronic "eye" records time, *zero*, when the soap bubble passes an initial point, while a second electronic eye, representing a set volume relative to the initial point, records time, *t*. The elapsed time divided into the known volume the soap-bubble traversed between the electronic eyes provides the flow rate. The instrument's digital readout is typically in units of liters per minute. Automated bubble flowmeter kits, such as the Gilibrator, are equipped with 3 cells that allow for flow measurements of a few milliliters per minute to up 30 liters per minute.

Because the liquid used to form the bubbles is usually water-based, a water vapor correction may be required to compensate for a volume increase due to evaporation of the water in the instrument, as discussed in the moving-bubble meter section above. Furthermore, the instrument cannot be used below 0°C because the soap solution will freeze. It is also susceptible to persistent drying of the cell wall and temperature variations when exposed to direct sunlight, which results in diminished accuracy.

Automated Dry-Piston Flowmeters

Dry-piston flowmeters are similar to soap-bubble flowmeters except they use a lightweight, low-friction, rigid piston in place of the soap-bubble. These flowmeters are relatively easy to use and are not subject to the water vapor correction of the liquid-freezing limitation of the bubble flowmeters or the dry influence of sunlight when used in the field. However, they may still be subject to a lower operational temperature limit due to LCD readouts.

Wet Test Meter (WTM) - Secondary Standard

The wet test meter consists of a series of inverted buckets or traps mounted radially around a shaft and partially immersed in water (Figure 3-23a). The location of the entry and exit gas ports is such that the entering gas fills a bucket, displacing the water and causing the shaft to rotate due to the lifting action of the bucket full of air. The entrapped air is released at the upper portion of the rotation and the bucket again fills with water. In turning, the drum rotates index pointers that register the volume of gas passed through the meter (Figure 3-23b).

After the meter is leveled, the proper water level is achieved by using the filling funnel, fill cock, and drain cock (Figure 3-23c) to bring the meniscus of the water in touch with the tip of the calibration index point. The calibration gas should be passed through the meter for one hour to saturate the water with the gas. The water in the meter should be at the same temperature as the surrounding atmosphere, to avoid the need to make a correction for temperature. If any water is added, sufficient time must be allowed for complete equilibration.

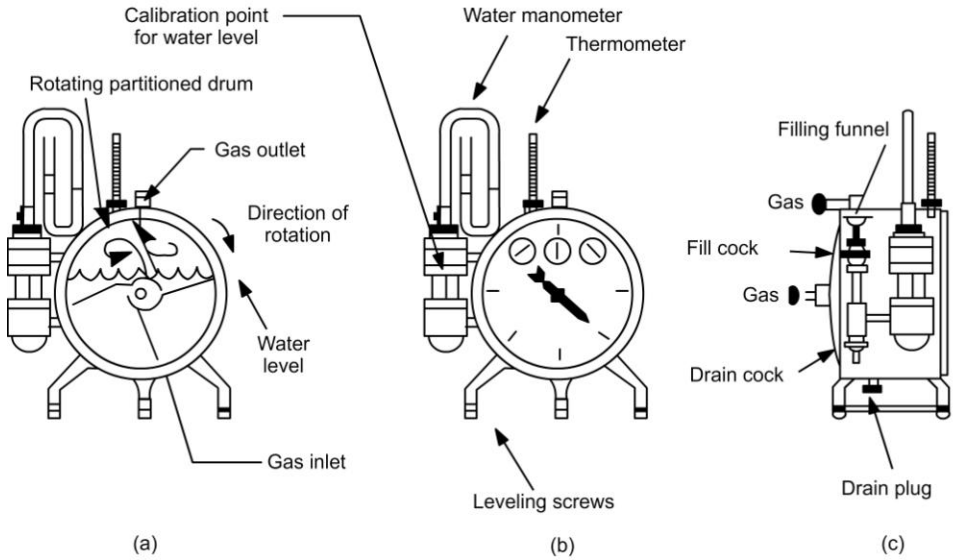

Figure 3-23. Wet test meter.

Once the water level is set and the meter is equilibrated, the wet test meter is ready for calibration (or for use if it is already calibrated). An accurate calibration of a wet test meter can be done with a spirometer (Figure 3-24).

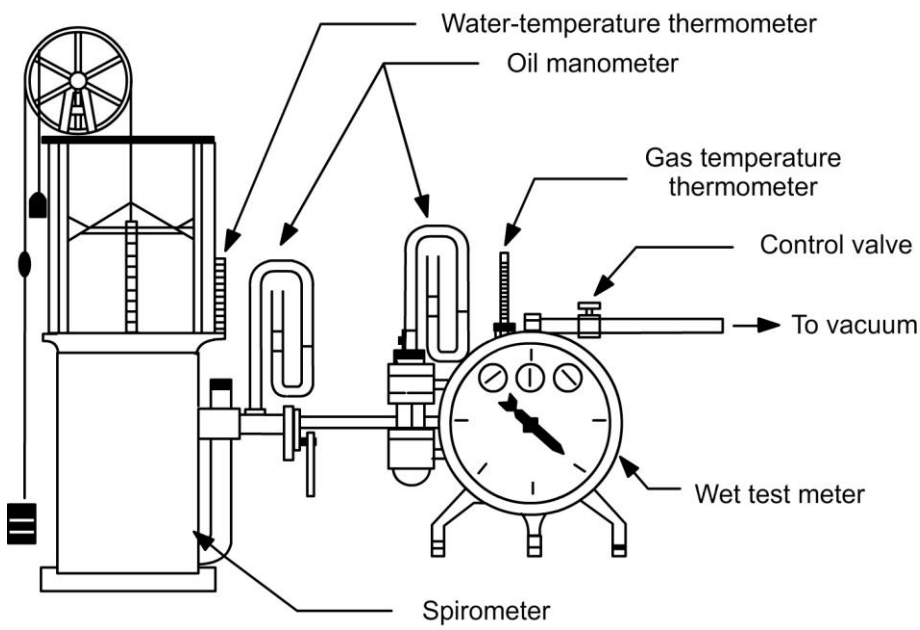

Figure 3-24. Setup for calibrating a wet test meter against a spirometer.

The wet test meter can also be calibrated against a bubble flowmeter or dry-piston meter.

Enough gas is drawn through either system to turn the wet test meter at least three revolutions and to significantly move the spirometer drum, soap bubble, or piston. The measurement is made several times. Atmospheric pressure and temperature, and the temperature and pressure differential for both the wet test meter and calibrating device, are needed to correct the volume to standard conditions (taking pressure differentials, as indicated by the oil manometers, into consideration). Since both the calibration device and the wet test meter are measuring a dry gas stream, a significant error is introduced if the measured volume is not corrected to dry conditions. This correction is the same as for the soap-bubble meter correction:

(Eq. 3-13)

$$V_c = V_{meas}\left(\frac{P_b - P_w}{P_b}\right)$$

Where:

V_c = *corrected volume* (V_2)

V_{meas} = *measured volume* (V_1)

P_b = *atmospheric pressure, mm Hg*

P_w = *vapor pressure of water at the room temperature, mm Hg*

A simple calibration check can be performed using a displacement bottle, as shown in Figure 3-25. After all the water is thermally equilibrated, the wet test meter is properly set up, the drain tube of the displacement bottle is filled, and the pinch clamp is opened, allowing 2 liters of water to drain into a 2-liter Class A volumetric flask. The corresponding wet test meter readings are taken. This is repeated several times (usually four).

