4.0 TECHNICAL REFERENCE FOR MONITORING EQUIPMENT AND INSTRUMENTS

4.1 INTRODUCTION

The objective of this section is to provide reference materials for various types of sensors commonly used to measure process and/or air pollution control equipment operating parameters. The owner or operator of a facility may use this chapter as guidance in developing a QA/QC program. This section is in no way intended to specify prescriptive QA/QC procedures that must be used. Instead, the focus of this section is on (1) identifying the types of sensors commonly used to monitor a given parameter, and (2) identifying basic calibration techniques that may be used in the development of an integrated QA/QC program for assuring continued accurate performance over time.

This section describes the various types of sensors, the measurement principle(s), other system components used with the sensor to perform measurements, and basic calibration techniques for the following measurement systems:

4.2 Temperature
4.3 Pressure
4.4 Flow rate
4.5 pH and conductivity
4.6 Electrical [Reserved]
4.7 Level indicators [Reserved]
4.8 Motion and rotation [Reserved]

For each type of measurement system, the following information is presented:

- Description of sensor, measurement principle, and measurement system components;
- Expected accuracy and precision ranges;
- Calibration techniques;
- QA/QC procedures; and
- Additional resources and references.

For each sensor system, descriptions of some of the different types of systems used are presented, including the operating principles and identification of individual components requiring QA/QC procedures. Operating and maintenance procedures and common problems, as well as calibration techniques and procedures and expected accuracy and precision ranges, are

included. Much of this information is drawn from manufacturers' data. References are provided at the end of each subsection.

In describing the characteristics and operation of many of the devices covered by this chapter, some general terms are used. Because these terms are used throughout the chapter, the definitions of the more important terms are provided below.

Accuracy: The closeness of an indicator or reading of a measurement device to the actual value of the quantity being measured; usually expressed as ± percent of the full scale output or reading.

Drift: The change in output or set point value over long periods of time due to such factors as temperature, voltage, and time.

Hysteresis: The difference in output after a full cycle in which the input value approaches the reference point (conditions) with increasing, then decreasing values or vice versa; it is measured by decreasing the input to one extreme (minimum or maximum value), then to the other extreme, then returning the input to the reference (starting) value.

Linearity: How closely the output of a sensor approximates a straight line when the applied input is linear.

Noise: An unwanted electrical interference on signal wires.

Nonlinearity: The difference between the actual deflection curve of a unit and a straight line drawn between the upper and lower range terminal values of the deflection, expressed as a percentage of full range deflection.

Precision: The degree of agreement between a number of independent observations of the same physical quantity obtained under the same conditions.

Repeatability: The ability of a sensor to reproduce output readings when the same input value is applied to it consecutively under the same conditions.

Resolution: The smallest detectable increment of measurement.

Sensitivity: The minimum change in input signal to which an instrument can respond.

Stability: The ability of an instrument to provide consistent output over an extended period during which a constant input is applied.

Zero balance: The ability of the transducer to output a value of zero at the electronic null point.

Calibration is the process of adjusting an instrument, or compiling a deviation chart for a probe, so that its readings can be correlated to the actual value being measured. Generally, inaccuracies within a monitoring system are cumulative; therefore, the entire system should be calibrated when possible. Many monitoring applications may rely more on repeatability than on accuracy. In such cases, documentation takes on added significance when detecting system drift.

While manual methods may be sufficient for CAM in some instances (e.g., visible emissions monitoring), electronic measurement of parameters such as temperature, pressure and flow provides the opportunity to incorporate that monitoring into other systems, such as process control. Although not discussed here, centralized control strategies, hierarchical plant-wide networks of programmable logic controllers (PLC's), single loop controllers, and PC's are now in use for monitoring process parameters. Many proprietary distributed control systems have been successfully implemented. Future control systems will include peer-to-peer networks of interconnected field devices that improve the reliability of sensor-actuator systems. Fuzzy logic-based software can be used to improve control systems efficiency. Incorporation of improved system controls can make industrial processes run more smoothly, thus making emissions control and monitoring easier.

4.2 TEMPERATURE MEASUREMENT SYSTEMS

4.2.1 Introduction

Temperature measurement can be accomplished using several types of sensing mechanisms. Temperature measurement systems generally consist of a sensor, a transmitter, an external power supply (for some types of systems), and the wiring that connects these components. The temperature measurement sensors most commonly used in engineering applications are thermocouples, resistance temperature detectors (RTD's), and infrared (IR) thermometers; these devices are described in detail in the following paragraphs. Integrated circuit (IC) temperature transducers and thermistors also are commonly used but have more limitations than thermocouples, RTD's, and IR thermometers. Table 4.2-1 lists some of the advantages and disadvantages of these types of temperature measuring devices.

TABLE 4.2-1 TEMPERATURE MONITORING SYSTEM CHARACTERISTICS[1-3]

Thermocouple	RTD	IR thermometer	IC sensor	Thermistor
Advantages				
• Self-powered • Simple • Rugged • Inexpensive • Many applications • Wide temperature range • Fast response	• More stable at moderate temperatures • High levels of accuracy • Relatively linear output signal	• Fast response • Non-contact • T < 3000°C • Less sensitive to vibration • Less sensitive to interference	• Relatively linear • High output • Inexpensive	• High output • Fast • Two-wire ohms measurement
Disadvantages				
• Nonlinear output signal • Low voltage • Reference required • Accuracy is function of two separate measurements • Least sensitive • Sensor cannot be recalibrated • Least stable	• Expensive • Self-heating • Lower temperature range	• Expensive • Must be protected • Affected by emissivity of target	• T < 200°C • Slower response • Self-heating	• Nonlinear • Limited temperature range • Fragile • Current source required • Self-heating

Other types of temperature sensors include bimetallic devices, fluid expansion devices, and change-of-state devices. Bimetallic temperature sensors relate temperature to the difference

in thermal expansion between two bonded strips of different metals. Fluid expansion devices, such as the common thermometer, measure temperature as a function of the thermal expansion of mercury or organic liquid, such as alcohol. Change-of-state temperature sensors change appearance when a specific temperature is reached. One major drawback of these types of sensors is that they do not readily lend themselves to automatically recording temperatures on a continuous or periodic basis.

The following paragraphs describe temperature measurement systems that are based on three types of temperature sensors: Section 4.2.2 describes thermocouples, Section 4.2.3 describes RTD's, and IR thermometers are described in Section 4.2.4. For each type of system, the system components, operation, accuracy, calibration, and QA/QC procedures are discussed. References are listed in Section 4.2.5.

4.2.2 Thermocouples[1,2]

Due to their simplicity, reliability, and relatively low cost, thermocouples are widely used. They are self-powered, eliminating the need for a separate power supply to the sensor. Thermocouples are fairly durable when they are appropriately chosen for a given application. Thermocouples also can be used in high-temperature applications, such as incinerators.

4.2.2.1 Measurement Principle and Description of Sensor

A thermocouple is a type of temperature transducer that operates on the principle that dissimilar conductive materials generate current when joined (the Seebeck effect). Such a device is made by joining two wires made of different metals (or alloys) together at one end, generating a voltage e_{AB} when heated, as shown schematically in Figure 4.2-1.

The generated voltage is proportional to the difference between the temperatures of the measured point and an experimentally determined reference point (block temperature) and is also dependent on the materials used. A basic temperature monitoring system using a thermocouple is made up of the thermocouple, connectors, extension wires, isothermal block (also called temperature blocks, terminal blocks, or zone boxes), and a voltmeter or transmitter, as shown schematically in Figure 4.2-2.

This schematic is for a type J iron (Fe)-constantin (Cu-Ni) thermocouple. As the thermocouple junction point (J_1) is heated or cooled, the resulting voltage can be measured using a potentiometer or digital voltmeter (DVM), which is calibrated to read in degrees of temperature. In practice, a programmed indicator or a combination indicator/controller is used to

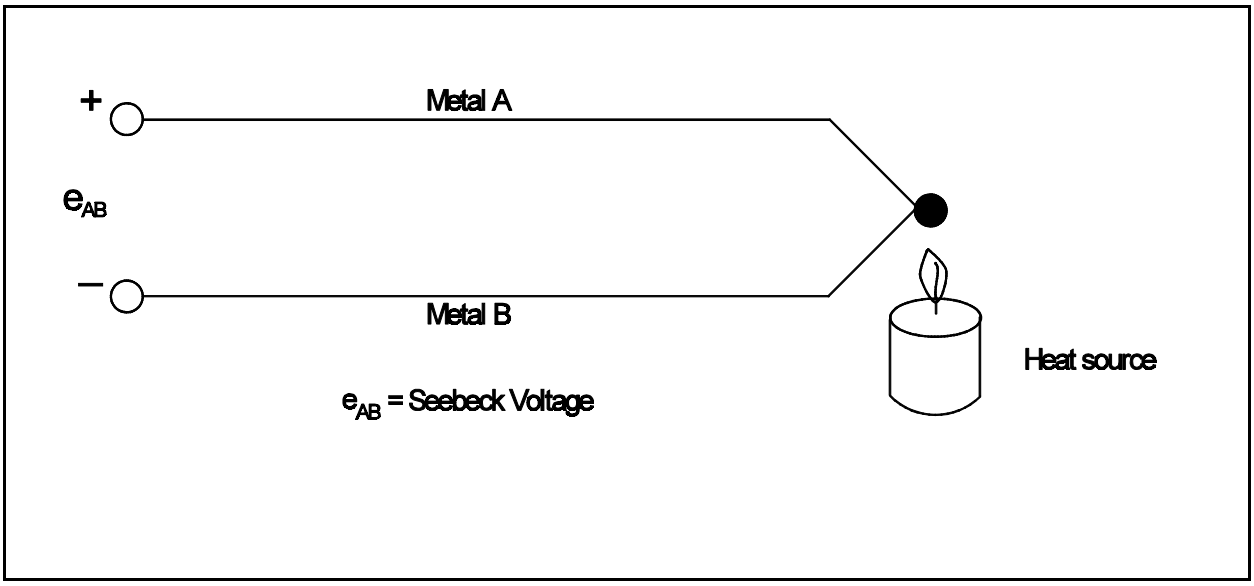

Figure 4.2-1. The Seebeck effect.[1]

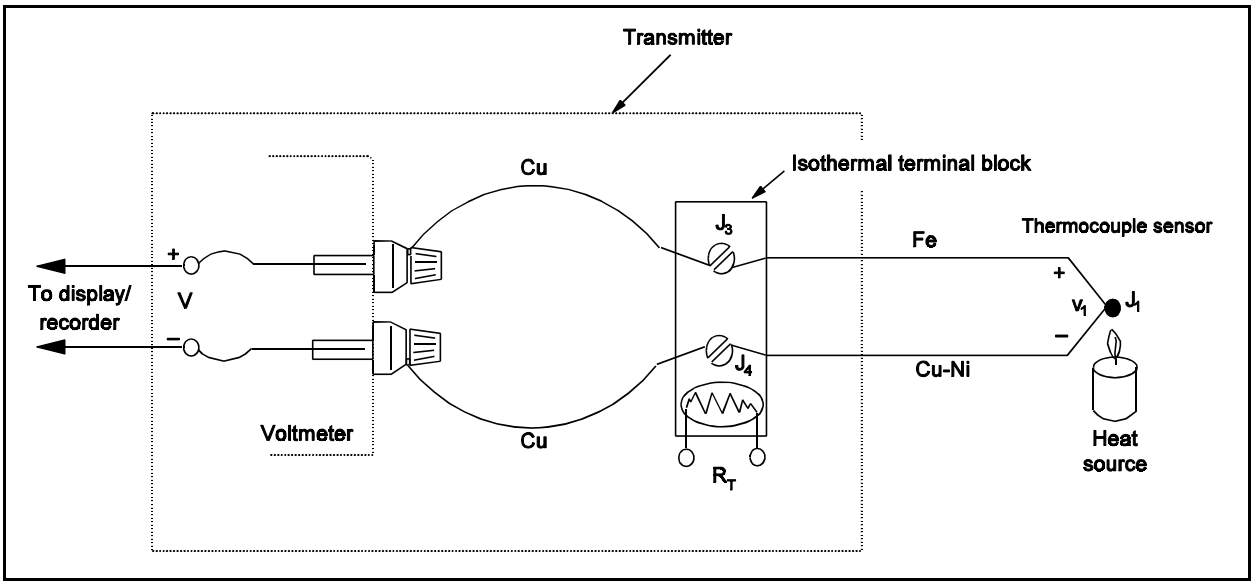

Figure 4.2-2. Temperature measurement using a thermocouple.[1]

convert the signal from voltage to temperature using the appropriate equation for the particular thermocouple materials and compensation for voltage generated at terminal connection points (J_3 and J_4). The temperature of the isothermal terminal block or zone box is measured using a proportional resistance device (R_T) such as an IC detector. That temperature is used as the reference temperature, T_{ref}, for determining the temperature being monitored at the thermocouple junction, J_1.

The voltmeter, terminal block, and associated circuitry generally are incorporated into the system transmitter. The terminal block may be located in the transmitter adjacent to the process being monitored or it may be located remotely with the controller or recorder. In the latter case, one terminal block can be used for several thermocouples simultaneously.

Figure 4.2-3 depicts a typical thermocouple assembly. In the figure, the thermocouple sensor is located inside the sheath. At the transition, the thermocouple wire from the sensor is welded or brazed to the extension lead wire, which generally is made of a more flexible material. The head consists of a small junction box, which is connected to the conduit through which the thermocouple wire passes to the controller and recorder.

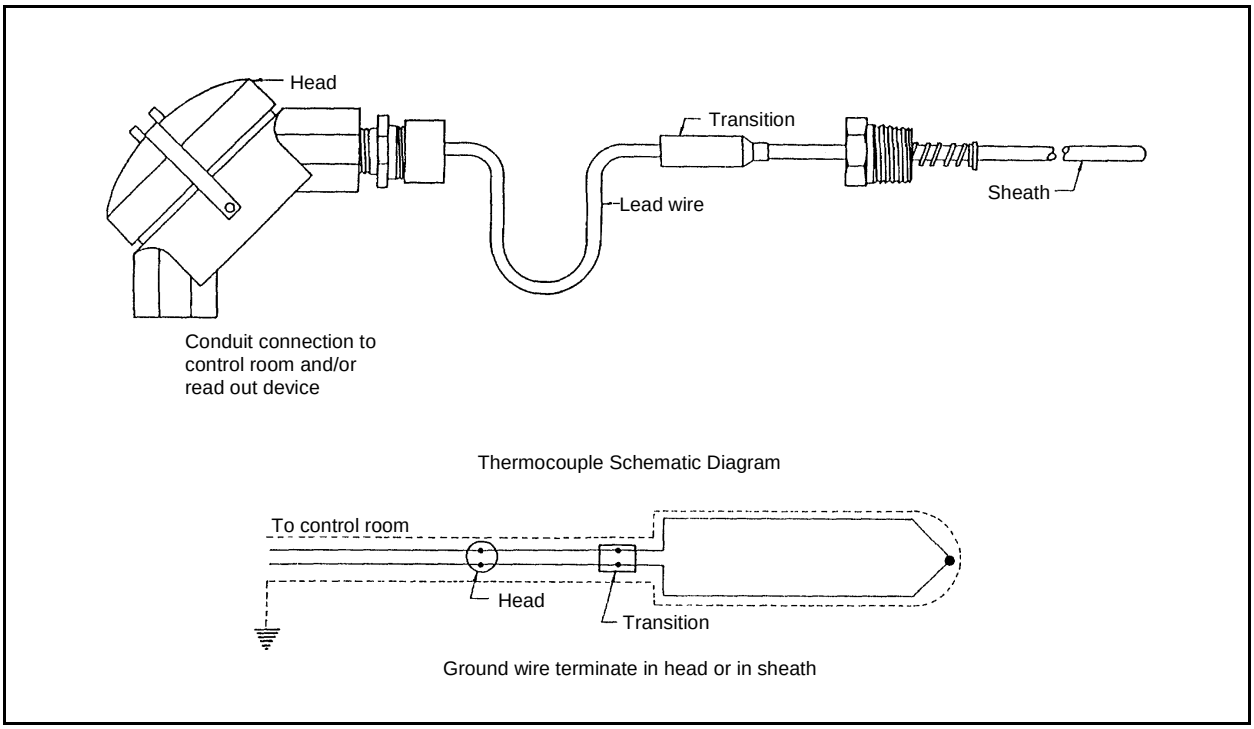

Figure 4.2-3. Thermocouple assembly.[2]

A sheath is a closed-end metal tube that protects the sensor from moisture and corrosive-process environments. The sheath also provides mechanical protection and flexibility of the assembly, isolates the thermocouple electronically, and improves the quality and reliability of the thermocouple. The sheathed thermocouple is constructed as a single unit. A commonly used

type of sheathed thermocouple is the mineral-insulated metal sheathed (MIMS) thermocouple. In this device, the thermocouple wires are surrounded with a mineral-based insulating material (typically, magnesium oxide) within the sheath to provide further protection. Thermowells also are used to protect thermocouple sensors. Thermowells are tubes into which the thermocouple is inserted. Thermowells generally are bolted onto the wall of the process vessel, pipe, or duct. In some applications, the annular space between the inside wall of the thermowell and the ethermocouple inserted into the thermowell is filled with a heat transfer fluid to shorten the response time of the sensor. Other options for protecting thermocouple sensors include vinyl tips for use in environments subject to moisture and moderate temperatures, and ceramic fiber insulation.