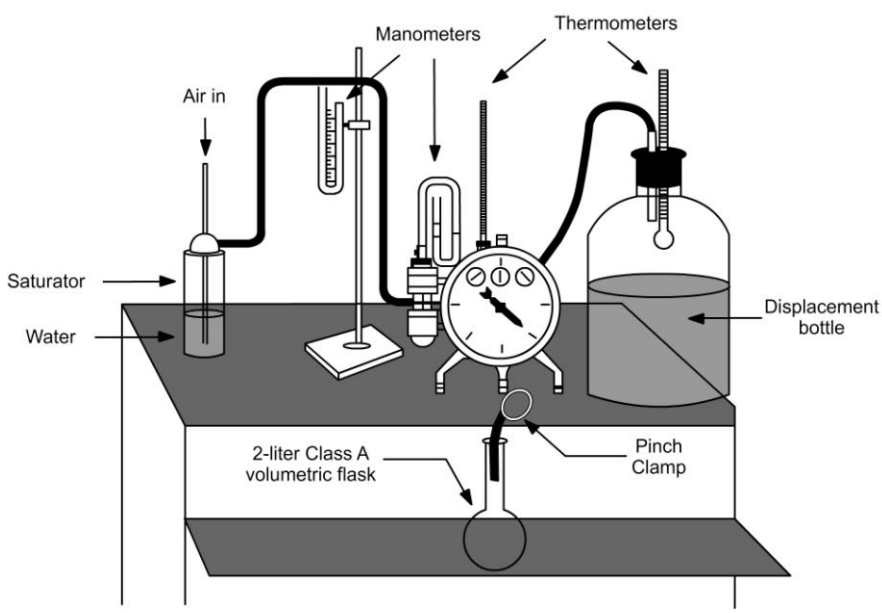

Figure 3-25. Calibration of wet test meter with displacement bottle.

The calibration data can be used to:

1. Draw a multipoint calibration curve.
2. Adjust the calibration index point so that the meter volume is correct.
3. Calculate a correction factor for the wet test meter.

Wet test meters should check within ± 0.5 % if option 2 is used. All volumes measured by a wet test meter should be corrected to standard conditions by Equation 3-10.

Wet test meters are used as transfer standards because of their high accuracy (less than ± 1%). Because of their bulk, weight, and equilibration requirements, they are seldom used outside a laboratory setting. Wet test meters are useful for laboratories that need an accurate standard yet do not have the funds or space for a spirometer. Wet test meters can be used to measure flow rates up to 3 revolutions/min, at which point the meter begins to act as a limiting orifice and obstructs the flow. Wet test meters are available in sizes that correspond to 1, 3, and 10 L/rev.

Roots Meter - Secondary Standard

The Roots meter is a positive displacement, rotary-type meter for measuring volume flow. It is suitable for handling most types of clean, common gases. It is not suitable for handling liquids, and its operation can be impeded by excessive particulate matter carried in the gas stream.

Roots meters consist basically of two oppositely rotating impellers of two-lobe or "figure eight" contour, operating within a rigid casing (Figure 3-26). The casing is arranged with inlet and outlet gas connections on opposite sides. Impeller contours are mathematically developed and accurately produced, and are of such form that a continuous seal without contact can be maintained between the impellers at all positions during rotation. To accomplish this, the correct relative impeller positions are established and maintained by precision-grade timing gears. Similar seals exist between the tips of the impeller lobes and the two semicircular parts of the meter casing. As a result of this design, the gas inlet side of the meter is always effectively isolated from the gas at the outlet side of the impellers. Consequently, the impellers can be caused to rotate by a very small pressure drop across the meter.

The rotation of the impellers is in the direction indicated in Figure 3-26, and as each impeller reaches a vertical portion (twice in each revolution), it traps a known specific volume of gas between itself and the adjacent semicircular portion of the meter casing at A and B (Figure 3-26, Position 2). Thus, in one complete revolution, the meter will measure and pass four similar gas volumes, and this total volume is the displacement of the meter per revolution.

The displacement of volume of the Roots meter is precisely determined by the manufacturer, both by calculation and by testing it using a known volume of air or other gas. Roots meters are usually calibrated against large spirometers prior to shipment. Users do not usually have a way to calibrate Roots meters and must depend on the supplied calibration data. Volumetric accuracy of the Roots meter is permanent and nonadjustable (except for linkage adjustment), because its measuring characteristics are established by the dimensions and machined contours of nonwearing fixed and rotating parts.

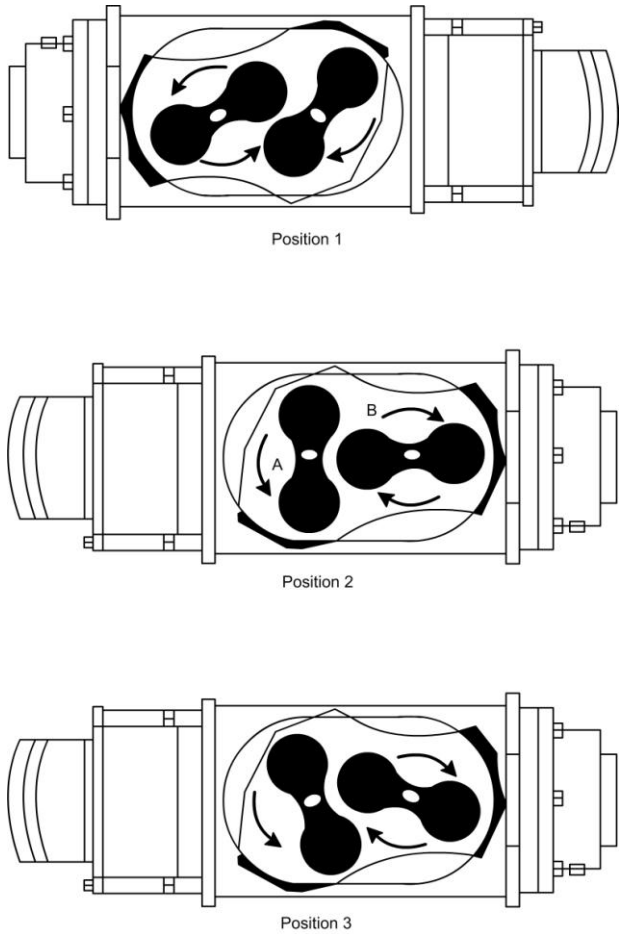

Figure 3-26. Principle of gas flow through the Roots meter.

The revolutions of the impellers are indexed with the meter reading calibrated in a volume unit (i.e., ft^3 or m^3). Units are sold that have temperature compensation devices, but corrections to standard temperature and pressure conditions are easily made with the previously mentioned formula given in Equation 3-10 (pressure drop across the Roots meters should be taken into consideration).