Thermocouples have been classified by the Instrument Society of America and the American National Standards Institute (ANSI), and are available for temperatures ranging from -200° to 1700°C (-330° to 3100°F). These standard tolerance thermocouples range in tolerance from ±0.5 percent to ±2 percent of true temperature. Table 4.2-2 presents commonly available thermocouple types and operating ranges.

Thermocouples must be selected to meet the conditions of the application. Thermocouple and extension wires (used to transmit the voltage from the thermocouple to the monitoring point) are generally specified and ordered by their ANSI letter designations for wire types. Positive and negative legs are identified by the letter suffixes P and N, respectively. General size and type recommendations are based on length of service, temperature, type of atmosphere (gas or liquid constituents), and desired response times. Smaller wire gauges provide faster response but do not last as long under adverse conditions. Conversely, larger gauges provide longer service life but with longer response times. Thermowells and sheaths are recommended by thermocouple manufacturers for the extension of thermocouple life. Instruments used to convert thermocouple voltage to temperature scales are coded using the same letter designations. Failure to use matching thermocouples and instruments will result in erroneous readings.

Type J thermocouples use iron for the positive leg and copper-nickel (constantin) alloys for the negative leg. They may be used unprotected where there is an oxygen-deficient atmosphere, but a thermowell is recommended for cleanliness and generally longer life. Because the iron (positive leg) wire oxidizes rapidly at temperatures over 1000°F, manufacturers recommend using larger gauge wires to extend the life of the thermocouple when temperatures approach the maximum operating temperature.

Type K thermocouples use chromium-nickel alloys for the positive leg and copper alloys for the negative leg. They are reliable and relatively accurate over a wide temperature range. It is a good practice to protect Type K thermocouples with a suitable ceramic tube, especially in reducing atmospheres. In oxidizing atmospheres, such as electric arc furnaces, tube protection

TABLE 4.2-2. THERMOCOUPLE DESIGNATIONS, RANGES, AND TOLERANCES[4]

Thermocouple type	Temperature Range °Celsius	Temperature Range °Fahrenheit	Standard tolerance[a]
B	800 to 1700	1500 to 3100	±0.5%
C[b]	430 to 2300	800 to 4200	±1%
D[b]	0 to 2300	32 to 4200	±4.4°C (±8°F)
E	0 to 900	32 to 1650	±1.7°C or ±0.5%
G[b]	0 to 2300	32 to 4200	±4.4°C (±8°F)
J (common)	0 to 750	32 to 1400	±2.2°C or ±0.75%
K (common)	0 to 1250	32 to 2300	±2.2°C or ±0.75%
M[b]	-50 to 1400	-60 to 2600	±0.75%
N	0 to 1250	32 to 2300	±2.2°C or ±0.75%
P[b]	0 to 1400	32 to 2550	±0.10 mV
R (common) or S	0 to 1450	32 to 2650	±1.5°C or ±0.25%
T	0 to 350	32 to 660	±1.0°C or ±0.75%
Cryogenic Ranges			
E	-200 to 0	-330 to 32	±1.7°C or ±1%
K	-200 to 0	-330 to 32	±2.2°C or ±2%
T	-200 to 0	-330 to 32	±1.0°C or ±2%

[a]Where tolerances are given in degrees and as a percentage, the larger value applies. Where tolerances are given in percent, the percentage applies to the temperature measured in degrees Celsius. For example, the standard tolerance of Type J over the temperature range 277° to 750°C is ±0.75 percent. If the temperature being measured is 538°C, the tolerance is ±0.75 percent of 538, or ±4.0°C. To determine the tolerance in degrees Fahrenheit, multiply the tolerance in degrees Celsius by 1.8.
[b]Non-ANSI coded materials.

may not be necessary as long as other conditions are suitable; however, manufacturers still recommend protection for cleanliness and prevention of mechanical damage. Type K thermocouples generally outlast Type J, because the iron wire in a Type J thermocouple oxidizes rapidly at higher temperatures.

Type N thermocouples use nickel alloys for both the positive and negative legs to achieve operation at higher temperatures, especially where sulfur compounds are present. They provide better resistance to oxidation, leading to longer service life overall.

Type T thermocouples use copper for the positive leg and copper-nickel alloys for the negative leg. They can be used in either oxidizing or reducing atmospheres, but, again, manufacturers recommend the use of thermowells. These are good stable thermocouples for lower temperatures.

Types S, R, and B thermocouples use noble metals for the leg wires and are able to perform at higher temperatures than the common Types J and K. They are, however, easily contaminated, and reducing atmospheres are particularly detrimental to their accuracy. Manufacturers of such thermocouples recommend gas-tight ceramic tubes, secondary porcelain protective tubes, and a silicon carbide or metal outer protective tube depending on service locations.

4.2.2.2 System Components and Operation

Thermocouples are often placed in thermowells built into process equipment to allow convenient maintenance and to protect the thermocouples. Optional equipment includes external reference devices, data acquisition systems using scanners to switch between thermocouples, and a computer to calculate and display the measured temperatures. Electronic data logging systems can be used to store temperature data, and digital systems are often integrated with production process control. Manufacturers of thermocouple systems use some standardization in terminology and connectors, making it easier to make sure that all system parts are compatible.

4.2.2.3 Accuracy

In general, thermocouples are capable of temperature measurement within 1 to 2 percent of the temperature in degrees Celsius (see Table 4.2-2). Overall system accuracy depends on the type of calibrations performed and on the type of signal processing used.

4.2.2.4 Calibration Techniques[3,5-7]

Thermocouple systems can lose their calibration and should be inspected regularly to determine the need for replacement of thermocouples, connectors, extension wires, zone boxes, or voltmeters. Loss of calibration indicates that something besides the temperature at the

measured point is affecting the current generated in the system and is causing an erroneous temperature reading. Electrical interferences may be present, requiring the use of twisted extension wires and shielded contacts. Oxidation also may occur at the thermocouple junction, changing the composition of the junction and therefore the voltage generated. Erosion of the thermocouple by entrained particles can have the same effect. When possible, final calibration should be performed under actual electromagnetic, radio frequency, and ambient temperature conditions.

4.2.2.4.1 Sensor. Although thermocouple systems can lose their calibrated accuracy, thermocouples themselves cannot be adjusted. Once they fail they must be replaced. Thermocouple sensors can be obtained with certificates of calibration at multiple points and then monitored using simple checks for evidence of drift. Comparative measurement of known temperatures (e.g., ice point, boiling point, etc.) with an American Society for Testing and Materials (ASTM) certified mercury thermometer, or even a voltage/current generator, should be enough to show that the sensor has not deteriorated significantly. Testing of thermocouples can be accomplished by measuring known temperatures and using a calibrated voltmeter to compare performance to the manufacturers' specifications. Thermocouple resistance can be checked using an ohmmeter, giving an indication of thermocouple condition. Abrupt changes in thermocouple resistance translate into voltage changes, signaling some type of problem or failure, such as an open wire, short circuit, changes due to vibration fatigue, or overheating. Voltmeters used to check thermocouple resistance must be capable of offset compensation; that is, compensation for the voltage the thermocouple generates.

4.2.2.4.2 System. Ideally, calibration should be performed on the system as a whole by measuring known temperatures at the thermocouple junction and adjusting the voltmeter accordingly. System calibration devices typically use either physical or electronically-simulated comparison methods. Figure 4.2-4 shows the setup for calibrating a thermocouple system.

First, the instrument should be electronically calibrated according to the procedures (e.g., zero and span adjustment) in the manufacturer's owners manual. Then, the thermocouple probes are placed in a device which creates a known reference temperature, traceable to National Institute for Standards and Technology (NIST) standards. Simulated temperatures using standardized voltage sources (such as "electronic ice points") can also be used. Decalibration errors (differences in electrochemical characteristics from original manufacturer design specifications) may be induced by physical or chemical changes in the thermocouple, making the task of system calibration more difficult. Decalibration errors can be caused by the absorption of atmospheric particles by the thermocouple (thus changing its chemical makeup), by radiation, or if the metal's structure is changed by heat annealing or cold-working strain. Finally, the results of the calibration efforts must be tabulated, showing the deviations between the thermocouple

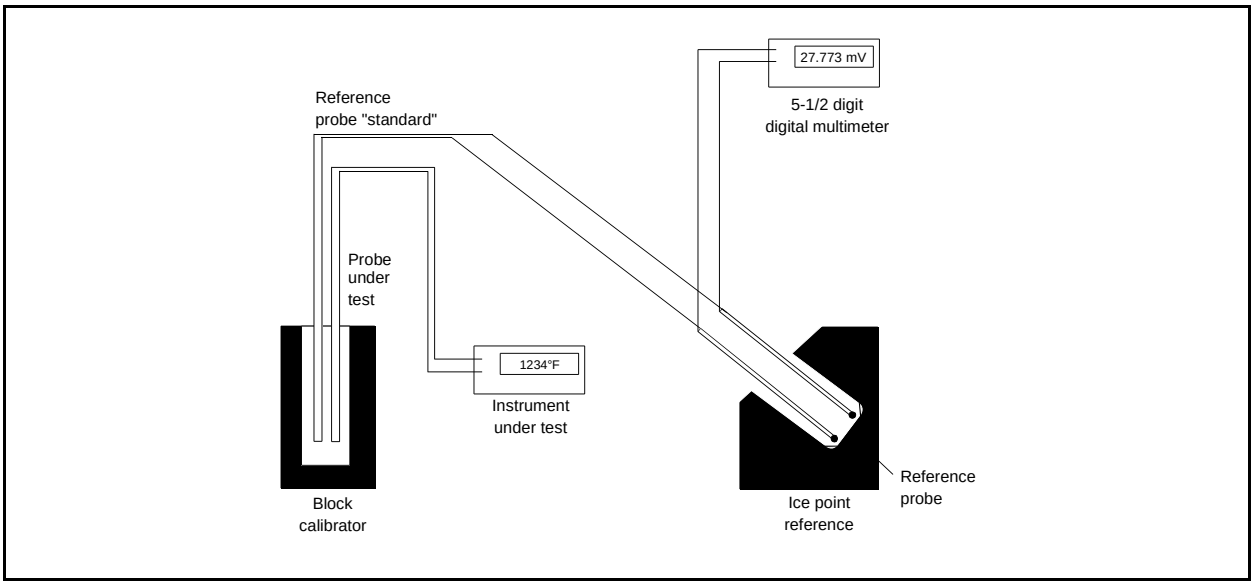

Figure 4.2-4. Setup for calibrating temperature measurement systems.[1]

system readings and known temperatures used in calibrating the system. The table can then be used to track changes in system performance and correct readings to actual temperatures. If the temperatures measured are within the tolerance (expected "accuracy") range, calibration is complete.

The ASTM provides standard test methods, which can be helpful in calibration. The appropriate thermometer can be determined using ASTM Method E 1. The ASTM Method E 220 specifies the standard method of calibrating thermocouples by comparison techniques, and the following paragraphs summarize the calibration procedures specified in that standard. The ASTM Method E 563 describes the procedure for preparing freezing point reference baths. The ASTM Method E 452 gives the standard test method for calibration of refractory metal thermocouples using an optical pyrometer. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) provides standard methods for temperature measurement for the ANSI under ANSI/ASHRAE Standard 41.1. This guide is especially relevant for gas handling systems such as air pollution control equipment.

The ASTM E 220, "Standard Method for Calibration of Thermocouples by Comparison Techniques" covers the calibration of thermocouples using comparison to another, more accurate, thermometer. The reference thermometer could be another thermocouple, a liquid-in-glass thermometer, or an RTD. The most important consideration is that both the thermocouple to be calibrated and the reference thermometer are held at approximately the same temperature. Air is a poor conducting medium for this kind of comparison; liquid immersion or uniformly heated metal blocks, tube furnaces, or sand baths are more appropriate. Platinum resistance thermometers are the most accurate reference thermometers in stirred liquid baths from

temperatures of approximately -180° to 630°C (-300° to 1170°F). Liquid-in-glass thermometers generally may be used for temperatures ranging from -180° to 400°C (-300° to 750°F), although special thermometers may be used at even higher temperatures. Types R and S thermocouples (24-gauge) can be used for very high temperatures 630° to 1190°C (1170° to 2190°F).

The general procedure specified in ASTM Method E 220 is to measure the electromotive force of the thermocouple being calibrated at selected calibration points; the temperature of each point is measured with a standard thermocouple or other thermometer standard. The number and choice of test points will depend upon the type of thermocouple, the temperature range to be covered, and the accuracy required. Thermocouples should generally be calibrated at least at three points or every 100°C (200°F). For example, if the range of measurement is 0° to 870°C (32° to 1600°F), the system should be calibrated at 300°, 600°, and 870°C (572°, 1110°, and 1600°F); if the range of measurement is 135° to 245°C (300° to 500°F), the thermocouple should be calibrated at 135°, 180°, and 245°C (300°, 400°, and 500°F). If another thermocouple is used as the reference, very precise comparisons can be made using potentiometers with reflecting devices on them. The reflected spots can be focused on a common scale, which will amplify very small differences. This procedure is especially useful because it can be used to test the monitoring system as a whole.

A useful diagnostic procedure in the event of an unexpected temperature reading is the "block test." Block tests check for proper operation of the voltmeter and isothermal block itself. To perform a block test, the thermocouple in question is temporarily short-circuited directly at the block. The system should read a temperature very close to that of the block (i.e., room temperature). If that is not the case, it is likely that either the thermocouple itself must be replaced or there is a faulty connector or extension wire in the system prior to the isothermal block. Once the system has been repaired, it can be recalibrated. In systems using redundant thermocouples, the difference in temperature readings can be monitored, indicating thermocouple drift or failure. In particularly harsh applications, scheduled thermocouple replacement may be the most expedient method for maintaining thermocouple accuracy.

A simpler method of checking thermocouple sensor performance is to install a pair of thermocouples in close proximity. The temperature readings on both thermocouples are checked simultaneously. As soon as the temperatures diverge, indicating a failure of one or both of the thermocouples, both are replaced. Another simple method for checking sensor accuracy is to insert another thermocouple with lower tolerances adjacent to the thermocouple in question and compare the temperature readings of the two thermocouples. The practices described in this paragraph do not preclude the need to calibrate the transmitter periodically. Figures 4.2-5 and 4.2-6 illustrate the equipment and connections needed to calibrate a thermocouple transmitter by means of a thermocouple simulator and an ice bath, respectively.

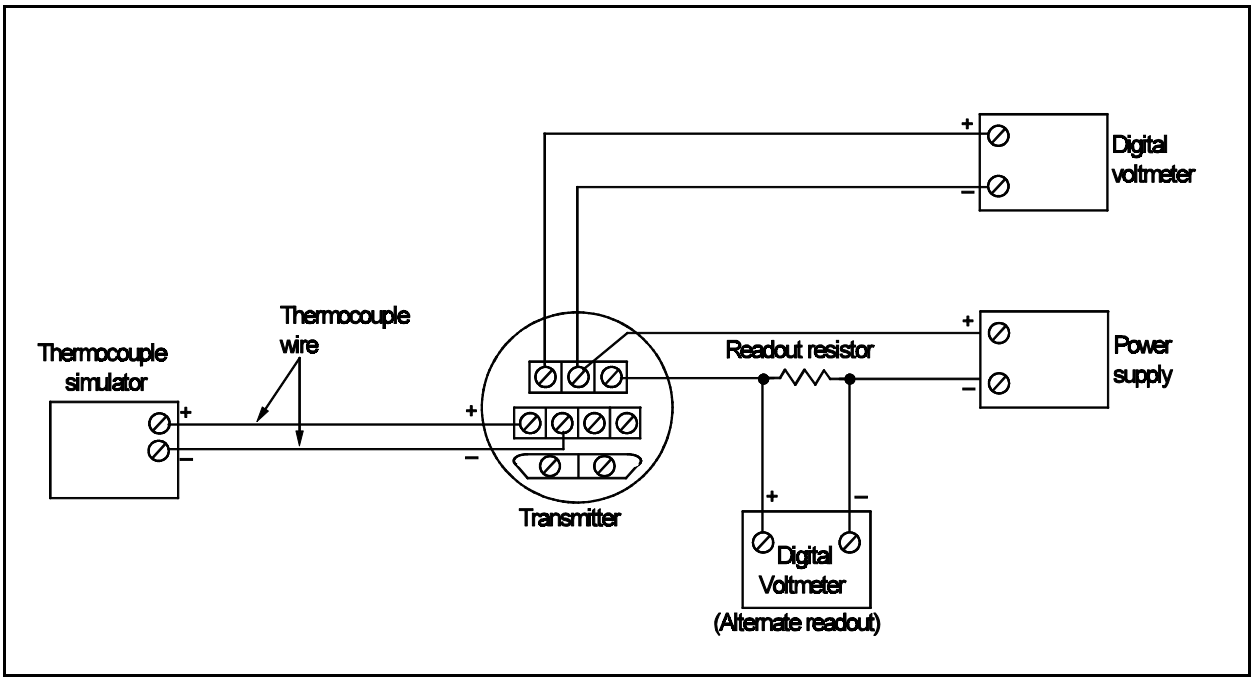

Figure 4.2-5. Setup for calibrating a thermocouple transmitter using a thermocouple simulator.[8]

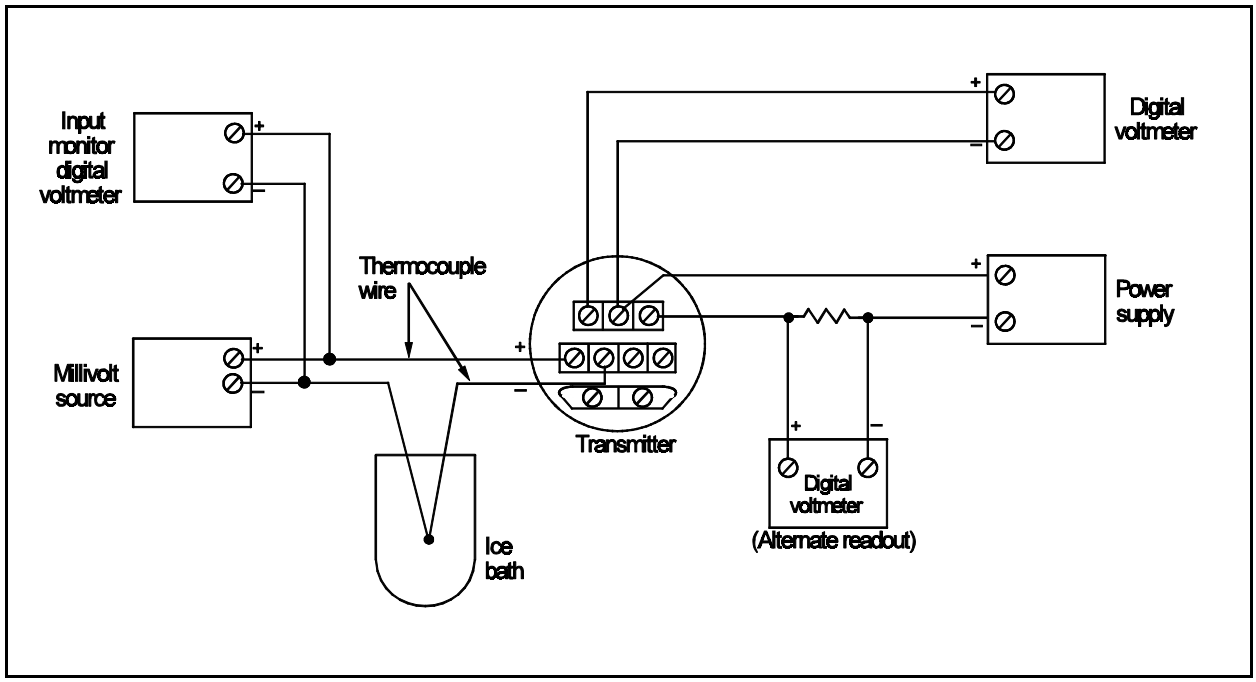

Figure 4.2-6. Setup for calibrating a thermocouple transmitter using an ice bath.[8]

4.2.2.5 Recommended QA/QC Procedures.[1,3-5,7,9-10]

Proper use and maintenance of thermocouple systems begin with good system design based on the strengths and weaknesses of various thermocouple types. Because these sensors contain sensitive electronics, general good practice includes use of shielded cases and twisted-pair wire, use of proper sheathing, avoidance of steep temperature gradients, use of large-gauge extension wire, and use of guarded integrating voltmeters or ohmmeters, which electronically filter out unwanted signals. The signal conditioner should be located as close as possible to the sensor, and twisted copper-wire pairs should be used to transmit the signal to the control station. To minimize electromagnetic field interference, sensor system wires should not be located parallel to power supply cables. The primary causes of loss of calibration in thermocouples include the following:

1. Electric "noise" from nearby motors, electric furnaces, or other such electrically noisy equipment;

2. Radio frequency interference from the use of hand-held radios near the instrument; and

3. "Ground loops" that result when condensation and corrosion ground the thermocouple and create a ground loop circuit with another ground connection in the sensing circuit.

Most problems with thermocouples are aggravated by use of the thermocouple to measure temperatures that approach or exceed their upper temperature limits. Careful recording of events that could affect measurements should be kept in a logbook. Any adjustments or calibrations should also be recorded. The logbook should contain the names of individuals performing maintenance and calibrations as well as defined procedures. In systems monitoring many locations, such a log is especially useful for fault diagnosis.

Thermocouples sometimes experience catastrophic failures, which may be preceded by extreme oscillations or erratic readings. In such cases, all connections associated with the thermocouple should be checked for loose screws, oxidation, and galvanic corrosion. In many cases, drift may be a more serious problem because it can go unnoticed for long periods of time. The most common causes of loss of calibration are excessive heat, work hardening, and contamination. Work hardening generally is due to excessive bending or vibration and can be prevented with properly designed thermowells, insertion lengths, and materials. Contamination is caused by chemicals and moisture, which sometimes attack wiring by penetrating sheaths, and can result in short-circuiting. A simple test to check for this problem is to disconnect the sensor at its closest connection and check for electrical continuity between the wires and the sheath using a multimeter. If the meter indicates continuity, the sensor should be replaced. Because the electromotive force (EMF) produced by thermocouples is so small, electrical noise can severely affect thermocouple performance. For that reason, it also is very important that transmitters be

isolated. Thermocouples used in the vicinity of electrostatic precipitators must be shielded to avoid electrical interference. If the potential electrical interference is high, an RTD or other type of sensor may be preferred to thermocouples. With respect to thermocouple and protection tube selection, the following should be noted:

1. Type J thermocouples particularly should not be used in applications in which they might be exposed to moisture because the iron in the thermocouple will rust and deteriorate quickly;

2. Type K thermocouples should not be used in the presence of sulfur, which causes the element to corrode; because cutting oils often contain sulfur, protection tubes should be degreased before being used; stainless steel sheaths should be used to protect Type K thermocouples in stacks where SO_2 emissions are significant;

3. Platinum thermocouple elements (Types R, S, or B) should not be used with metal protection tubes unless the tubes have a ceramic lining because the metal will contaminate the platinum;

4. Ceramic, silicon carbide, and composite (metal ceramic, Cerite-II, Cerite-III) protection tubes are subject to thermal shock and should be preheated prior to inserting in high temperature process environments; and

5. Molybdenum- or tantalum-sheathed thermocouples will fail rapidly if placed in oxidizing atmospheres.

During one study of thermocouple performance, 24 combinations of thermocouple and sheath material types were tested at temperatures up to 1200°C (2200°F). The results indicated that above 600°C (1110°F) thermocouples are affected by complex chemical interactions between their components; even though wires and sheaths were physically separated, exchange of constituents occurred. The study concluded that thermocouples maintain calibration better if sheath material is similar in composition to thermocouple alloys. By using similar alloys longer performance can be expected for sensors subjected to temperatures above 600°C (1110°F), and the use of similar alloys is essential for temperatures above 1000°C (1830°F).

4.2.2.5.1 Frequency of calibration.[7,11-12] Calibration of thermocouple systems should follow a consistent procedure in order to allow comparisons of performance change over time. The recommended frequency of calibration depends largely on site-specific conditions. The starting point for determining calibration intervals, according to independent calibration laboratories, is a search for applicable military specifications. These specifications are issued by the procurement arm of the Department of Defense (DOD). Military Standards (MIL-STD) define requirements for manufacturers of equipment purchased by the military. Applicable standards include MIL-STD-1839A, which lists detailed calibration and measurement requirements, including frequency, imposed on equipment suppliers by the DOD. As a result,

calibration intervals should be available for each component of military-acceptable (specified by a Military Specification (MIL-SPEC) number) monitoring systems. Typically, the desired calibration intervals, as well as accuracy requirements, are part of the MIL-SPEC. Manufacturers of commercial items generally supply this information as a Calibration and Measurements Requirements Summary (CMRS) included in the owner's manual.

If there is no applicable MIL-SPEC calibration interval and no information can be obtained from the manufacturer for a particular sensor system, 1 year should be the initial default calibration interval if there are no moving parts, as is the case for thermocouples; for sensors with moving parts, the initial calibration period should be 6 months. More frequent system calibration cycles may be indicated when thermocouples near the upper range of their temperature capabilities are used or following prolonged excursions above the recommended maximum temperature or other events causing suspect temperature readings. One reference recommends an initial calibration period of 3 months for Type K thermocouples.

These default calibration intervals should not be relied on indefinitely; they are the starting points for a method to determine the maximum calibration period for a particular installation. At the end of the manufacturer's or otherwise determined initial calibration period, the system should be calibrated and the data obtained should be charted. If the system is near or beyond the limit of acceptable accuracy (80 percent of acceptable error), and there were no process excursions or conditions suspected of causing the decalibration, it can be concluded that the calibration interval is too long. In such a case, the system should be recalibrated to the center of the acceptable band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be continued until the system is determined to be within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, recalibration is not necessary, but the results should be recorded and the same calibration interval should be maintained for another calibration period. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system measures outside the acceptable band, it can be concluded that it took between one and two periods to lose calibration, and the calibration interval was acceptable. In any case, it is important to maintain a log of calibration checks and the results and actions taken. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.2.2.5.2 Quality control. A written procedure should be prepared for all instrument calibrations. These procedures should include:

1. The recommended interval for zero and span checks of each component of the temperature system. Readings before and after adjustment should be recorded.

2. A requirement that each thermocouple and related system components are calibrated in accordance with manufacturers' recommended procedures. Calibrations should be performed at intervals determined according to the procedures described in Section 4.2.2.5.1. Readings before and after adjustment should be recorded; if no adjustments are necessary, that should also be recorded.

3. Designation of person(s) to perform the calibrations. All records should include identification of the instrument component calibrated, the date of calibration, and the initials of the person who performed the calibration.

4.2.2.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the review frequency also should be specified. The written calibration procedures should be reviewed and updated in the event of any system modifications or instrumentation changes.

4.2.3 Resistance Temperature Detectors[1-4,13]

Resistance temperature detectors are attractive alternatives to thermocouples when high accuracy, stability, and linearity (i.e., how closely the calibration curve resembles a straight line) of output are desired. The superior linearity of relative resistance response to temperature allows simpler signal processing devices to be used with RTD's than with thermocouples. Resistance Temperature Detector's can withstand temperatures up to approximately 800°C (~1500°F).

4.2.3.1 Measurement Principle and Description of Sensor

Resistance temperature detectors work on the principle that the resistivity of metals is dependent upon temperature; as temperature increases, resistance increases. Table 4.2-3 lists the resistivities of various metals used for RTD's. Platinum is usually used, because it is stable at higher temperatures and provides a near-linear temperature-to-resistance response.

Since it is a nonreactive precious metal, platinum is also corrosion resistant. Platinum wire is generally wound around a glass or ceramic core, then encased for protection. Platinum or other metals may also be made into a slurry with glass, screened or otherwise deposited on a ceramic substrate, and laser-etched. This device can then be sealed or coated to protect the element. This type of RTD is known as a thin-film RTD, and is less expensive than wire-constructed RTD's. Both types of RTD's are specified by their ice point resistance (R_0 at 0°C) and their temperature coefficient of resistance (the fractional change in element resistance for

TABLE 4.2-3. RESISTIVITY OF RTD ELEMENTS[6]

Metal	Resistivity, microhm-cm	Relative resistance[a] (R_t/R_o) at °C			
		0	100	500	900
Silver	1.50	1.00	1.408	3.150	5.091
Copper	1.56	1.00	1.431	3.210	5.334
Platinum	9.83	1.00	1.353	2.844	4.109
Nickel	6.38	1.00	1.663	5.398	7.156

[a]Ratio of resistance at temperature t (R_t) to resistance at 0°C (R_o).

each degree Celsius, in ohms per ohm per degree Celsius, [Ω/Ω/°C]), or "alpha value (α)" in order to insure system compatibility. The alpha value is calculated as follows:

$$\alpha = (R_{100} — R_0) / (100 \times R_0)$$

Many common RTD elements manufactured in the U.S. and Europe have a base resistance of 100Ω or 200Ω at 0°C and α = 0.00385 Ω/Ω/°C. Elements with other alpha values, such as 0.003916 Ω/Ω/°C, are also common in American and Japanese scientific apparatus.

4.2.3.2 System Components and Operation

Resistance temperature detector systems consist of the detector itself, extension wires, dc power supply, a Wheatstone Bridge, and an ohmmeter or voltmeter. In practice, a "transmitter," which can be installed near the detector, is often used to integrate the detector output, it produces a linearized 4 to 20 mA signal, which is converted to temperature units and displayed by the indicator/controller. Figure 4.2-7 depicts schematically a typical RTD system, and Figure 4.2-8 illustrates a typical RTD assembly. The components of the assembly are essentially the same as those described in Section 4.2.2 for thermocouple assemblies.

Detector elements are often placed in thermowells, which allow temperature monitoring of closed systems and convenient sensor maintenance. Measurement errors are caused by damage to the detector or self-heating. Damage to detectors is common because they are somewhat more fragile than thermocouples. Self-heating is due to the Joule heating caused by the measurement current sent through the RTD by the ohmmeter. The typical amount of error caused by self-heating ranges from ½°C to 1°C per milliwatt (°C/mW) (in free air). This error is reduced if the medium being measured is flowing (this effect can be used to construct flow meters based on thin film RTD's) or the RTD is immersed in a thermally conductive medium. The time it takes for an RTD to return a certain percentage response to a step change in temperature depends on the thermal conductivity and flow rate of the medium being monitored

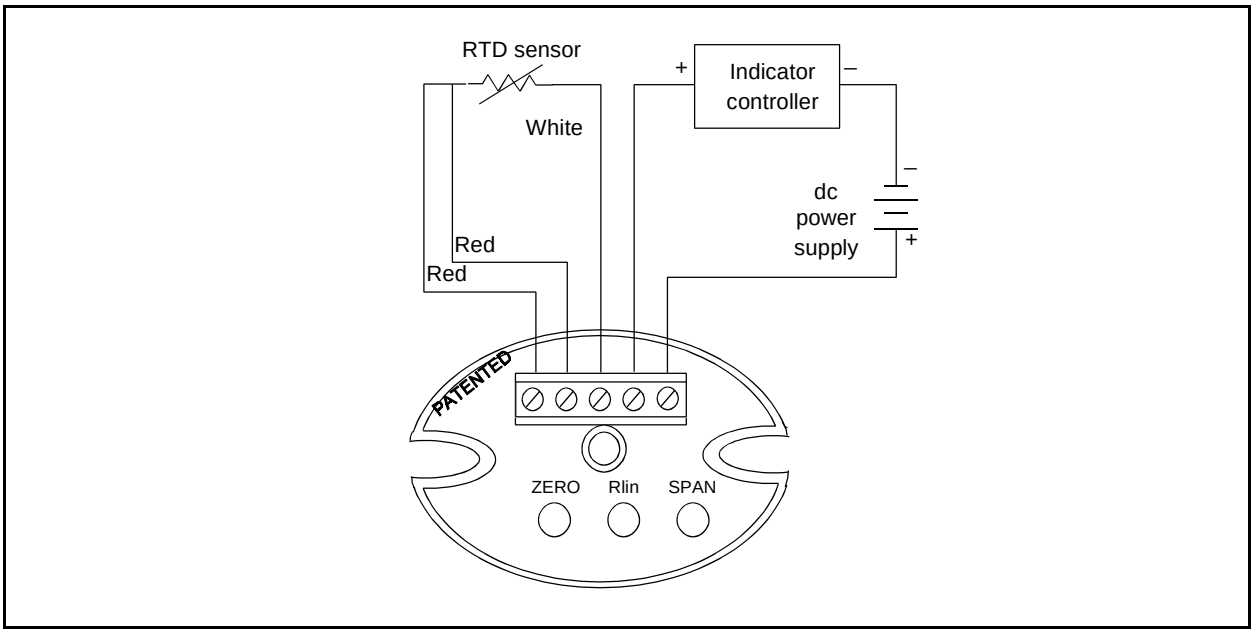

Figure 4.2-7. Resistance temperature detector (RTD) system schematic.[13]

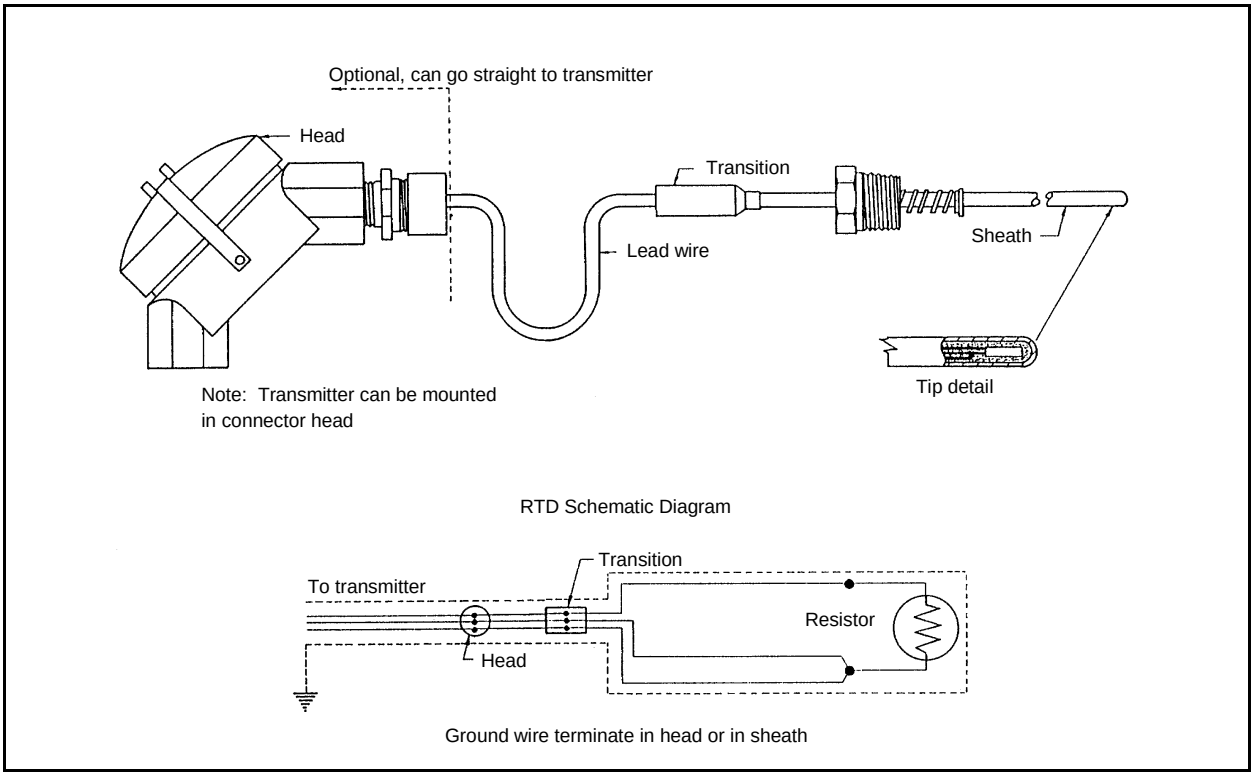

Figure 4.2-8. Resistance temperature detector (RTD) assembly.[2]

(if any) and can be termed the "time constant" of the RTD. Time constants are experimentally determined and provide a basis for comparison of response time between different commercially available RTD elements.