(Eq. 3-14)

$$V_2 = V_1 \left(\frac{P_1}{760\,\text{mm Hg}} \right) \left(\frac{298\,\text{K}}{T_2} \right)$$

Where:

V_2 = *volume of gas at 2nd conditions or at* P_2 *and* T_2
V_1 = *a volume of gas at 1st conditions of* P_1 *and* T_1
T_1 = *initial temperature of gas, K*
T_2 = *final temperature of gas (in this case, 298 K)*

P_1 = *initial pressure of gas, mm Hg*
P_2 = *final pressure of gas (in this case, 760 mm Hg)*

The symbol P_1, in this instance, is the atmospheric room pressure (P_b, in mm Hg) minus the pressure drop across the Roots meter Δp , in mm Hg.

(Eq. 3-15) $$P_1 = P_b - \Delta p$$

The metering unit is magnetically coupled to the impellers. The entire counting unit is enclosed in a plastic cover. The cover also holds oil that lubricates the metering device. The proper oil level is set by the inscribed oil level lines on the ends of the plastic covers. The user of a Roots meter must be careful not to severely tilt the meter when oil is in the plastic cover, as this can force oil into the impeller casing. If the oil gets into the impeller casing, flushing with kerosene can remove the oil.

Although Roots meters are widely used in industrial applications, they have been used almost exclusively as the standard for high-volume sampler flow rate in atmospheric sampling applications.

Dry Test Meter - Secondary Standard

Dry *test* meters are an improvement over the more common dry *gas* meters (Figure 3-27). Dry gas meters (a secondary standard) are most commonly used in residential and industrial settings to measure gas flow (e.g., natural gas). The dry test meter (a secondary standard) works on the same principle as the dry gas meter (a secondary standard), but a different indexing method (read-out) makes it more accurate (usually ± 1 to 2% when new). The dry test meter shown in Figure 3-28 shows the new read-out mechanism.

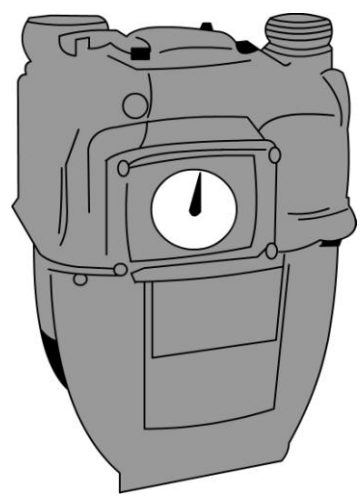

Figure 3-27. Dry gas meter.

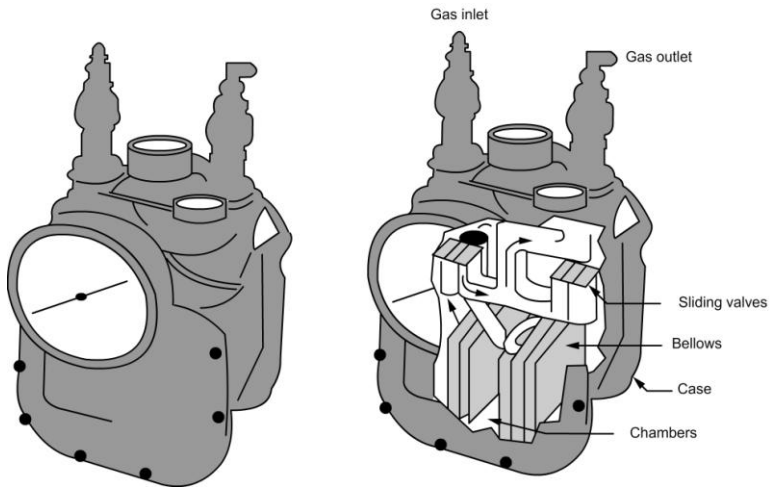

Figure 3-28. Dry test meter.

The interior of the dry test meter contains two or more movable partitions, or diaphragms, attached to the case by a flexible material so that each partition may have a reciprocating motion (Figure 3-29). The gas flow alternately inflates and deflates each bellows chamber, simultaneously actuating a set of slide valves that shunt the incoming flow at the end of each stroke. The inflation of the successive chambers also actuates, through a crank, a set of dials that register the volume of gas passed through the meter.

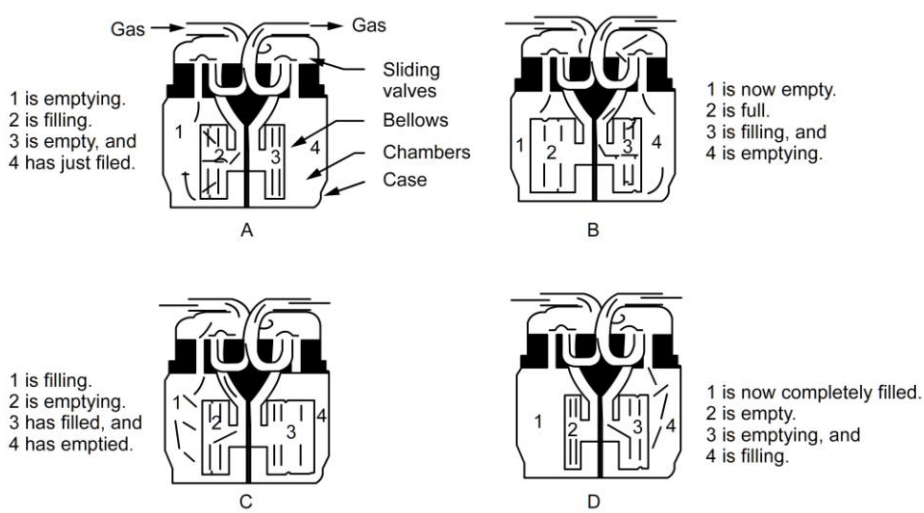

Figure 3-29. Working mechanism of dry test meter.

The dry test meter is calibrated against a spirometer, bubble flowmeter, piston flowmeter, or displacement bottle similar to the wet test meter. One big

advantage of the dry test meter over the wet test meter is that no correction for water vapor is needed. If the dry test meter is off calibration by more than 2%, it can be corrected by adjustment of the meter linkage. If linkage adjustment cannot correct the problem, then the dry test meter must be returned to the manufacturer for repairs.

Dry test meters are used in the field as well as in laboratory calibrations. Since the dry test meter does not contain water, it is lighter and easier to use than the wet test meter. Also, the dry test meter is more rugged than the wet test meter. Accuracy of the dry test meter does, however, worsen with age.

3.11 Rate Meters

Rate meters measure, indirectly, the time rate of the fluid flow through them. Their response depends on some property of the fluid related to the time rate of the flow.

Variable-Pressure Meters - Head Meters

Head meters are those in which the stream of fluid creates a significant pressure difference that can be measured and correlated with the time rate of flow. The pressure difference is produced by a constriction in the stream of flow causing local increase in velocity.

Orifice Meter – Noncritical – Secondary Standard

An orifice meter can consist of a thin plate having one circular hole coaxial with the pipe into which it is inserted (Figure 3-30). Two pressure taps, one upstream and one downstream of the orifice, serve as a means of measuring the pressure drop, which can be correlated to the time rate of flow. Watch jewels, small bore tubing, hypodermic needles, and specially manufactured plates or tubes with small holes have been used as orifice meters. The pressure drop across the orifice can be measured with a manometer, magnehelic, or pressure gauge.