4.2.3.3 Accuracy

Platinum resistance RTD elements are capable of their best accuracy near ambient temperatures. Maximum allowable deviations of ±0.12Ω (±0.3°C [±0.5°F]) at the freezing point of water are reported by one manufacturer. The term "accuracy" as applied to RTD's often is defined as the difference in the base resistance of the element from its design specification at one temperature point; typically 0°C. Deviations rise to ±0.56Ω (±1.3°C [±2.3°F]) at -200°C (-330°F), which is near the lowest temperatures recommended for RTD use. Deviations rise to ±1.34Ω (±4.6°C [±8.3°F]) at the maximum recommended temperature of 850°C (1560°F). Self-heating errors in flowing air (v = 1m/s) should be less than approximately +0.1°C/mW for glass elements and up to +0.4°C/mW in flowing air for ceramic elements. Overall, systems should be calibrated such that deviation less than ±1 percent of the actual temperature is observed, which is similar to the accuracy expected of thermocouples.

4.2.3.4 Calibration Techniques[3,5-6]

Resistance temperature detector systems can lose their calibration and should be inspected regularly to determine the need for replacement of RTD elements, probes, connectors, extension wires, thermowells, power supplies, transmitters, and indicators. Loss of calibration indicates that something besides the temperature at the point being measured is affecting the current difference measured by the system and is causing an erroneous temperature reading. Electrical interferences may be present, requiring the use of twisted extension wires and shielded contacts. Vibration or exceedance of the upper temperature specification can affect the structure of the metal in the sensor, causing decalibration.

4.2.3.4.1 Sensor. Although RTD systems can lose their calibrated accuracy, RTD elements usually cannot be adjusted (unless the resistivity or the amount of metal in the element can be changed). Once RTD's fail, they must be replaced. Testing of RTD's can be accomplished by measuring known temperatures and using a calibrated voltmeter to compare performance to manufacturers' specifications. Element resistance can be checked using an ohmmeter, giving an indication of its condition. Abrupt changes in resistance translate into changes in current, signaling some type of problem or failure, such as an open wire, a short circuit, changes due to vibration fatigue, or overheating. Sensor element resistance can be checked by comparing the readings to manufacturers' specifications or to known values, as presented in Table 4.2-3.

4.2.3.4.2 System. Ideally, the system should be calibrated using known standard temperatures. Intermediate checks should be made electronically and compared to manufacturers' data and calibrations. System calibration devices typically use either physical or electronically simulated comparison methods. Figure 4.2-4 depicts the general setup for calibrating a temperature measurement system, and Figure 4.2-8 illustrates the setup used to calibrate an RTD transmitter using a resistance decade box, which is a device that allows one to simulate resistances with high precision. When installing RTD's, the system should be calibrated and allowed to stabilize at the highest likely service temperature. When possible, final calibration should be performed under actual electromagnetic, radio frequency, and ambient temperature conditions.

Individual parts of the system should be visually inspected for damage and electrically checked and compared to specifications. Then the RTD elements or probes are placed in a device that creates a known reference temperature. A resistance decade box also can be used to simulate signals equivalent to calibration temperatures. Finally, the results of the calibration efforts must be tabulated, showing the deviations between the system readings and known temperatures used in calibrating the system. The table can then be used to track changes in system performance and correct readings to actual temperatures. If the temperatures measured are within the tolerance (expected "accuracy") ranges, calibration is complete.

The ASTM provides standard test methods, which can be helpful in calibration. The appropriate thermometer can be determined using ASTM Method E 1, and ASTM Method E 644 specifies standard methods for verifying the calibration of RTD's. As stated in Section 4.2.2, ASHRAE provides standard methods for temperature measurement for ANSI under ANSI/ASHRAE Standard 41.1.

As explained in Section 4.2.2.4.2 for thermocouples, an alternate method of checking the operation of RTD's sensors is to install them in pairs; when the temperature readings on the two RTD's diverge, both can be replaced.

4.2.3.5 Recommended QA/QC Procedures[3,9,13-16]

Resistance temperature detectors sometimes experience catastrophic failures, which may be preceded by extreme oscillations or erratic readings. In such cases, all connections associated with the RTD should be checked for loose screws, oxidation, and galvanic corrosion. Although drift is less common in RTD's than in thermocouples, it still may occur and cause serious problems because it can go unnoticed for long periods of time. The most common causes of loss of calibration are excessive heat, work hardening, and contamination. Work hardening generally is due to excessive bending or vibration and can be prevented with properly designed thermowells, insertion lengths, and materials. Resistance temperature detector elements are

particularly sensitive to vibrations. Contamination is caused by chemicals and moisture, which sometimes attack wiring by penetrating sheaths, and can result in short-circuiting. A simple test to check for this problem is to disconnect the sensor at its closest connection and check for electrical continuity between the wires and the sheath using a multimeter. If the meter indicates continuity, the sensor should be replaced.

During one study, 47 RTD's were tested to determine the effects of aging at temperatures in the range of 0° to 300°C (32° to 572°F). The test conditions included thermal aging for 18 months, vibration aging for 2 months, high-temperature testing for 2 days at 400°C (750°F), and thermal cycling for a 2-week period. The results indicated that most RTD's maintained their calibration within ±0.2°C (±0.4°F) for at least 2 years over the temperature range of 0° to 300°C (32° to 572°F).

4.2.3.5.1 Frequency of calibration. Calibration of RTD systems should follow a consistent procedure, in order to allow comparisons of performance change over time. The recommended frequency of calibration depends largely on site-specific conditions. The procedures described in Section 4.2.2.5.1 for thermocouple systems can generally be used to determine the calibration frequency for RTD systems.

More frequent zero reset and span checks should be performed if deemed necessary by experience with a particular installation. More frequent calibration cycles may also be advantageous if RTD's are used near the upper range of their specifications or after prolonged excursions above the recommended maximum temperature.

4.2.3.5.2 Quality control. A written procedure should be prepared for all instrument calibrations. These procedures should include:

1. The recommended interval for zero and span checks of each component of the temperature system. Readings before and after adjustment should be recorded.

2. A requirement that each RTD sensor and related system components are calibrated in accordance with manufacturers' recommended procedures. Calibrations should be performed at intervals determined according to the procedures described in Section 4.2.2.5.1. Readings before and after adjustment should be recorded; where no adjustments are necessary, that should also be recorded.

3. Designation of person(s) to perform the calibrations. All records should include identification of the instrument component calibrated, the date of calibration, and the initials of the person who performed the calibration.

4.2.3.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and also the review frequency should be specified. The written calibration procedures should be reviewed and updated in the event of any system modifications or instrumentation changes.

4.2.4 Infrared Thermometry[6,17-21]

Infrared thermometers are more expensive than thermocouples or RTD's, but IR temperature measurement has applications in areas where high electrical interference or extremely high temperatures exist. Because the IR sensor is remote from the measurement point, vibration problems can also be eliminated. In addition, IR instruments can provide rapid response to temperature changes.

4.2.4.1 Measurement Principle and Description of Sensor

All objects with a temperature greater than absolute zero emit IR radiation. Infrared radiation is part of the electromagnetic spectrum that extends from wavelengths of approximately 0.75 micrometers (μm), which is just beyond the wavelength of visible light, to more than 1,000 μm. However, for practical purposes, the IR spectrum generally is considered to range from wavelengths of 0.75 to 30 μm. As the temperature of an object increases, the amplitude of the emitted IR radiation increases, and the wavelength associated with the peak energy shifts toward the shorter wavelengths. Below wavelengths of 0.75 μm, the radiation emitted by an object enters the visible range, and the object begins to glow red.

An IR thermometer measures the IR emitted by an object and converts the measurement to the corresponding temperature. The measurement principle is based on the theoretical radiation wavelength that would be emitted by an ideal radiator, which is referred to as a blackbody. However, real objects (graybodies) emit only a portion of the IR that would be emitted by a blackbody at the same temperature. This characteristic is called the emissivity of an object and is defined as the ratio of the thermal radiation emitted by a graybody to that of a blackbody at the same temperature. In addition to temperature, the emissivity of an object is a function of the object's surface temperature, surface treatment, and the orientation of the object to the IR thermometer. To determine the temperature of an object, an IR thermometer must compensate for the emissivity of the object. Because IR thermometers measure the radiation emitted by an object, they can be used for remote sensing without contacting the object directly.

4.2.4.2 System Components and Operation

Infrared temperature monitoring systems, (often referred to as pyrometers), consist of an optical assembly, signal conditioner, recorder (or display), and a power supply. The optical assembly includes an aperture, lenses, and optical filters. The lenses and filters collect the incoming IR radiation, emitted by the source, and focus it on the detector. The detector converts the incoming IR radiation to an electrical signal. The most common detectors are made of mercury/cadmium/telluride or indium/antimony. Silicon, lead sulfide, indium/arsenide, and lead selenate detectors also are used as well as nonphotosensitive detectors made of thermopiles. (Thermopiles are arrays of thermocouples arranged to provide a higher output signal than a single

thermocouple.) Lead sulfide detectors are the most sensitive, indium-based detectors fall in the mid-range of sensitivity, and thermopile detectors are the least sensitive.

In the signal conditioner, the electric signal from the detector is amplified, thermally compensated and stabilized, linearized, and converted to a digital signal, which then appears on the display or is recorded. A typical system is shown schematically in Figure 4.2-9. This basic configuration must be adapted for monitoring different objects or substances within different temperature ranges and under different conditions.

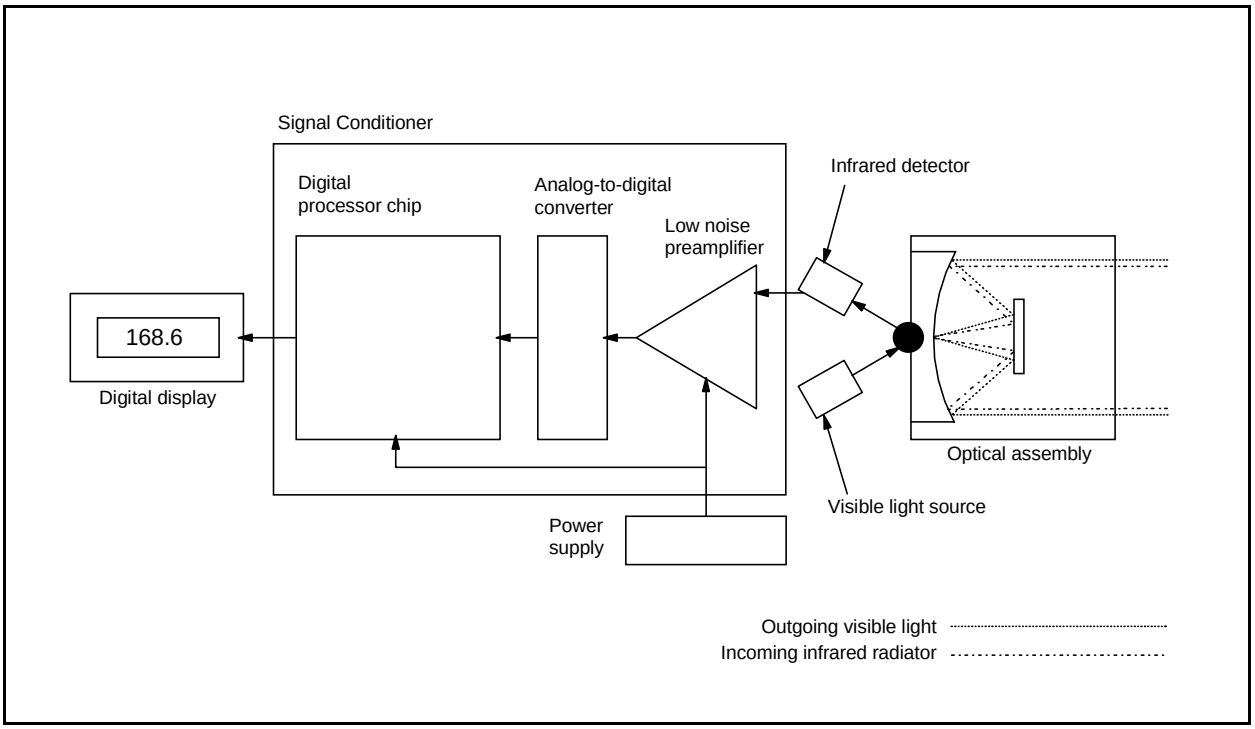

Figure 4.2-9. Infrared temperature measurement system.[18]

A recent development in IR temperature sensing is the IR "thermocouples." These devices have proprietary IR detection systems, which can be used with thermocouple controllers. These also are noncontact devices. When the sensor is aimed at the target object, it converts the radiation to an electrical signal, which is scaled to the thermocouple characteristics.

Infrared pyrometers generally have faster response times than other types of temperature measurement devices (on the order of 100 milliseconds to 1 second). Commercial IR thermometers generally measure temperatures up to approximately 815°C (1500°F). However, high-performance IR thermometers are available that measure temperatures in excess of 2760°C (5000°F) with response times of 0.5 to 1.5 seconds. Infrared thermometers are able to monitor the temperature of vibrating equipment that would fatigue thermocouple wiring or damage RTD's, and are able to measure higher temperatures than can be measured by thermocouples or RTD's. Infrared thermometry is also useful in areas where high electrical interference precludes

use of thermocouples or RTD's. However, infrared thermometers are somewhat sensitive, and must be protected from dirt, dust, flames, and vapors. Infrared energy can be channeled through fiber optics, sight tubes, or reflected from front-surfaced mirrors in order to avoid subjecting the detector to damaging environments. Water-cooled shells, flame shutters, and explosion-proof housings also are available for ensuring that the IR system is protected. By using such precautions, IR thermometry can be used where corrosion precludes the use of other temperature measurement devices or where accessibility is difficult. Signal processor considerations include choices of analog or digital and control and alarm functions.

4.2.4.3 Accuracy

Analog IR thermometer systems generally are capable of measurement to within ±1 percent to ±4 percent of the true temperature at distances of 5 to 7 m (15 to 20 ft). Digital systems can include electronic compensation for emissivity and linearity, which can allow calibration to within ±0.1 °C at specific temperatures.

4.2.4.4 Calibration Techniques

Calibration of IR temperature monitoring devices is similar in principle to calibration of simpler systems. Targets of known temperature are measured, and the instrumentation is adjusted to give the same readings. Since the emissivity of the target directly affects the amount of IR energy received by the sensor, the emissivity of the target must either be known or determined.

4.2.4.4.1 Sensor. Infrared sensors can provide thermocouple, current, or millivolt outputs. Calibration is performed to adjust the output to correlate with the correct temperature. Digital systems often include internal reference temperature devices, which allow them to self-calibrate at predetermined intervals. The results of the calibration cycle are then sent to the PC or microcomputer that controls the system.

4.2.4.4.2 System. Blackbody calibration sources are available that use a temperature-controlled device to present a calibration target of known temperature and emissivity. A black-body is defined as a theoretical object that absorbs all energy incident upon it and emits the maximum amount of energy for a given temperature. Blackbody devices should be accurate within 1 to 2 percent of the actual temperature over the range of the instrument to be calibrated.