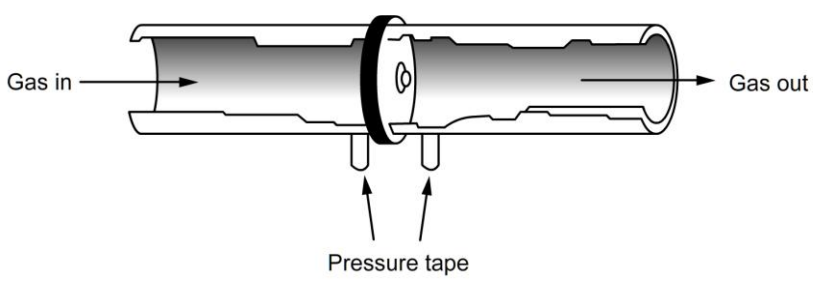

Figure 3-30. Orifice meter.

Flow rates for an orifice meter can be calculated using Poiseuille's Law; however, this is not done for practical use. Instead, the orifice meter is usually

calibrated with either a wet or dry test meter, or a bubble meter. A typical calibration curve is shown in Figure 3-31.

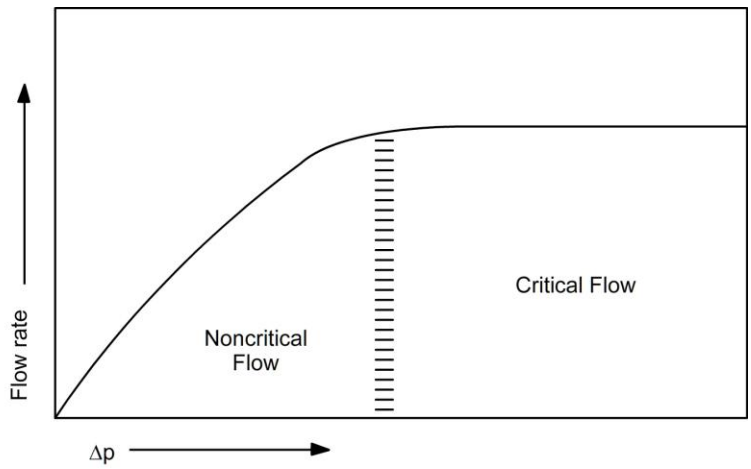

Figure 3-31. Typical orifice meter calibration curve.

Calibration curves for orifice meters are nonlinear in the upper and lower flow rate regions and are usually linear in the middle flow rate region.

Orifice meters can be made by laboratories with a minimum of equipment. They are used in many sampling trains to control the flow. However, since a non-critical orifice meter is operated in the noncritical (or subsonic, below the speed of sound) portion of the curve (Figure 3-31), change in flow occurs as a result of variations in pressure. The change in pressure over the orifice meter may be from an alteration to the driving force of the air mover (e.g., pump) or as a result of a "filter cake" building up on a filter, creating increased resistance in the sampling train, as more and more particles are captured. A sampling train which utilizes an orifice meter must be properly designed and operated to ensure a known volume of gas is sampled and the collection device is operated at its design flow rate.

Care must be exercised to avoid plugging the orifice with particles. A filter placed upstream of the orifice can eliminate this problem. Orifice meters have long been used to measure and control flows from a few mL/min to 50 L/min.

Orifice Meter – Critical – Secondary Standard

If the pressure drop across the orifice (Figure 3-30) is increased until the downstream pressure on an absolute basis is equal to approximately 0.53 times the upstream pressure on an absolute basis (for air and some other gases), the velocity of the gas in the constriction will become acoustic, or sonic. Orifices used in this manner are called critical orifices. The constant 0.53 is purely a theoretical value and may vary. Any further decrease in the downstream pressure or increase in the upstream pressure will not affect the rate of flow. As long as the 0.53 pressure relationship exists, the flow rate remains constant for a given

upstream pressure and temperature, regardless of the value of the pressure drop (Figure 3-31). The error of an orifice meter is approximately 2%.

Only one calibration point is needed for a critical orifice. The critical flow is usually measured with a moving-bubble meter, or a wet or dry test meter. Corrections for temperature and pressure differences in calibration and use are made with the following formula:

(Eq. 3-16)

$$Q_2 = Q_1\left(\frac{P_1 \times T_2}{P_2 \times T_1}\right)$$

Where:
Q = *flow*
P = *pressure*
T = *temperature in K*
1 = *initial conditions*
2 = *final conditions*

The same formula can be used to correct orifice meter flows to standard conditions by substituting P_2 = 760 mm Hg and T_2 = 298 K. Note the square root function of T and P. *Any time that rate meters are corrected for T and P_1 this square root function is needed.*

Critical orifices are used in the same types of situations as noncritical orifices and many of the same design and operational considerations apply. However, since critical orifice meters operate in the critical (or supersonic, above the speed of sound) portion of the curve (Figure 3-31), flow does not change unless the relative variation in pressure falls below the ratio of 0.53 ($P_{downstream}$ / $P_{upstream}$). In other words, even as a filter cake builds, as long as the air mover (e.g., pump) has sufficient capacity, flow is unaffected until the ratio of the pressures across the orifice meter falls below the theoretical value of 0.53. Care must also be taken not to plug the orifice.

Critical orifice meters are often used when sampling with an evacuated flask. A critical orifice at the inlet of the flask maintains a constant flow rate over a known period of time.

Venturi Meter - Secondary Standard

The venturi meter consists of a short cylindrical inlet, an entrance cone, a short cylindrical throat, and finally a diffuser cone (Figure 3-32). Two pressure taps, one in the cylindrical inlet and one in the throat, serve to measure the pressure drop. There is no abrupt change of cross section as with an orifice; thus the flow is guided both upstream and downstream, eliminating turbulence and reducing energy losses. Venturi meters are, of course, more difficult to fabricate. The probable error of a venturi is 1%.

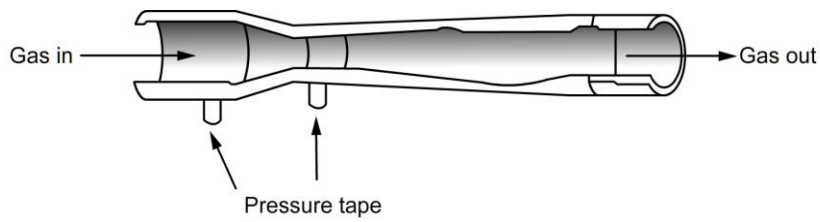

Figure 3-32. Venturi meter.

The venturi meter is calibrated in the same manner as the orifice meter. The calibration curve generated plots pressure drop across the venturi versus flow rates determined by the standard meter. Venturi meters are always used in the noncritical flow region and are therefore analogous to a noncritical orifice meter; however, they are typically designed to operate at much higher flow rates than the orifice meter. Venturi meters are generally used to calibrate the rotameter (i.e. visi-float) integral to a "Hi-Vol" vacuum cleaner-type pump used in high volume sampling.

Variable Area Meters

The variable area meter differs from the fixed orifice; the pressure drop across it remains constant while the cross-sectional area of the constriction (annulus) changes with the rate of flow. A rotameter is an example of a variable area meter.

Rotameter – Secondary Standard

The rotameter consists of a vertically graduated glass tube, slightly tapered in bore with the diameter decreasing from top to bottom, containing a float of the appropriate material and shape (Figure 3-33). The fluid to be measured passes upward through the conical tube, which is inserted in the flow circuit.

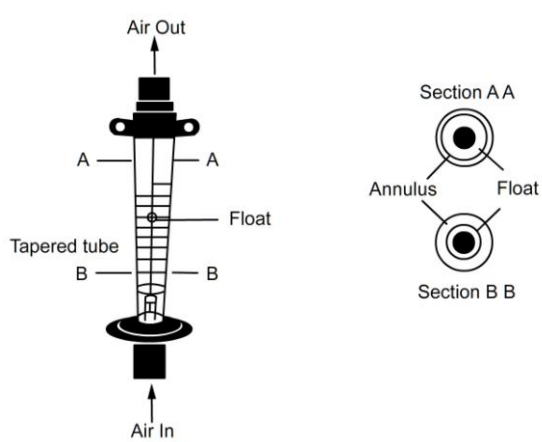

Figure 3-33. Rotameter.

A specially-shaped float, with a diameter slightly greater than the minimum bore of the conical tube, is carried upward by the passage of the fluid until it

reaches a position in the tube where its weight is balanced by the upward forces due to the fluid flowing past it. A variable ring or annulus is created between the outer diameter of the float and the inner wall of the tube. As the float moves upward in the tube, the area of the annulus increases (Figure 3-33, Sections AA and BB). The float will continue to move upward until a pressure drop across the float, which is unique for each rotameter, is reached. This pressure drop across the float is constant regardless of the flow rate. A measure of the flow is noted by the float position on a vertical scale and compared with a calibration chart to determine the corresponding flow rate in units such as mL/min or L/min.

The flow rate through a rotameter can be calculated from the tube diameters, float dimensions, float composition, and gas characteristics; this is not commonly done for calibration purposes. A detailed development of the flow equations for rotameters is contained in the appendix of this manual. Manufacturers generally provide accurate calibration curves for rotameters; it is advisable, however, to calibrate a rotameter under its operating conditions (i.e., connected to the other components of the sampling train as it will be used).

Most rotameters are used and calibrated at room temperature with the downstream side at atmospheric pressure. Corrections for pressure and temperature variations can be made using the previously mentioned formula:

(Eq. 3-17)

$$Q_2 = Q_1\left(\frac{P_1 \times T_2}{P_2 \times T_1}\right)$$

Where:

Q = *flow*
P = *pressure*
T = *temperature in K*
1 = *initial conditions*
2 = *final conditions*

If a gas is measured with a different density from the calibration gas, the flow rate can be corrected using the following formula:

(Eq. 3-18)

$$Q_1 = Q_2\left(\frac{q_2}{q_1}\right)^{1/2}$$

Where:

Q_1 = *flow rate with gas 1*
Q_2 = *flow rate with gas 2*
q_2 = *density of gas 2*
q_1 = *density of gas 1*

Because corrections of this type are cumbersome and add inaccuracies, rotameters are usually calibrated under normal operating conditions against a primary standard.

Rotameters are the most widely used laboratory and field method for measuring gas or liquid flow. Their ease of use makes them excellent for spot flow checks. With proper calibration, the rotameter's probable error is 2 to 5%. In the past, many atmospheric sampling instruments used rotameters to indicate

the sample flow rate. Today, they have been, to a great extent, replaced by mass flow meters and/or mass flow controllers.

Mass Flow Meters – Heat Transfer Meters – "Hot-Wire" Meters

Mass flow meters (MFMs) operate on the principle that when a gas passes over a heated surface, heat is transferred from the surface to the gas. For gases that approximate the behavior of ideal gases, the quantity of heat transferred and the resulting temperature differential is proportional to the mass (or weight) of the gas. The mass flow of the gas, as measured by the meter, is also directly proportional to volumetric flow rate.

There are two basic applications of the principle of mass flow to atmospheric sampling and monitoring instrumentation: mass flow meters (measures volumetric flow rate) and mass flow controllers (measures and controls volumetric flow rate).

Mass Flow Meter – Secondary Velocity Standard

A mass flow meter (MFM) consists of a transducer and separate power supply and electronic digital readout. The sample gas passes through the transducer, which contains a heated surface (e.g., wire, coil-wire metallic block combination) that transfers heat to the sample gas; heat is transferred from this surface to the gas. The amount of current required to keep the surface at a constant temperature is proportional to the mass and velocity of the gas, which is in turn proportional to the volumetric flow rate. The MFM provides a digital readout in volumetric flow rate units such as SLPM, SCCM, or SCFM.

Atmospheric sampling applications of the MFM are usually limited to the measurement of volumetric flow. Since these devices measure mass flow directly, they should be calibrated against a primary or secondary volumetric standard. The standard flow meter is corrected to standard conditions (STP) and compared to the mass flow rate measured by the MFM.

No corrections for temperature and pressure need to be made to the mass flow meter readings since the principle of measurement is mass flow, which is not influenced by changes in temperature and pressure. However, mass flow meters are designed based on a particular standard temperature and pressure. It may have been designed and initially calibrated at the same standard temperature and pressure typically used in atmospheric sampling and ambient monitoring (298 K, 760 mm Hg), or it may have been performed at other conditions (e.g., 273 K, 760 mm Hg). If the latter is true, a correction to the flow rate, as measured by the MFM, should be performed using Equation 3-16.

Calibration must be done with the same gas as will be measured in use, because different gases have different thermal properties. If the sample gas differs from the manufacturer design and calibration gas for a particular MFM (typically N_2), the flow rate as measured by the MFM should be corrected by applying a gas correction factor (GCF). The GCF can be determined experimentally by passing the sample gas through a standard flow meter (e.g., automated bubble meter) and the MFM to determine the difference in volumetric flow. Alternatively, a GCF can be calculated based on the ratio of the molar specific heat for the standard gas and the sample gas, using Equation 3-18.

(Eq. 3-18)

$$GCF = \frac{C_{pN2}}{C_{pgasx}}$$

Where: GCF = *gas correction factor*
C_{pN2} = *molar specific heat for* N_2 *gas (the typical gas used to calibrate a MFM)*
C_{pgasx} = *molar specific heat for the sample gas*

The more accurate published molar specific heat data is determined empirically by investigators. These data (i.e., C_p) can be found in the literature or from the National Institute of Standards and Technology (NIST).

The accuracy of a MFM is typically +/- 1-2% of full scale and is most often used for flow measurement or as calibration transfer devices in the field and laboratory. Their insensitivity to temperature and pressure makes them a useful tool for standard conditions measurement.

It is advisable not to use a MFM in applications where corrosive and/or explosive gases are present. Another potential limitation is in applications whether the relatively large pressure drop associated with most MFMs is problematic (e.g., pump capacity too low). Manufacturers have designed a low pressure drop MFM to accommodate applications where pressure drop is critical.

Mass Flow Controller – Secondary Standard

The principle of operation for a mass flow controller (MFC) is the same as for the mass flow meter (MFM). The MFC has a very useful feature in addition to measuring the volumetric flow rate; it is capable of controlling the flow at a user-selected rate within the range of the instrument. This is accomplished with an electronic solenoid within the transducer which opens or closes to control the flow. This unique feature makes MFCs particularly useful in dynamic calibration devices. Dynamic calibrators are used to blend gases at precise flow rates to generate a known concentration used to calibrate automated air samplers and monitors. The disadvantages associated with a MFC are identical to those of a MFM.