Another method to calibrate an IR thermometer or pyrometer is to use published standard emissivity values for various materials. The emissivity is set to match the published value for the target material, and the IR system is then calibrated at known temperatures. Calibration of IR systems to measure the same target (such as the outlet duct of an incinerator) repeatedly can be

done by heating a sample of the material to be monitored (duct material) in an oven to the desired range using an accurate temperature measuring device and measuring its temperature with the IR pyrometer. The output of the IR pyrometer can then be adjusted to display the correct temperature. For relatively lower temperatures found in most air pollution control equipment, a piece of masking tape can be stuck to the target and the temperature of the masking tape measured with the IR pyrometer, using an emissivity setting of 0.95. The temperature of the target is then measured, and the emissivity compensator is adjusted until the display shows the correct temperature. When the target can be coated, flat black paint or other nonmetallic coating can be applied to adjust the emissivity to approach 1.0 (the greatest possible emission ratio). The known temperature is then measured as before with the emissivity adjustment set to 1.0, and the temperature reading is reset to the correct value.

4.2.4.5 Recommended QA/QC Procedures

Calibration of IR systems should follow a consistent procedure in order to allow comparisons of changes in performance over time. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances. Because the IR thermometer must correct for the emissivity of the source, the emissivity setting on the dial must be routinely checked and adjusted as needed. Losses in the transmission of IR radiation can be caused by objects and particles in the line of sight between the source and the IR detector, resulting in a lower than actual temperature reading. Therefore, it is important that the instrument lens and any windows in the line of sight are kept clean and maintained as transparent as possible. The line of sight also should be routinely checked for other objects that may interfere with the radiation path. Background radiation can be transmitted to the IR thermometer if the target source is a good reflector or transmitter, resulting in a temperature reading that is biased high. To overcome such potential problems, the instrument should be placed so that it is out of the geometric path of background reflections or transmissions. Alternately, a cool opaque shielding material can be placed between the background source and the target source.

4.2.4.5.1 Frequency of calibration. The recommended frequency of calibration depends largely on site-specific conditions. The procedures described in Section 4.2.2.5.1 for thermocouple systems can generally be used to determine the calibration frequency for IR thermometers systems. Zero reset and span checks can be performed more often; actual schedules may depend on operator experience. More frequent system calibration cycles may be dictated under certain conditions or should be initiated following events causing suspect temperature readings.

4.2.4.5.2 Quality control. A written procedure should be prepared for all instrument calibrations. These procedures could include:

1. The recommended interval for zero and span checks of each component of the temperature system. Readings before and after adjustment should be recorded.

2. A requirement that each IR thermometer and related system components are calibrated in accordance with manufacturers' recommended procedures. Calibrations should be performed at intervals determined according to the procedures described in Section 4.2.2.5.1. Readings before and after adjustment should be recorded; where no adjustments are necessary, that should also be recorded.

3. Designation of person(s) to perform the calibrations. All records should include identification of the instrument component calibrated, the date of calibration, and also the initials of the person who performed the calibration.

4.2.4.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing the review and the review frequency should be specified. The written calibration procedures should be reviewed and updated in the event of any system modifications or instrumentation changes.

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4.3 PRESSURE MEASUREMENT SYSTEMS[1-7]

Pressure measuring devices can be classified as those that require no outside source of power other than the applied pressure that is to be measured and those that require external, electrical power to operate. For the purposes of this document, these two groups are referred to as mechanical devices and electrical devices, respectively.

Mechanical pressure measurement devices measure pressure by balancing the force exerted on a unit area against the hydrostatic force applied by a liquid or against the deflection of an elastic element. A device that uses a hydrostatic force to measure pressure is referred to as a manometer. Devices that measure pressure as a function of the deflection of an elastic element can be classified according to the type of element as Bourdon, bellows, or diaphragm devices. Mechanical dial pressure gauges generally incorporate one of these three types of elastic elements as the pressure sensor.

Pressure measurement devices that rely on electrical energy to operate commonly are referred to as pressure transducers. Transducers can be defined as devices that receive energy from one system and transmit the energy, usually in another form, to another system. In this sense, the elastic element in a mechanical pressure gauge is a type of transducer because it transfers the applied pressure through mechanical linkage to a pointer to indicate pressure. However, the term pressure transducer is used in this document to pertain only to those devices that utilize electrical energy. Several types of pressure transducers are available. Some of the most commonly used pressure sensing elements used in pressure transducers include strain gauges, linear variable differential transformers (LVDT's), and capacitance transducers. Other commonly used pressure transducer types include force balance, potentiometric, variable reluctance, piezoelectric, and piezoresistive transducers. Tables 4.3-1 and 4.3-2 present comparisons of mechanical and electrical pressure measurement devices, respectively.

After a brief discussion of pressure terminology in the following paragraph, some of the commonly used pressure measurement devices are described. Mechanical devices are described first; manometers are addressed in Section 4.3.1, and mechanical dial pressure gauges are described in Section 4.3.2. The discussion of pressure gauges includes descriptions of Bourdon, bellows, and diaphragm elements. Pressure transducers are described in Section 4.3.3.

Gauge pressure is the difference between the pressure of a fluid and the surrounding ambient pressure. The zero point for gauge pressure is ambient pressure. Absolute-pressure gauges use an atmospheric pressure equal to zero as the zero point; subsequently, absolute pressure is a sum of the ambient pressure and the system pressure. Negative pressure gauges measure pressure below atmospheric pressure. Negative pressure is also called vacuum pressure. Compound pressure gauges are able to measure pressure both above (+) and below (-) ambient

TABLE 4.3-1. COMPARISON OF MECHANICAL PRESSURE SENSING ELEMENTS[6]

Characteristics	Bourdon	Diaphragm	Bellows
Pressure range, kPa (psi)	83 to 690,000 (12 to 100,000)	35 to 103 (5 to 15)	3.4 to 207 (0.5 to 30)
Temperature range, °C (°F)	-40 to 190 (-40 to +375)	-40 to 190 (-40 to +375)	-40 to 190 (-40 to +375)
Advantages	Low cost; field replaceable; variety of materials for media and range	Variety of materials for media and range; field replaceable; large force	Compact, accurate, field replaceable
Disadvantages	Slow response; large sensor volume sensitive to shock and vibration	Limited capacity; position sensitive in low ranges	Limited material; may be position sensitive

pressure. Differential pressure gauges measure the pressure difference between two points. Differential pressure has no reference to ambient pressure or to zero; the ambient pressure will have the same effect on both points.

4.3.1 Manometers[1,2,8]

Simple manometers, also known as piezometers, consist of a vertical open-ended tube in which the liquid in a pipe or pressure vessel is allowed to rise. The pressure in the pipe is proportional to the height to which the liquid rises in the piezometer. U-tube manometers can be used to measure the pressure of both liquids and gases by balancing the force exerted on the mouth of the U-tube against a liquid of known weight, generally water or mercury. For increased accuracy when measuring low-gas-pressure heads, manometers filled with two different fluids are sometimes used. Figure 4.3-1 illustrates a U-tube manometer. In the figure, the pressure at point A in the pipe can be determined by the following relationship:

$$P_A = \gamma_m \Delta h - \gamma_p L$$

where:

P_A = the pressure at point A;
γ_m = the specific weight of the manometer fluid;
Δh = the rise in elevation of the manometer above point B (which is located at the interface between the process fluid and the manometer fluid);
γ_p = the specific weight of the process fluid; and
L = the difference in elevation between point A and point B.

TABLE 4.3-2. COMPARISON OF ELECTRICAL PRESSURE MEASUREMENT DEVICES[7]

Sensor	Excitation signal	Output level	Accuracy, %	Pressure range, kPa (psi)	Temp. range, °C (°F)	Shock and vibration sensitivity	Stability, % per year	Life or calibration shift with use
Unbounded strain gauge	ac-dc Regulated 10 V ac-dc	Low	0.25	3.4 to 69,000 (0.5 to 10,000)	-195 to 315 (-320 to 600)	Good	0.5	<0.5% cal. shift after 10^6 cycles
Bonded-foil strain gauge	10 V ac-dc	Low	0.25	35 to 69,000 (0.5 to 10,000)	-54 to 121 (-65 to 250)	Very good	0.5	>10^6 cycles
Thin-film strain gauge	10 V ac-dc	Low	0.25	103 to 69,000 (15 to 10,000)	-195 to 315 (-320 to 600)	Very good	0.25	>10^6 cycles with <0.25% cal. shift
LVDT	ac Special	High	0.05	207 to 69,000 (30 to 10,000)	-18 to 74 (0 to 165)	Poor	0.25	>10^6 cycles life
Capacitance	ac-dc Special	High	0.05 to 0.5	0.07 to 69,000 (0.01 to 10,000)	-18 to 815 (0 to 1,500)	Poor to good	0.05 to 1.0	>10^7 cycles with <0.05% cal. shift
Force-balance	ac Line Power	High	0.05	6.9 to 35,000 (1 to 5,000)	4.4 to 74 (40 to 165)	Poor	0.05	>10^7 cycles with <0.05% cal. shift
Potentiometer	ac-dc Regulated	High	1	35 to 69,000 (5 to 10,000)	-54 to 149 (-65 to 300)	Poor	0.5	<10^6 cycles life
Variable reluctance	ac Special	High	0.5	3.0 to 69,000 (0.4 to 10,000)	-195 to 315 (-320 to 600)	Very good	0.5	>10^4 cycles life
Piezoelectric	dc Amp and self-generating ac	Medium	1	0.7 to 69,000 (0.1 to 10,000)	-268 to 204 (-450 to 400)	Excellent	1	Unmeasurable use effects
Piezoresistive	10 V to 28 V dc	Medium	0.25	0.7 to 35,000 (15 to 5,000)	-54 to 121 (-65 to 250)	Very good	0.25	<0.25% cal. shift after 10^6 cycles

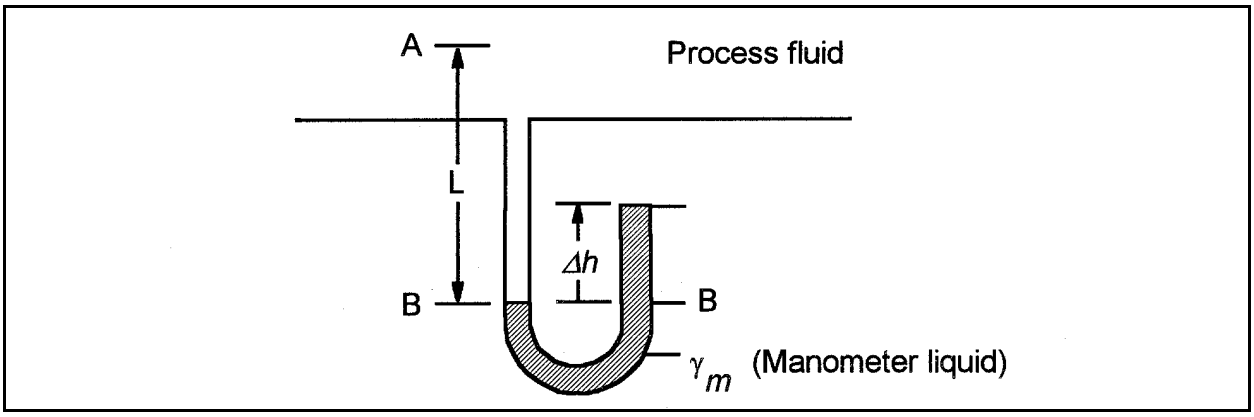

Figure 4.3-1. U-tube manometer.[1]

Differential manometers are used to measure the difference in pressure between two points. Figure 4.3-2 depicts a differential manometer. In the figure, the difference in pressure can be determined as:

$$\Delta P = \gamma_m \Delta h$$

where:

ΔP = the difference in pressure, and

γ_m and Δh = as defined previously.

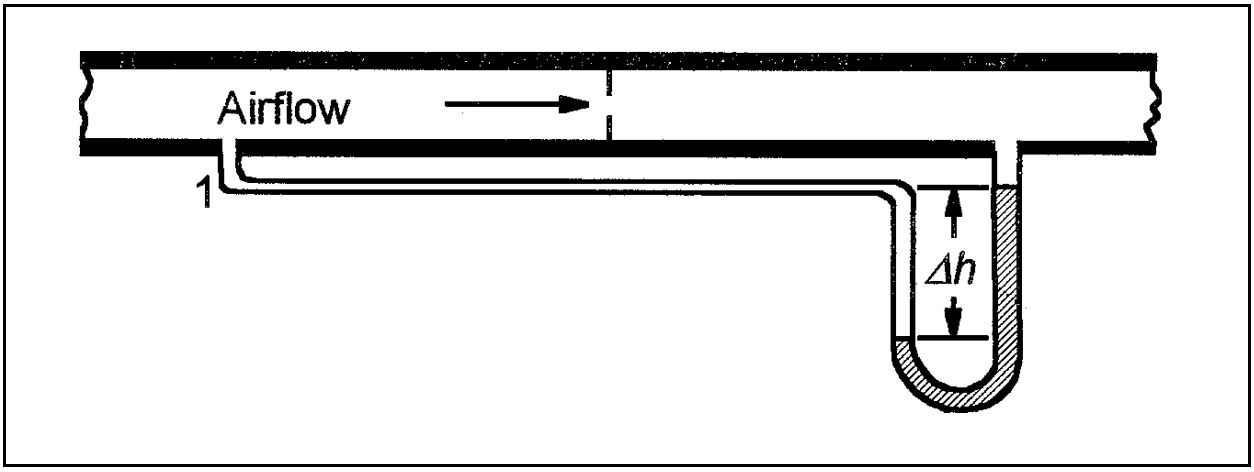

Figure 4.3-2. Differential manometer.[1]

Manometers can be used to make accurate measurements of pressure at specific points and pressure drop across two points, such as the inlet and outlet of an air pollution control device. However, measuring pressure by manometers tends to be labor-intensive and is not practical in many applications. Furthermore, manometer measurements do not lend themselves readily to automated recording. For these reasons, they generally are not used where frequent or continuous pressure measurement is required. Manometers often are used in conjunction with pitot tubes to measure the difference between impact and static pressure in a gas stream for velocity determinations or to measure pressure drop. For gas velocity measurement, the two

most common pitot tube types are the standard and the S-type. The standard pitot tube consists of a small (impact) tube within a larger tube that is positioned so the open end of the smaller tube faces the gas stream. Static pressure is measured by holes located radially around the large tube. The S-type pitot tube consists of separate impact and static pressure tubes, the ends of which are oriented 180 degrees relative to each other. The pitot is positioned so that the impact pressure tube faces the gas stream. Differential measurement using pitot tubes also is commonly made in combination with a Magnehelic™ gauge, which is described in the following section.

Properly designed manometers, which incorporate accurate scales and are constructed to minimize the effect of capillarity, do not require calibration. As a result they are often used as standards for calibrating other types of pressure measuring devices. Conventional U-tube manometers are used as pressure standards in the range of 0.025 to 690 kilopascals (kPa) (0.0036 to 100 pounds per square inch [psi]) with a calibration uncertainty of 0.02 to 0.2 percent. Specially designed manometers, known as micromanometers, are used as pressure standards to measure pressure differences in the range of 5.0×10^{-5} to 5.0 kPa (7.0×10^{-6} to 0.72 psi).

4.3.2 Mechanical Dial Pressure Gauges[2-5,8]

Mechanical dial pressure gauges are used in a wide variety of applications and offer an economical solution for noncontinuous or manually recorded pressure measurement. As explained previously, mechanical dial pressure gauges incorporate a mechanical sensing element. In addition to the type of sensor, pressure gauges are classified according to function, case type, general type of use, and accuracy. Classifications by function include standard gauge for measuring gauge pressure; vacuum gauge for negative pressure; compound gauge for both positive and negative pressure; duplex gauge for measuring two separate pressure sources; differential pressure gauge for measuring the difference in pressure between two points; retard gauge, in which a portion of the gauge scale, usually the upper portion, is compressed to allow a larger range of full scale; and suppressed scale gauge, in which pressure is indicated only between two values, a lower limit and an upper limit.

Classification of pressure gauges by case type is based on size, which ranges from 3.8 to 40.6 cm (1.5 to 16 in.); method of mounting; location of connection; and case construction. The pressure gauge classifications by use include commercial, industrial, process, and test gauges. Classification by accuracy is described in Section 4.3.2.3. The classifications of mechanical dial pressure gauges by element type include Bourdon, bellows, and diaphragm. These types of sensing elements are described in detail in Section 4.3.2.2.

The ANSI has published standards for mechanical dial pressure gauges, titled *Gauges - Pressure Indicating Dial Type - Elastic Element* under ANSI B 40.1 and ANSI B 40.1M-1979. Table 4.3-3 lists commonly available pressure gauges and their typical measurement ranges.

TABLE 4.3-3. PRESSURE GAUGES COMMONLY AVAILABLE[3]

Element	Application	Minimum range (commonly supplied)	Maximum range (commonly supplied)
Bourdon	Pressure	0-12 psi	0-60,000 psi
	Vacuum	0-30 in. Hg vac	0-30 in. Hg vac
	Compound	30 in. Hg-0-15 psi	30 in. Hg vac-0-300 psi
Bellows	Pressure	0-1 in. Hg	0-100 psi
	Vacuum	0-1 in. Hg vac	0-30 in. Hg vac
	Compound	Any total span of more than 1 in. Hg	Any total span of less than 100 psi
Metallic diaphragm	Pressure	0-10 in. H_2O	0-10 psi
	Vacuum	0-10 in. H_2O	0-30 in. Hg vac
	Compound	Any total span of more than 10 in. H_2O	30 in. Hg vac-0-10 psi

4.3.2.1 Measurement Principle and Description of Sensor

Mechanical dial pressure gauges use an elastic chamber to detect the pressure. As the pressure changes, the elastic chamber moves. This movement is converted into proportional motion and transferred to the pointer. The pointer's position gives a reading of the pressure measurement using a calibrated scale located immediately behind the pointer.