3.12 Velocity Meters

Velocity meters measure the linear velocity or some property that is proportional to the velocity of a gas. Several instruments exist for measuring the velocity of a gas; we will discuss only the pitot tube and the thermal anemometer. Volumetric flow information can be obtained from velocity data, if the cross-sectional area of the duct is known, using the following formula:

(Eq. 3-19) $$Q = A\bar{v}$$

Where: Q = *volumetric flow rate, m^3/min*
$\bar{v}$ = *average velocity, m/min*
A = *cross sectional area, m^2*

Pitot Tube – Primary Velocity Standard

The pitot tube is a simple pressure-sensing device used to measure the velocity of fluid flowing in an open channel. The complexity of the underlying fluid-flow principles involved in a pitot tube gas-velocity measurement is not apparent in the simple operation of this device. The pitot tube should, however, be considered and treated as a sophisticated instrument.

The pitot tube actually measures the velocity pressure (Δp) of a gas stream. Gas streamlines approaching a round object placed in a duct flow around the object, except at point "P_+," where the gas stagnates and the stagnation pressure (P_+) is found (Figure 3-34 and Figure 3-35a).

The static pressure in a gas stream is defined as the pressure that would be indicated by a pressure gauge if it were moving along with the stream so as to be at rest, or relatively "static," with respect to the fluid. The static pressure can be measured as shown in Figure 3-35b.

The difference between the stagnation pressure (P_+) and the static pressure ($P_\approx$) is the velocity pressure differential (Δp). This is shown in Figure 3-35c.

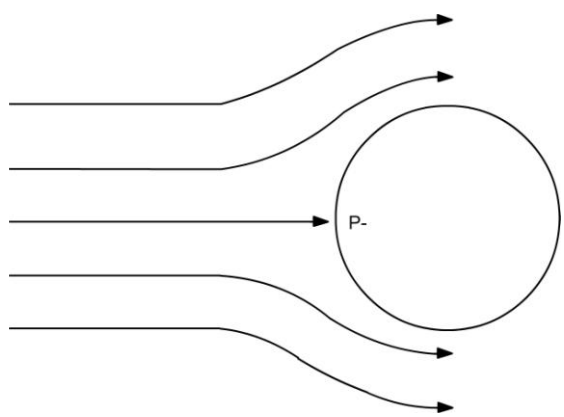

Figure 3-34. Gas stagnation against an object.

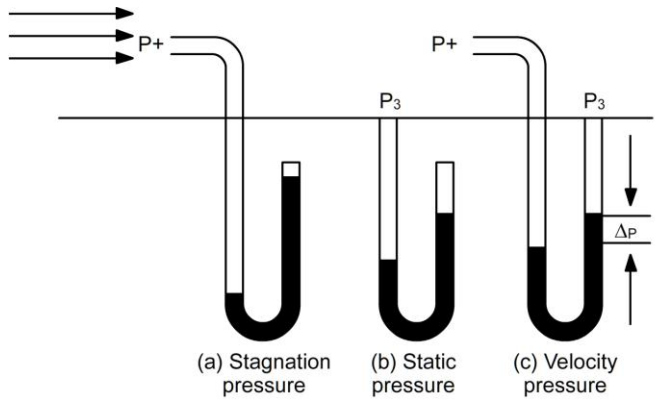

Figure 3-35. Pitot tube pressure components.

Bernoulli's Theorem relates pitot tube velocity pressure (Δp) to gas velocity in the following equation:

(Eq. 3-20)

$$v = K_p C_p \left(\frac{T \Delta p}{P\ M} \right)^{1/2}$$

Where:

v = *velocity of the gas stream, ft/sec*
T = *absolute temperature, R (°F+460)*
P = *absolute pressure, in. Hg*
M = *molecular weight of the gas, lb/lb-mole*
Δp = *velocity pressure, in.* H_2O

$$K_p = 85.49\ ft/\sec \sqrt{\frac{(lb/lb \bullet mole)(in.\ Hg)}{(in.\ H_2O)(°\mathrm{R})}}$$

C_p = *pitot tube coefficient, dimensionless.*

Pitot tubes are used extensively in ventilation work to measure air flow in ducts. Literature sources describe pitot tubes in detail. The standard and S-type pitot tubes are the most commonly used.

Standard Pitot Tube – Secondary Velocity Standard

The standard pitot tube (Figure 3-36) consists of two concentric tubes. The center tube measures the stagnation or impact pressure, and the static pressure is measured by the holes located on the side of the outer tube. The pitot tube must be placed in the flowing air stream so that it is parallel with the streamlines. The velocity pressure differential (Δp) can be measured with a U-tube manometer, inclined manometer, or any suitable pressure-sensing device. Only velocities greater than 2500 ft/min can be measured with a U-tube manometer, but flows as low as 600 ft/min can be measured with a carefully adjusted inclined manometer. Standard pitot tube velocity pressures are typically 0.14 inches of water at 1500 ft/min and 0.56 inches of water at 3000 ft/min.

The standard pitot tube was first calibrated against an orifice meter using Bernoulli's Theorem. Repeated calibrations proved that different standard pitot tubes have the same characteristic flow calibration. If the static pressure holes are six outer-tube diameters from the hemispherical tip and eight outer-tube diameters from the bend (Figure 3-39), then the theoretical C_p value in the previously mentioned formula is 1.0. Velocity determinations are seldom needed in atmospheric sampling, but are very common in source sampling. It is common practice in source sampling applications to assign a C_p value of 0.99 for a standard pitot, since empirical data indicates a slight positive bias, and to use English units (e.g., feet per second, inches of Hg, degrees Rankine [R]) as shown in Equation 3-21.

(Eq. 3-21)

$$v = K_p C_p \left(\frac{T \Delta p}{P\,M} \right)^{1/2}$$

Where:

v = *velocity of the gas stream, ft/sec*
T = *absolute temperature,* R *(°F + 460)*
P = *absolute pressure, in. Hg*
M = *molecular weight of the gas, lb/lb-mole*
Δp = *velocity pressure, in.* H_2O

$$K_p = 85.49\ ft/\sec \sqrt{\frac{(lb/lb \bullet mole)(in.\ Hg)}{(in.\ H_2O)(°\mathrm{R})}}$$

C_p = *pitot tube coefficient, dimensionless*

Standard pitot tubes can be used to measure linear velocity in almost any situation except in particle-laden gas streams. The particulate matter will foul the carefully machined tip and orifices. The velocity of gas streams with high particulate matter concentrations can be measured better with an S-type pitot tube.