4.3.2.2 System Components and Operation

The components of a mechanical dial pressure gauge consist of one or two sensing elements; a linkage that transfers the movement of the sensor to a geared sector and pinion; a needle connected to the pinion; a scale to indicate the pressure; a stem, which is connected to the pressure vessel or conduit; and a case. Figure 4.3-3 depicts these basic components.

Most mechanical dial pressure gauges use either a bourdon tube, bellows, or diaphragm to measure pressure. The following paragraphs describe each of these types of sensing elements.

4.3.2.2.1 Bourdon elements. Bourdon tubes are produced in four basic designs. The most commonly used type of Bourdon element consists of a narrow tube with elliptical cross section that is bent into a circular arc, as shown in Figure 4.3-3. This design is referred to as the C-shaped Bourdon. Other Bourdon designs include spiral, helix, or twisted tubes. The fitting end of the tube (shown at the bottom in the figure) is open to the process fluid; the free end of the tube is sealed and connected by linkage to the gauge pointer or needle. When pressure is applied to the gauge, the tube tends to straighten, thereby actuating the pointer to read the corresponding pressure on the scale.

Bourdons are springs reacting to the force of pressure. The tubing material type, wall thickness, and length vary greatly to allow for a broad range of applications and accuracy.

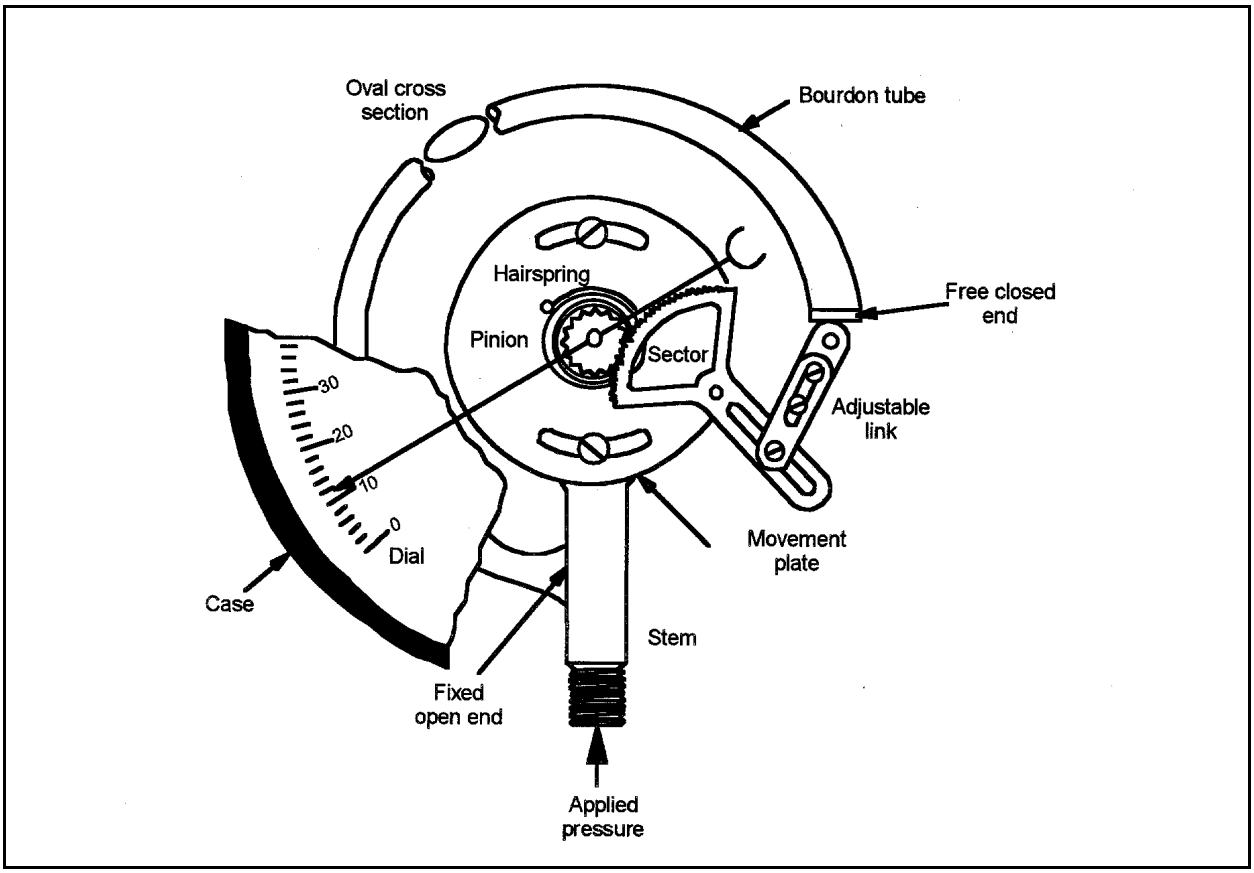

Figure 4.3-3. Bourdon-tube pressure gauge.[4]

Bourdon-tube gauges are reliable if not subjected to excessive pulsations in pressure or external shock. To dampen the effect of pulsations, some gauges are designed with fluid-filled cases.

4.3.2.2.2 Bellows elements. In a bellows-type pressure gauge, the applied pressure pushes against a miniature thin-walled bellows, forcing the bellows to move as shown in Figure 4.3-4. The bellows movement is transferred to a pointer. Brass is the material most often used for bellows elements. A coil spring added to the bellows reduces fatigue and stress. Bellows most commonly are used for low-pressure measurements.

4.3.2.2.3 Diaphragm elements. For mechanical dial gauges, diaphragms typically are made from thin metallic material joined to form small capsules. Figure 4.3-5 illustrates a diaphragm-type pressure gauge. Diaphragm elements work well in low-pressure applications and for absolute-pressure gauges.

A Magnehelic™ gauge is a special type of diaphragm-based pressure gauge commonly used with pitot tubes for gas velocity measurements. Magnehelic™ gauges also are commonly used to measure differential pressure across air pollution control devices. The Magnehelic™ uses a proprietary magnetic linkage to translate the deflection of the diaphragm to the movement on the pointer.

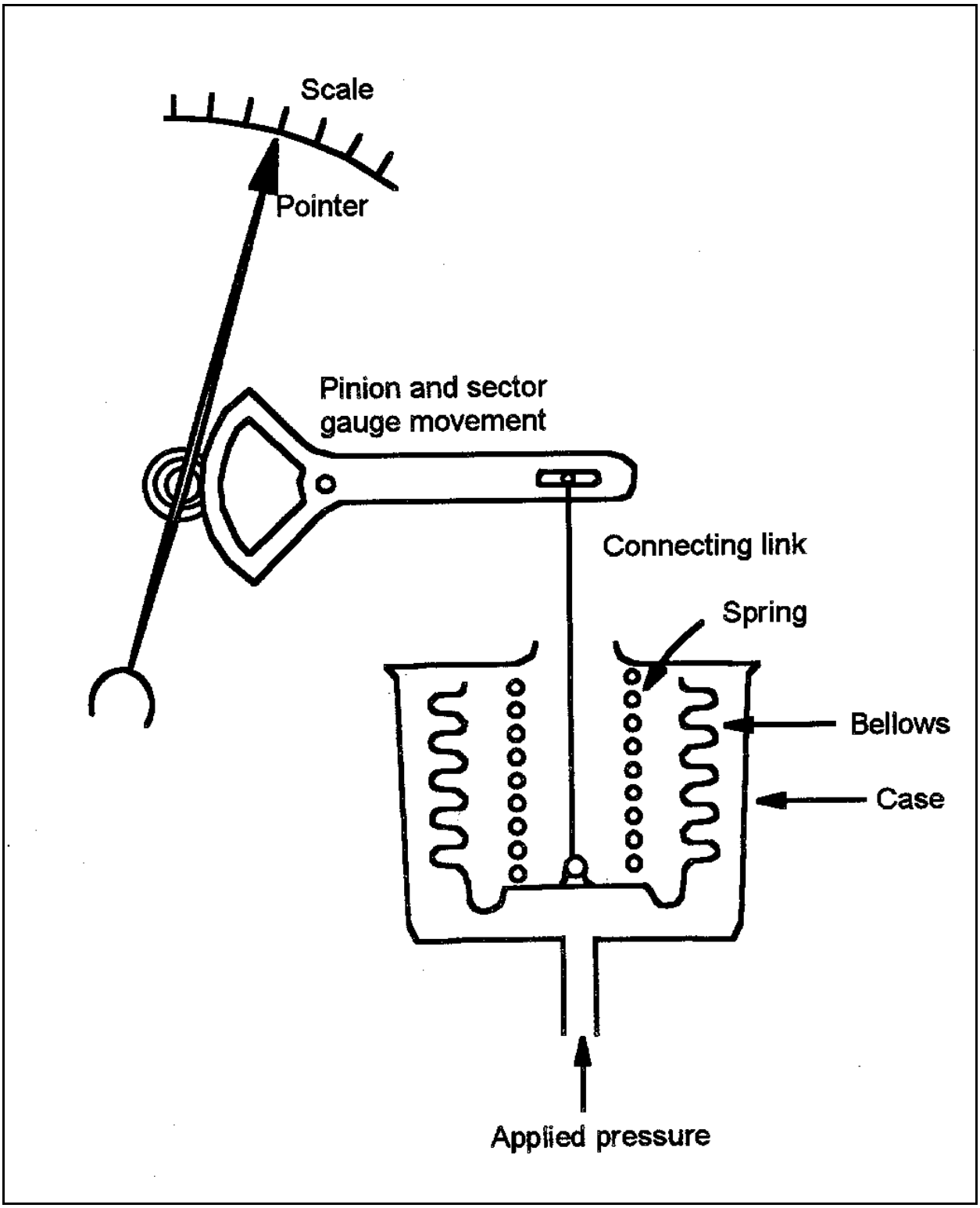

Figure 4.3-4. Bellows-type pressure gauge.[4]

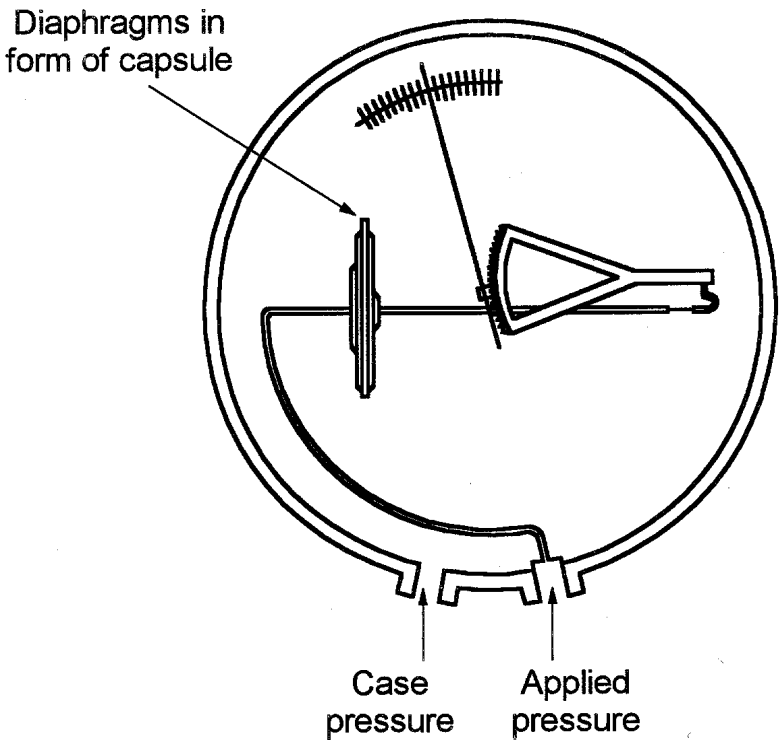

Figure 4.3-5. Diaphragm-type pressure gauge.[4]

4.3.2.3 Accuracy[3,9]

The accuracy of the pressure gauge is generally represented as a percentage of the gauge's range. A pressure gauge with the range of 0 to 250 psi with an accuracy of 1 percent would have a maximum error of 2.5 psi.

A wide range of accuracies are available for pressure gauges. The ANSI classifies the accuracies into seven grades as shown in Table 4.3-4. Increasing accuracy of the pressure gauge also increases the cost of the gauge. Grade B gauges are manufactured in the largest quantities and considered as the commercial class; common uses include water pumps, paint sprayers, and air compressors. Grade 2A gauges are used in petroleum, chemical, and industrial processes and are commonly referred to as process gauges. Grade A and 2A gauges often are used to measure the pressure drop across air pollution control devices. Grade 3A and 4A gauges, which are referred to as test gauges, have lighter moving parts and smaller bearings than do gauges of other grades, resulting in reduced friction and increased sensitivity to small pressure changes. Grade 4A gauges also incorporate temperature-compensating linkages to minimize calibration shifts due to dimensional changes of the gauge components.

TABLE 4.3-4. PRESSURE GAUGE CLASSIFICATIONS[3]

Grade	Permissible error ±% of span		
	First 25%	Middle 50%	Last 25%
4A	0.1	0.1	0.1
3A	0.25	0.25	0.25
2A	0.5	0.5	0.5
A	2.0	1.0	2.0
B	3.0	2.0	3.0
C	4.0	3.0	4.0
D	5.0	5.0	5.0

4.3.2.4 Calibration Techniques[3-4]

The required accuracy, the type of gauge, and the operating conditions help to determine the frequency of calibration required. Operating conditions such as vibration, pulsating pressure, and corrosion affect the useful life of the pressure gauge. Lower-grade gauges, such as Grade B, are usually inexpensive enough that it is more economical to replace the gauge than to repair and recalibrate it.

Calibrating a pressure gauge involves applying a controlled pressure source to the pressure gauge and comparing it to a pressure standard of known accuracy. Controlled pressure sources include air pressure, vacuums, and hydraulic pressure. Pressure standards include precision mercury-column manometers, precision test gauges, and deadweight testers, which use standard weights mounted on a piston to apply specific pressure values to the pressure gauge. Deadweight testers generally are used for higher pressures (4.1 to 103 MPa [600 to 15,000 psi]).

For the actual calibration, the pressure standard is placed in-line with the gauge to be calibrated. A tee is placed as close as possible to the gauge to be calibrated. After the system has been proven to be leak tight, the controlled pressure is applied. The pressure gauge and the pressure standard are compared at incremental pressures for the entire range of the pressure gauge. From this comparison, the error of the pressure gauge can be determined. Figures 4.3-6 and 4.3-7 illustrate the setups for calibrating pressure gauges using precision manometers and deadweight testers, respectively.

Calibration can be checked using a tee in the pressure line to perform a zero check by nulling to the atmosphere and an operating pressure check by connecting the gauge to a calibrated reference meter or manometer.

4.3.2.5 Recommended QA/QC Procedures[3-4,10]

Those parts of the pressure monitoring system requiring special attention include the bellows, bourdon tubes, springs, and other interior components, all of which are subject to damage and corrosion. Before installation, it is important to check that the pressure gauge is to be used for its intended purpose. The conditions most detrimental to pressure gauges are pulsating pressure, vibration, and internal and external corrosion. Steps also should be taken to ensure that pressure gauges are not subjected to excessive pressure or temperature extremes. According to one manufacturer of air pollution control devices, gauges for measuring pressure drop across a control device generally should be calibrated or replaced quarterly.

4.3.2.5.1 Quality control. Inspection and calibrations of the pressure gauge should be made and recorded at periodic intervals. As stated in Section 4.3.2.4, the frequency of these events depends on the operating conditions, required accuracy, and the type of gauge.

The gauge manufacturer can best recommend at what interval these inspection and calibrations should occur with regard to specific operating conditions for the gauge. Calibration measurements should be recorded both before and after any adjustments are made to the pressure gauge. Calibration records should identify the instrument calibrated, date of calibration, person that performed the calibration, and the measurements observed.

Inspections should visually check that the pressure gauge appears to be operating normally. An inspection log will provide a record to ensure that inspections take place at recommended intervals and can help identify potential problems with pressure gauges. Quick checks include possible leaks, no dial reading, and excessive vibration.

4.3.2.5.2 Quality assurance. Quality assurance should include review of recorded pressure measurements, calibration records, and inspection log. The QA should be performed by a person not involved with regular measurements or calibrations of the pressure gauge.

4.3.3 Pressure Transducer[3-5,7]

As explained in the introduction to Section 4.3, the term pressure transducer in this document refers to devices that convert pressure to electrical signals, which then are displayed and/or recorded as pressure measurements. Thus, pressure transducers include the sensor, power supply, output signal conditioner, and the associated electronic circuitry. Pressure transducers can be made using many different types of pressure elements and sensing systems. Among the types of pressure transducers in use are strain gauges, LVDT's, capacitance, force balance, potentiometric, variable reluctance, piezoelectric, and piezoresistive transducers.