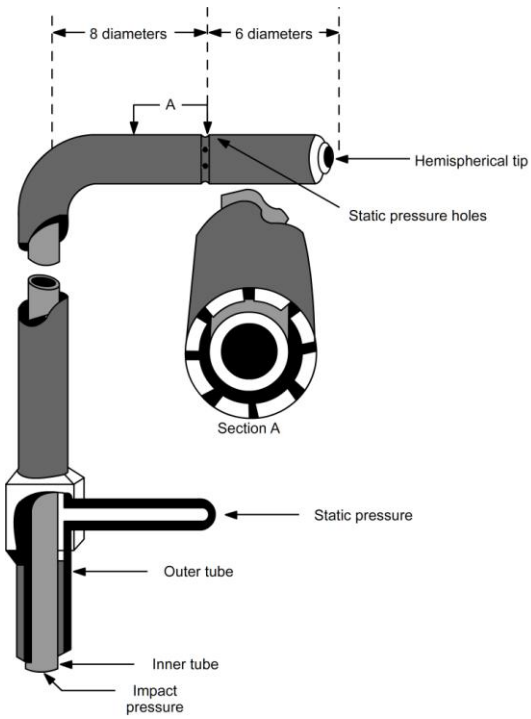

Figure 3-36. Standard pitot tube.

S-Type Pitot Tube – Secondary Velocity Standard

The S-type pitot tube consists of two identical tubes mounted back-to-back (Figure 3-37). The sampling ends of the tubes are oval with the openings parallel to each other. In use, one oval opening should point directly upstream, the other directly downstream. The tubes should be made of stainless steel or quartz if they are used in high temperature gas streams. The alignments shown in Figure 3-37 should be checked before use or calibration, as this may cause variations in the calibration coefficient (C_p).

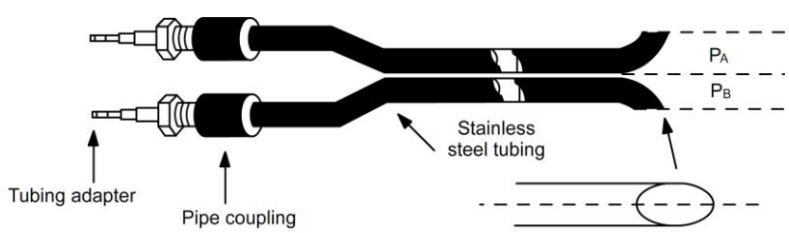

Figure 3-37. S-type pitot tube.

Calibration of the S-type pitot tube is performed by comparing it to a standard pitot tube. Both the standard and S-type pitot tubes are placed alternately into a constant air flow. Pressure readings are taken for the standard

pitot tube and for leg A of the S-type tube, facing the direction of flow, and leg B, facing the direction of the flow (Figure 3-40). The pitot tube coefficient (C_p) is calculated using the following formula:

(Eq. 3-22)

$$C_{p(S)} = C_{p(STD)}\left(\frac{\Delta p_{STD}}{\Delta p_s}\right)$$

Where:

$C_{p(S)}$ = *S-Type Pilot tube coefficient*

$C_{p(STD)}$ = *Standard pitot tube coefficient*

Δp_{STD} = *velocity pressure of Standard pitot tube, in.* H_2O

Δp_s = *velocity pressure of S-Type pitot tube, in.* H_2O

The average C_p is calculated from several readings and should have a value of approximately 0.84. The C_p for leg A and leg B should differ by less than 0.01. The C_p value can then be used to calculate velocity by the previously mentioned formula.

(Eq. 3-23)

$$v = K_p C_p \left(\frac{T\Delta p}{P\,M}\right)^{1/2}$$

Where:

v = *velocity of the gas stream, ft/sec*

T = *absolute temperature,* R *(°F + 460)*

P = *absolute pressure, in. Hg*

M = *molecular weight of the gas, lb/lb-mole*

Δp = *velocity pressure, in.* H_2O

K_p = $85.49\ ft/sec\sqrt{\dfrac{(lb/lb \bullet mole)(in.\ Hg)}{(in.\ H_2O)(°\mathrm{R})}}$

C_p = *pitot tube coefficient, dimensionless*

The S-type pitot tube maintains calibration in abusive environments. The large sensing orifices minimize the chance of being plugged with particulates. The S-type pitot tube also gives a high manometer reading for a given gas velocity pressure, which can be helpful at low gas velocities. These features make the S-type pitot tube the most frequently used instrument to measure stack gas velocity.

Thermal Anemometer – Secondary Velocity Standard

A thermal anemometer measures fluid velocities by measuring heat transfer from a small wire or film held in the gas stream of a stack or duct or in the ambient air to measure wind speed. The rate by which heat is removed from the sensor is directly related to the velocity of the fluid flowing over the sensor. So, by measuring the amount of current required to maintain the sensor at a constant

temperature, the fluid velocity can be obtained.

As suggested in the description of a thermal anemometer, these devices are typically used in source sampling applications to determine the velocity of a gas within a stack or duct. The use of a thermal anemometer in atmospheric sampling and monitoring is limited to wind speed determinations insofar as it influences sampling activities.

The advantages of thermal anemometry include high accuracy, an easily-automated collection procedure, and a high frequency response allowing measurement of turbulent flows.

3.13 Sample Problems

Problem 1: Volume Conversion to Standard Conditions

A volume of 20 m^3 was drawn from a spirometer at 20°C and 700 mm Hg. What was the standard volume drawn, based on EPA reference conditions for atmospheric sampling and monitoring?

$$V_2 = V_1\left(\frac{P_1T_2}{P_2T_1}\right)$$

Where:

V_2 = *volume at condition* 2
V_1 = *volume at condition* 1 = 20 m^3
P_1 = *pressure at condition* 1 = 700 mm Hg
P_2 = *pressure at condition* 2 = 760 mm Hg
T_1 = *temperature at condition* 1 = 20°C + 273 = 293K
T_2 = *temperature at condition* 2 = 25°C + 273 = 298K

$$V_2 = \left(20\text{m}^3\right)\left(\frac{700\,\text{mm Hg}}{760\,\text{mm Hg}}\right)\left(\frac{298\,\text{K}}{293\,\text{K}}\right)$$

$$V_2 = 18.7\ \text{m}^3$$

Problem 2: Orifice Conversion When Used at Other Calibration Conditions

An orifice was calibrated at 21°C and 760 mm Hg. It is to be used to calibrate a sampler at conditions of 25°C and 700 mm Hg. The flow at field conditions is 0.85 m^3/min (30 CFM). (a) What is the flow rate at calibration conditions? (b) What is the flow rate at standard conditions?

$$Q_2 = Q_1\left(\frac{T_2P_1}{P_2T_1}\right)^{1/2}$$

Where:

		Part a	Part b:
Q_2	= Flow 2	? (cal. condt.)	? (STD condt.)
Q_1	= Flow 1	0.85 m^3/min	Q_2 in Part a
P_2	= Press. 2	760 mm Hg	760 mm Hg
P_1	= Press. 1	700 mm Hg	700 mm Hg
T_2	= Temp. 2	21° + 273° = 294 K	298 K
T_1	= Temp. 1	25° + 273° = 298 K	294 K