Different types of pressure-monitoring systems are available, including those using millivolt output, amplified voltage output, and current loop output transducers. Millivolt systems use small sensors remote from the signal-conditioning device. Amplified voltage systems

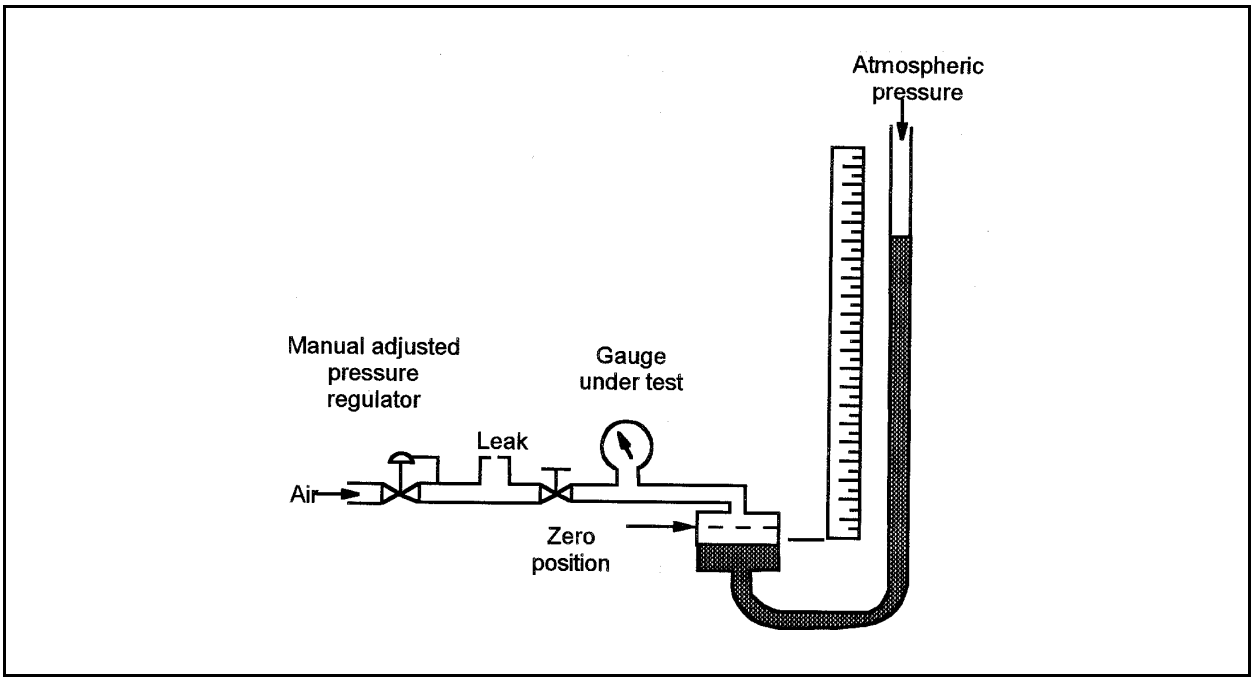

Figure 4.3-6. Setup for calibrating a pressure gauge using mercury column manometer.[2]

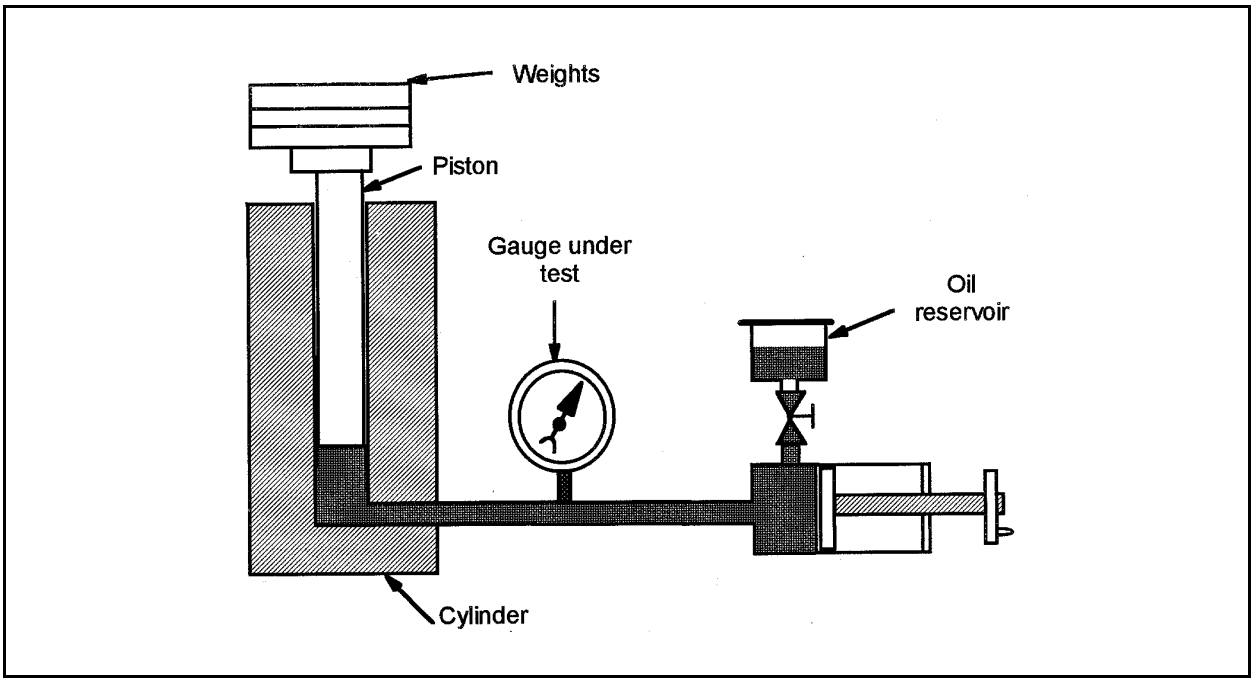

Figure 4.3-7. Setup for calibrating a pressure gauge using a deadweight tester.[2]

employ sensor-contained amplifiers in order to overcome electromagnetic interferences. Current loop systems have built-in transmitters, allowing long runs of direct-wire connection between the sensor and the signal processor. Selection of pressure-sensing elements depends on the pressure range to be monitored, temperature, and the advantages and disadvantages of specific devices.

4.3.3.1 Measurement Principle and Description of Sensor

4.3.3.1.1 Strain gauge transducers.[3-5,8,11] Strain gauge transducers operate on the principal that the electrical resistance in a metal (usually in the form of a fine wire or foil) changes when it is elastically deformed due to an applied stress. The change in resistance results in an electrical output signal, which varies proportionally to compressive or tensile strain (compression or expansion of the diaphragm). Strain gauge transducers use several sensor designs, the most common of which are the bonded foil, unbonded metallic filament, thin film, and the diffused semiconductor strain gauges. Diffused semiconductor strain gauges are also referred to as piezoresistive pressure transducers and are described in Section 4.3.1.4. The other types of strain gauge transducers are described in the following paragraphs.

In a bonded strain gauge transducer, four strain gauges are bonded to the diaphragm in a Wheatstone bridge configuration, as shown in Figure 4.3-8. When the diaphragm is subjected to pressure, two opposing strain gauges (e.g., R1 and R3 in the figure) are put into tension, and the other two gauges (i.e., R2 and R4 in the figure) undergo compression and there will be a potential difference in voltage across terminals B and D. The Wheatstone bridge arrangement has the advantage that it compensates for strain induced by changes in temperature because the ratio of R1 to R4 remains the same as the ratio of R2 to R3. Figure 4.3-9 depicts a bonded strain gauge pressure transducer.

In an unbonded strain gauge transducer, one or more filaments of resistance wire are stretched between supporting insulators. The supports are either attached directly to an elastic element or are attached by means of an insulating coupling. When the sensing element is displaced, the filament length changes, causing a change in resistance. Thin-film strain gauge transducers use a metallic or semiconductor film for the resistance elements.

4.3.3.1.2 Capacitance transducers.[3,5,12] Capacitance transducers consist of two parallel conducting plates placed a short distance apart and operate on the principle that the capacitance between plates varies with their separation distance. As the diaphragm, which acts as one of the conducting plates, deflects under the applied pressure, the distance to the other conducting plate decreases, resulting in a change in the charge between plates. Figure 4.3-10 depicts a capacitance transducer.

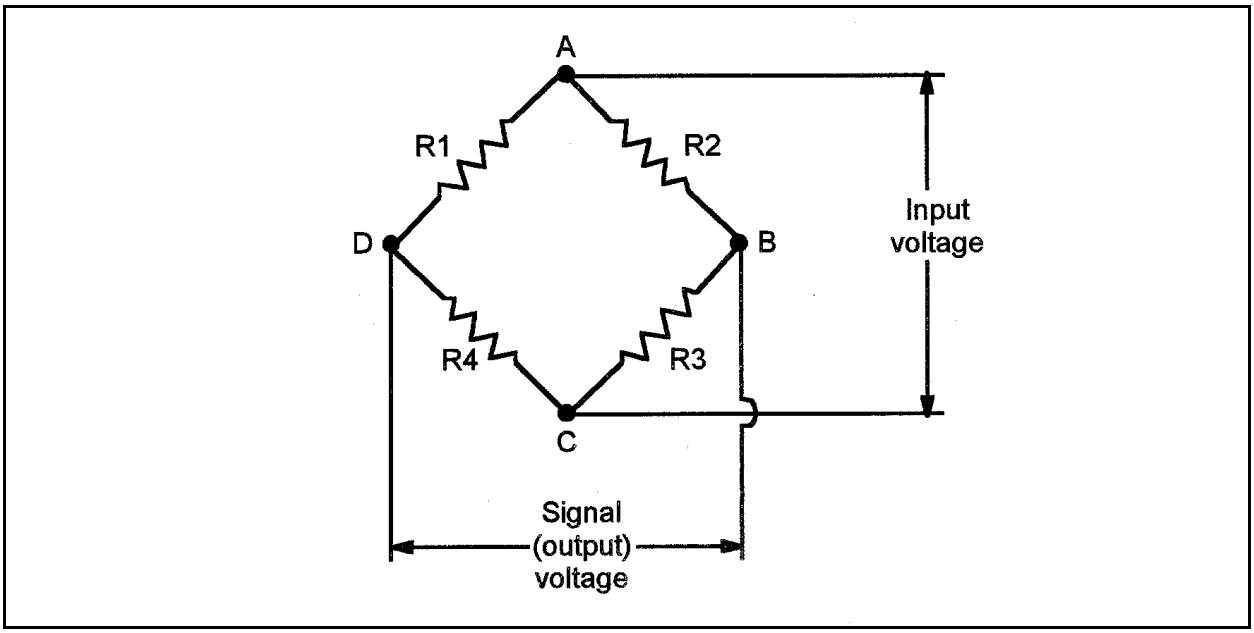

Figure 4.3-8. Wheatstone bridge.[3]

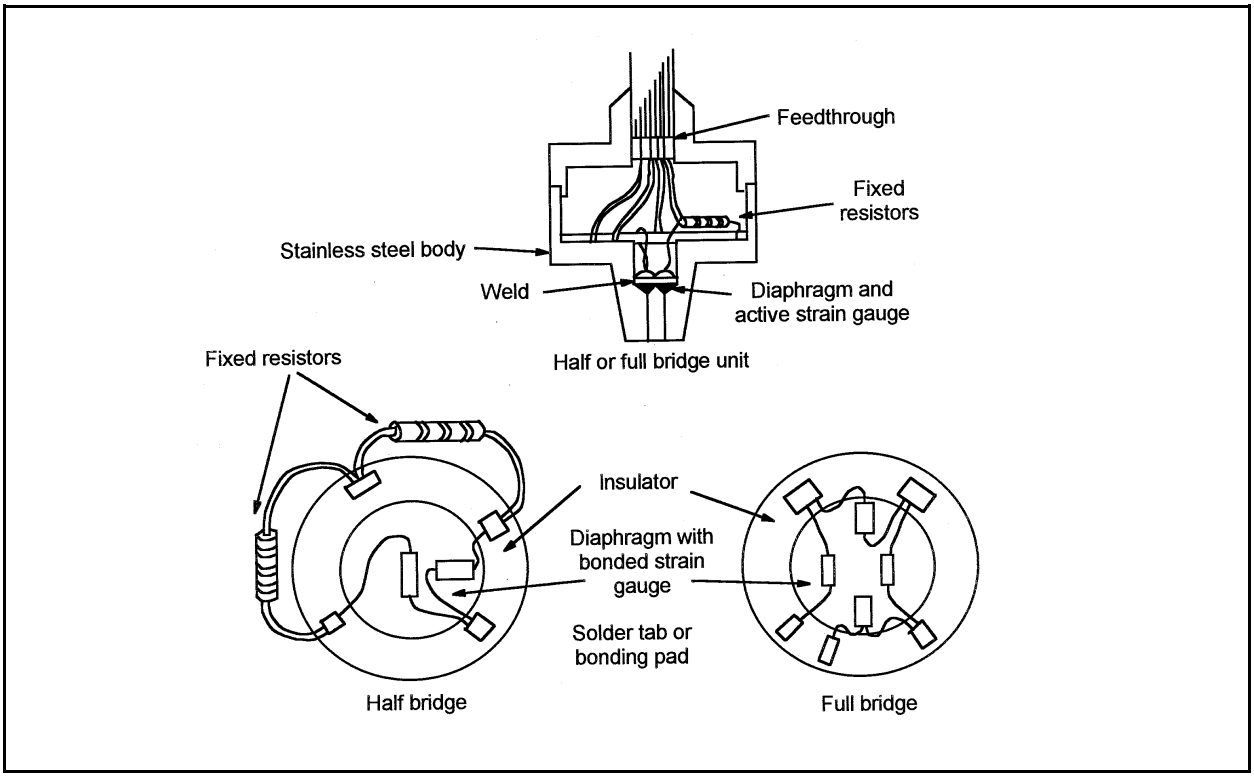

Figure 4.3-9. Strain gauge pressure transducer.[5]

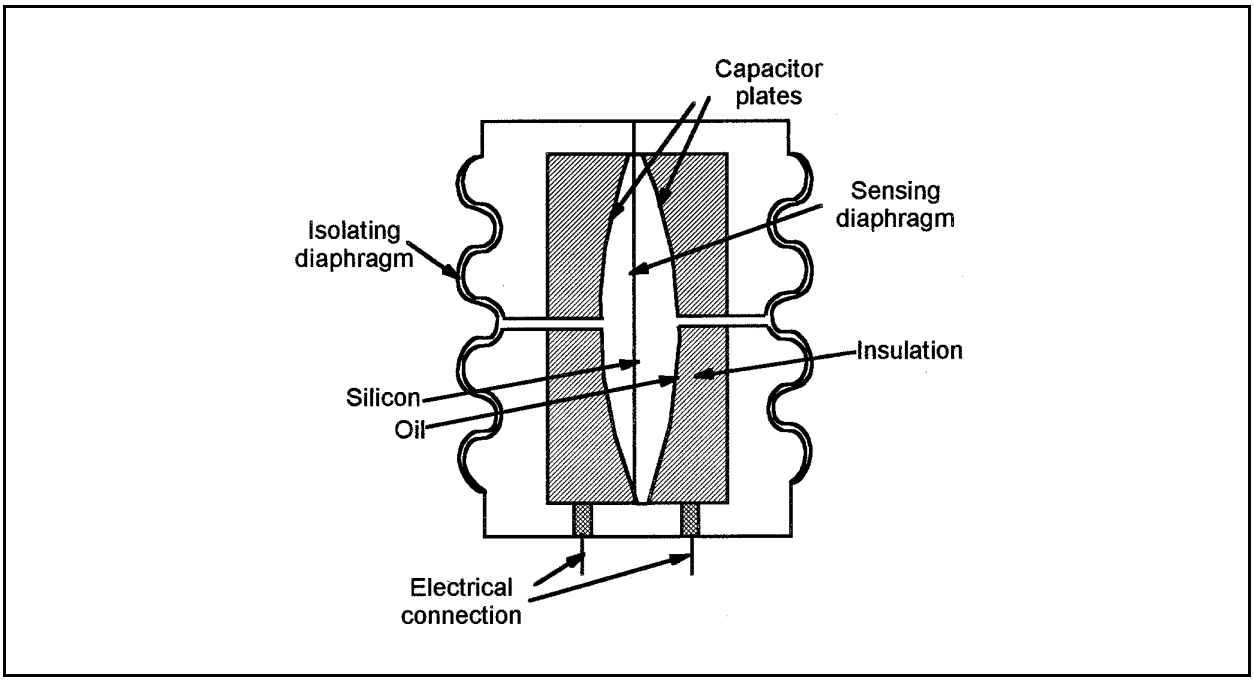

Figure 4.3-10. Capacitance pressure transducer.[5]

Diaphragms in capacitance transducers can be fabricated of stainless steel, ceramics, or other chemically nonreactive materials. Capacitance elements generally produce a stronger electrical signal than strain gauge elements generate, and less signal amplification is required with capacitance transducers. However, because capacitance transducer diaphragms undergo less movement than strain gauge diaphragms, small dimensional changes due to temperature are more critical for this type of transducer.

4.3.3.1.3 LVDT's.[3-5] Linear variable differential transformers convert small motions to electrical signals when a magnetic core moves between a primary and two secondary wire coils. A constant ac voltage is applied to the primary coil. The secondary coils are in opposition so that the signal induced in one is 180 degrees out of phase with the signal in the other secondary coil. When the metallic core is moved from the zero position, the voltage in the secondary coils becomes unbalanced and an electronic signal is induced in the leads. Figure 4.3-11 depicts an LVDT pressure transducer.