(a) The flow rate at calibration conditions:

$$Q_2 = \left(0.85\,\mathrm{m}^3/\mathrm{min}\right)\left(\frac{700\,\mathrm{mm\ Hg} \times 294\,\mathrm{K}}{760\,\mathrm{mm\ Hg} \times 298\,\mathrm{K}}\right)$$

$$Q_2 = 0.81\,\mathrm{m}^3/\mathrm{min}$$

(b) The flow at standard conditions, using orifice data at calibration conditions and the flow derived in part (a):

$$Q_2 = Q_1\left(\frac{P_1 \times 298\,\mathrm{K}}{760\,\mathrm{mm\ Hg} \times T_1}\right)^{1/2}$$

$$Q_2 = 0.81\left(\frac{760\,\mathrm{mm\ Hg} \times 298\,\mathrm{K}}{760\,\mathrm{mm\ Hg} \times 294\,\mathrm{K}}\right)^{1/2}$$

$$Q = 0.82\,\mathrm{m}^3/\mathrm{min}$$

Problem 3: Conversion for Different Gas Used with a Rotameter

A rotameter was calibrated with air at 0°C and 760 mm Hg. The rotameter is now to be used to add helium as a carrier gas at 0°C and 760 mm Hg. If the flow reading at point X on the rotameter corresponded to 28.3 liters/min (1 ft^3/min) when air is used, to what flow will point X correspond when helium is used? (Density of helium = 0.1785 g/L; density of air = 1.2929 g/L.)

$$Q_2 = Q_1\left(\frac{q_1}{q_2}\right)^{1/2}$$

Where:

Q_2 = *flow with gas* 2

Q_1 = *flow with gas* 1 = 28.3 L/min

q_1 = *density of gas* 1 = 1.2929 g/L *(air)*

q_2 = *density of gas* 2 = 0.1785 g/L *(helium)*

$$Q_2 = 28.3\left(\frac{1.2929\text{g/L}}{0.1785\text{g/L}}\right)^{1/2}$$

$$= 28.3(7.2431)^{1/2}$$

$$Q_2 = 76.2\ \text{L/min}$$

Problem 4: Pump Capacity

Can a pump with the following capacity curve (Figure 3-38) be used to drive critical orifices that have flow rates of (a) 50 cc/min and (b) 250 cc/min at criticality? (Hint: atmospheric pressure = 30 in. Hg.)

For an orifice to be critical,

$$P_{downstream} \le 0.53 \text{ or } \le 0.53(30) \text{ or } \le 16 \text{ in. Hg.}$$

$$P_{downstream} = P_b + p_{\tilde{z}}, \text{ therefore}$$

$$P_{\tilde{z}} = 30 - 16 = 14 \text{ in. Hg gauge vacuum}$$

At a gauge vacuum of 14 in. Hg, the pump can pull approximately 130 to 140 cc/min. Therefore, this pump could operate orifice (a) at 50 cc/min, but not (b) at 250 cc/min.

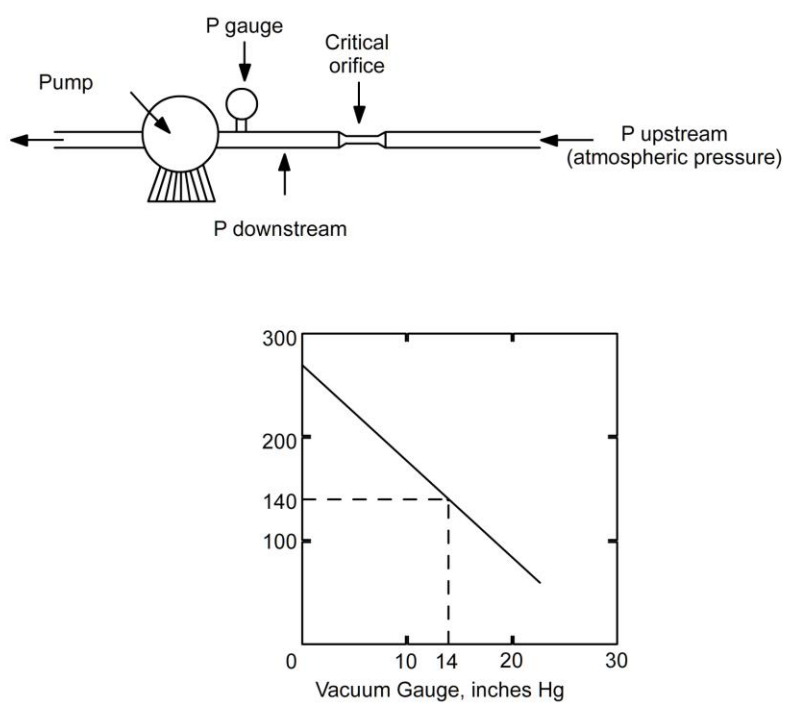

Figure 3-38. Problem 4: Pump capacity.

3.14 Additional $PM_{2.5}$ Flowmeters and Devices

Flow rate standards used for calibrating or verifying a $PM_{2.5}$ sampler's flow rate measurement device must have an accuracy of ± 2%. This flow rate standard must be a separate, stand-alone device designed to connect to the flow rate measurement adapter. The flow rate standard must have its own certification and must be traceable to a NIST primary standard for volume or flow rate.

The following section includes the advantages and disadvantages of some of the various types of flow rate standards that might be considered for $PM_{2.5}$ sampler calibration.

Bubble Flowmeters

Although manually-operated and timed bubble flowmeters are available, a semiautomatic instrument is easier to use and is likely to provide more uniform flow rate measurements. Because the liquid used to form the bubbles is usually water-based, a water vapor correction may be required to compensate for a volume increase due to evaporation of the water in the instrument. Furthermore, the instrument cannot be used below 0°C because the soap solution will freeze.

Piston Flowmeters

Automatic dry-piston flowmeters are relatively easy to use and are not subject to the water vapor correction of the liquid-freezing limitation of the bubble flowmeters. However, they may still be subject to a lower operational temperature limit due to LCD readouts. Alternatively, hard-copy printouts could be used to log results. Some models which are not equipped with a pressure release valve can create a series of momentary pressure drops as the piston is in operation, which the $PM_{2.5}$ sampler may compensate for by increasing the driving force to the pump.

Mass Flowmeters

Although mass flowmeters may be considered as calibration standards, they have a number of shortcomings in this application. They have a high pressure drop, which could change the sampler flow rate or otherwise affect the operation of the sampler. Mass flowmeters also require conversion of the measured mass flow rate to the actual volumetric flow rate for comparison to the $PM_{2.5}$ sampler displayed value. The flow rate measured by the sampler may also have to be corrected to account for significant pressure drop introduced by the mass flowmeter itself. Finally, mass flowmeters are subject to zero or span drift, particularly over the wide range of temperatures encountered at field sites, so their accuracy should be reverified frequently over a wide temperature range.

Orifice Devices

Orifice devices are simple and reliable, but they require corrections for temperature and pressure and may have a significant pressure drop. They also require a very accurate and sensitive differential pressure measurement device, such as a manometer or an aneroid differential pressure gauge, whose accuracy

must be reverified frequently. Electronic micromanometers are convenient to use with an orifice device. Readings from electronic micromanometers should be crosschecked against a water manometer prior to a round of sampler verifications or calibrations.

Laminar Flow Elements

Laminar flow elements generally have a lower pressure drop than orifice devices but otherwise have the same requirements and disadvantages.

Wet Test Meters

Wet test meters are generally not practical for field use but may be used for laboratory calibrations.

Dry Gas Meters

Dry gas meters may be considered for field calibration. Some meters may have a substantial pressure drop. They should be checked for leaks and mechanical problems and be recertified at least annually. Dry gas meters may take a much longer period of time to use since instantaneous and semi-instantaneous values are not available.

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