4.3.3.1.4 Other types of pressure transducers. The following paragraphs briefly describe some of the other commonly used types of pressure transducers.

Force Balance. In a force balance transducer, a mechanical pressure sensor moves one end of a balance beam, which generates an inductive or reluctive signal that is amplified and converted to pressure units.

Potentiometric. A potentiometric pressure transducer uses a mechanical pressure element such as a bellows to drive the wiper arm of a potentiometer and an ammeter to measure the

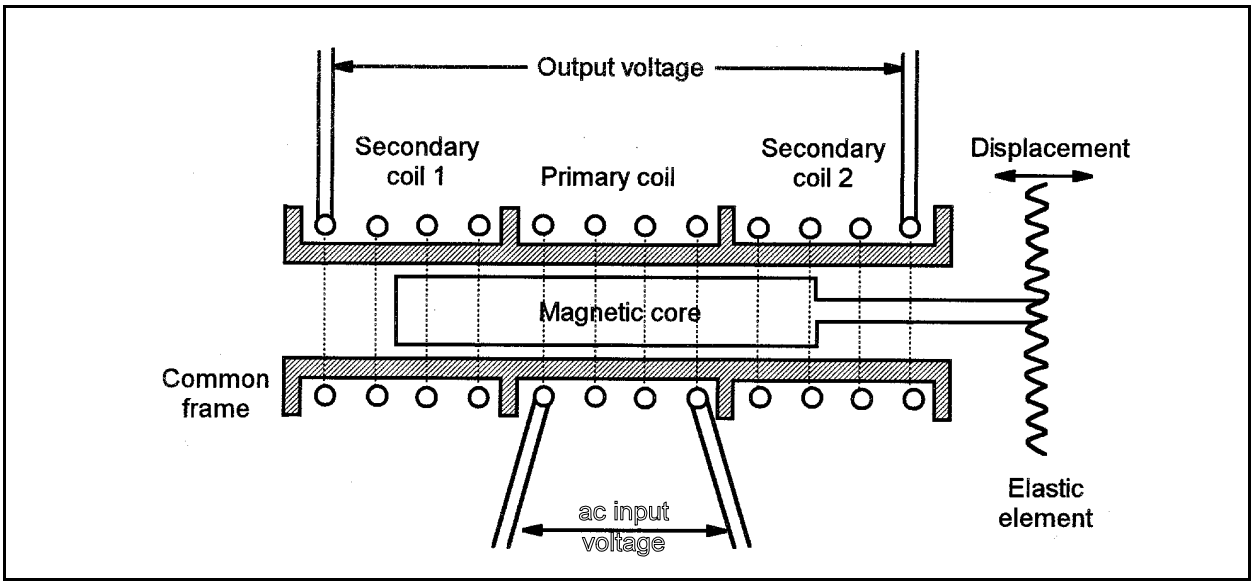

Figure 4.3-11. Linear variable differential transformer (LVDT).[4]

change in circuit current resistance resulting from the change in pressure on the bellows. The amount of change is then correlated to the change in pressure, and the ammeter may be calibrated in units of pressure.

Variable Reluctance. In a variable reluctance transducer, two coils with equivalent impedances are wired in series with a magnetically permeable stainless steel diaphragm mounted between them. When pressure is applied, the diaphragm deflects, and the magnetic flux density in one coil changes. The induction in the coil changes and the resulting output signal is proportional to the applied pressure.

Piezoelectric. The principle behind the piezoelectric transducer is that certain crystals, such as quartz or polycrystalline ceramics, generate an electric charge when strained. In a piezoelectric transducer, thin crystal wafers are stacked in series (positive side to negative side). One side of the stacked wafers is in contact with a diaphragm, and an electrical connection is made on the other side of the crystal stack. As pressure is applied, the crystal wafers are compressed, and a charge proportional to the pressure is generated.

Piezoresistive. Piezoresistive transducers are a variation of the bonded strain gauge transducer. In a piezoresistive transducer, strain-sensitive resistors are implanted or diffused into silicon wafers and connected in a Wheatstone bridge configuration. A diaphragm is then created by etching or grinding the silicon wafer. As pressure is applied, the resistors are strained, causing an imbalance across the Wheatstone bridge proportional to the applied pressure.

4.3.3.2 System Components and Operation

Pressure transducer monitoring systems consist of pressure transducers, a power supply, and a signal processor with an output device such as a meter, controller, or recorder.

4.3.3.3 Accuracy

Initial accuracy of general purpose pressure transducers ranges from approximately 0.05 percent to 1.5 percent of true pressure. Good sensor system calibration and compensation results in an error of less than 2 percent of scale. Strain gauge pressure transducers respond quickly and have virtually infinite resolution. Linear variable differential transformers exhibit good linearity with extremely high resolution.

4.3.3.4 Calibration Techniques

Pressure transducer systems must be calibrated for sensitivity, zero balance, nonlinearity, hysteresis, and thermal pressure coefficient. Sensitivity calibration is done by adjusting bridge resistance by adding fixed resistors or adjusting potentiometers to produce output calibrated to a known pressure source. Zero balance is also calibrated using potentiometers or fixed resistors to adjust the bridge resistance. Zero balance is affected by temperature, so it should be adjusted at operating temperature of the equipment or by using a calibrated temperature chamber. Nonlinearity and hysteresis can be compensated for using equations programmed into a microprocessor-controlled signal-conditioning device or transmitter. Thermal effects on sensitivity may be difficult to compensate for and require the use of a calibrated pressure source and temperature chamber.

A simple calibration check can be performed using a tee in the pressure line to perform a zero check by nulling to the atmosphere and an operating pressure check by connecting the gauge to a calibrated reference meter or manometer.

4.3.3.4.1 Sensor. Pressure transducers can usually be returned to the manufacturer for recalibration and scaling. Calibrating a pressure sensor involves applying a controlled pressure source to the pressure sensor and comparing it to a pressure standard of known accuracy. Controlled pressure sources include air pressure, vacuums, and hydraulic pressure. Pressure standards include deadweight testers, precision test gauges, and manometers.

4.3.3.4.2 System. Pressure transducer systems can be calibrated in the field using a series of pressure manifolds. A tee is placed as close as possible to the gauge to be calibrated. After the system has been demonstrated to be leak tight, the controlled pressure is applied. The pressure gauge and the pressure standard are compared at incremental pressures for the entire range of the pressure gauge. From this comparison, the error of the pressure sensor can be determined, allowing adjustments to be made.

Specifications and tests of potentiometric pressure transducers are standardized by the ANSI and the Instrument Society of America (ISA) in standard ISA-S37.6. This guide specifies calibration procedures, gives examples of recordkeeping sheets, and contains bibliographic references. The ISA-S37.3 standard gives similar specifications and tests for strain gauge pressure transducers. The ISA-S37.6 standard is intended to be a guide for technical personnel at user facilities as well as a guide for manufacturers. It provides standard practices for specifying, calibrating, and testing performance characteristics of potentiometric pressure transducers. This group includes absolute pressure transducers, differential pressure transducers, and gauge pressure transducers. Many types of measurement errors and other terminology are defined.

The basic equipment required for acceptance tests and calibrations consists of a pressure source, an "excitation" (voltage) source, and an output voltmeter. The combined errors or uncertainties of the measuring system made up of these three components should be less than 20 percent of the acceptable error of the system being tested and should be traceable to NIST standards. A pressure medium similar to the one intended to be measured by the monitoring system should be used. The pressure source should be capable of producing 125 percent of the full scale of the transducer. These pressure sources are typically air or oil piston devices, which are measured using a precision dial gauge or mercury manometer. Voltage sources can be batteries or electronically regulated power supplies with current-limiting devices. The output-indicating device or voltmeter/ratiometer may be analog or digital.

Calibration and testing is to be performed at ordinary room conditions. The procedure is summarized as follows:

1. Visually inspect for defects and other mechanical problems.

2. Use a precision ohmmeter to measure transduction element resistance; verify the number of potentiometric elements or taps, and check electrical connections.

3. Use a megohmmeter to measure the insulation resistance between all the element terminals or leads connected in parallel and the case (ground pin) at 50 V unless another voltage is specified.

4. Verify the dielectric withstand voltage, using a sinusoidal ac voltage test with all the transduction element terminals paralleled and tested to case and ground pin.

5. Connect the transducer to the pressure source, the power supply, and indicating instrument (readout). After allowing adequate warmup, leak check the setup. Once leak check is passed, recheck the electrical connections for correctness and impedance. Run two or more complete calibration cycles, generating at least 11 data points (pressures). Record the readout at each pressure in both the ascending and descending directions (increasing and decreasing pressures). From these readings, determine the endpoints, full scale output, linearity, hysteresis (or combine linearity and hysteresis), friction error, and repeatability.

6. For differential pressure transducers, perform a three-point (e.g., 10, 50, and 90 percent) calibration cycle at both the minimum and maximum specified reference pressures, to establish reference pressure error.

4.3.3.5 Recommended QA/QC Procedures[4-5,7,11-12]

Those parts of the pressure monitoring system requiring special attention include the diaphragms of the pressure transducers, which are subject to damage and corrosion, and the electronic calibration of the signal processor, which can drift over time.

Subjecting pressure transducers to pressures beyond their design limits is a common problem. Manufacturers typically specify a normal operating pressure range and a proof pressure; exceeding the proof pressure generally results in a permanent calibration shift. Exposing pressure transducers to temperatures above or below the specified operating ranges also can degrade the stability of the instrument or result in permanent calibration shifts. Excess vibration is another cause of transducer stability degradation.

Sensors and transmitters, as well as data acquisition systems, are all adversely affected by harsh environments. The more sensitive the sensor, the more susceptible to corrosion, heat decalibration, and other problems. Picking the correct sensor requires some determination of its operating environment. Sensors that will be exposed to moisture, the outdoors, a hazardous (explosive) environment, temperature extremes, shock, or vibration must be manufactured to withstand those conditions; or they will not give reliable service. If the sensor system will be exposed to strong electrical interference that can be characterized, sensor manufacturers can incorporate electromagnetic interference filters in the design. It is always recommended to use twisted-wire pairs for transmission of sensor outputs because of all the interference generated by walkie-talkies, motor brushes, static discharges, and general electrical activity in the vicinity of the instrument. Most of the time, shielding is not required for pressure transmitter wire because the signal is strong enough to prevail. Wire size is not that critical; 18 gauge is generally adequate unless the wires are very long. Because electrical excitation is required by all electronic pressure transducer elements, the quality and strength of electrical power supplied can impact performance.

Corrosion-resistant coatings and putties can be used to protect transducer diaphragms. High-precision voltage and current-calibrating devices are used to check and recalibrate signal processors according to manufacturers' specifications.

4.3.3.5.1 Frequency of calibration.[13-14] Calibration of pressure transducer systems should follow a consistent procedure in order to allow comparisons of performance change over time. The recommended frequency of calibration depends largely on site-specific conditions. The starting point for determining calibration intervals, according to independent calibration

laboratories, is a search for applicable military specifications. These specifications are issued by the procurement arm of the Department of Defense. Military Standards define requirements for manufacturers of equipment the military purchases. Applicable standards include MIL-STD-1839A, which lists detailed calibration and measurement requirements, including frequency, imposed on equipment suppliers by the Department of Defense. As a result, calibration intervals should be available for each component of military-acceptable (specified by a MIL-SPEC number) monitoring systems. Typically, the desired calibration intervals, as well as accuracy requirements, are part of the MIL-SPEC. Manufacturers of commercial items generally supply this information as a CMRS included in the owner's manual.

If there is no applicable MIL-SPEC calibration interval and no information can be obtained from the manufacturer for a particular sensor system, 6 months is the initial default calibration interval if there are moving parts, as is the case for pressure transducers. More frequent system calibration cycles may be indicated when using transducers outside the recommended operating pressure and temperature ranges.

These default calibration intervals should not be relied on indefinitely; they are the starting points for a method to determine the maximum calibration period for a particular installation. At the end of the manufacturer's or otherwise determined initial calibration period, the system should be calibrated, and the data obtained should be charted. If the system is near or beyond the limit of acceptable accuracy (80 percent of acceptable error) and there were no process excursions or conditions suspected of causing the decalibration, it can be concluded that the calibration interval is too long. In such a case, the system should be recalibrated to the center of the acceptable band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be continued until the system is determined to be within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, recalibration is not necessary, but the results should be recorded, and the same calibration interval should be maintained for another calibration period. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system measures outside the acceptable band, it can be concluded that it took between one and two periods to lose calibration, and the calibration interval was acceptable. In any case, it is important to maintain a log of calibration checks and the results and actions taken. Calibration data should be reviewed at least annually in order to spot significant deviations from defined procedures or tolerances.

4.3.3.5.2 Quality control. A written procedure could be prepared for all instrument calibrations. These procedures could include:

1. The recommended interval for zero and span checks of each component of the pressure measurement system. Readings before and after adjustment should be recorded.

2. A requirement that each pressure transducer and its related system components be calibrated in accordance with manufacturers' recommended procedures. Calibrations should be performed at intervals determined according to the procedures described in Section 4.3.3.5.1. Readings before and after adjustment should be recorded; if no adjustments are necessary, that also should be recorded in the log.

3. Designation of person(s) to perform the calibrations. All records should include identification of the instrument component calibrated, the date of calibration, and the initials of the person who performed the calibration.

4.3.3.5.3 Quality assurance. The calibration logs can be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the review frequency also should be specified. The written calibration procedures should be reviewed and updated in the event of any system modifications or instrumentation changes.

4.3.4 References for Pressure Measurement

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4.4 FLOW RATE MEASUREMENT SYSTEMS

4.4.1 Introduction

The need for quantifying fluids (i.e., liquids or gases) flowing through closed conduits (i.e., pipes) is widespread; and flow measurements have been conducted for about a hundred years. In an industrial setting, these flow measurements serve two main purposes: (1) as a means to account for fluid commodities (e.g., fluid product usage or production); and (2) as the basis for controlling processes and manufacturing operations (e.g., steam flow to a turbine and scrubber slurry flow). Additionally, in recent years, the flow rates of certain fluids have been correlated to process emission rates of air contaminants.

Considering the wide diversity in the nature of the fluids to be measured, the range of flow-measurement applications is vast. Additionally, the need to measure a wide range of flow rates has added to the expanse of measurement technology. No flow rate measurement technology is universal to all applications.

Flow rate measurement technology can be classified a variety of ways. For the purposes of this document, flow meters have been classified as either energy extractive or energy additive, either direct determination or indirect determination, and either velocity or mass rate. In general, most flow rate determining devices measure a physical principal (e.g., pressure drop across a restriction, momentum transfer to a propeller, heat transfer, or wave formation by a blunt object inserted in the fluid) and infer the fluid flow rate using a mathematical relationship. This section on flow rate measurement will present each technology for determining fluid flow (e.g., differential pressure, positive displacement, and ultrasonic), and the various techniques within a technology will be discussed. For each type of flow measurement device, the system components, operation, accuracy, calibration, and QA/QC procedures are discussed. Table 4.4-1 presents a comparison of the flow measurement devices described in this section.

4.4.2 Differential Pressure Flow Measurement Devices[1]

Differential pressure flow meters, or head meters, represent one of the most commonly used flow meter technologies. Their versatility, cost, and simplicity make them attractive for many applications. Differential pressure devices can be applied to virtually all low viscosity liquid flow measurement applications, as well as to most gas flow rate measurement applications.

Differential pressure devices utilize empirical correlations to quantify the relationship between the change in pressure and the volumetric flow through a carefully specified restriction in a pipe or duct. These devices do not measure the mass, velocity, or volume directly; instead

TABLE 4.4-1. COMPARISON OF FLOW MEASUREMENT DEVICES[1-10]

Type of flow meter	Type of measure-ment	Liquid, gas, or both	Applicable pipe diameter	Applicable flow rate	Straight pipe requirements[a]	Net pressure loss	Accuracy	Restrictions
Venturi tube	Volumetric	Both	5 to 120 cm (2 to 48 in.)	Limited to ~4:1 flow range	6 to 20 D up 2 to 40 D down	10 to 20% of ΔP depending on β	±0.75% flow rate w/o calibration	Eliminate swirl and pulsations
Flow nozzle	Volumetric	Both	7.6 to 60 cm (3 to 24 in.)	Limited to ~4:1 flow range	6 to 20 D up 2 to 4 D down	30 to 85% of ΔP depending on β	±1.0% flow rate w/o calibration	Eliminate swirl and pulsations
Orifice plate	Volumetric	Both	1.3 to 180 cm (½ to 72 in.)	Limited to ~4:1 flow range	6 to 20 D up 2 to 4 D down	Slightly more than flow nozzle	±0.6% flow rate w/o calibration	Eliminate swirl and pulsations
Magnetic	Velocity	Liquid (not petroleum)	0.25 to 250 cm (0.1 to 96 in.)	0.0008 to 9,500 L/min (0.002 to 2,500 gal/min)	None	None	±1% flow rate	Conductive liquid, not for gas
Nutating disk	Volumetric	Liquid	1.3 to 5 cm (½ to 2 in.)	7.5 to 600 L/min (2 to 160 gal/min)	None		±0.5% flow rate	Household water meter; low maximum flow rate
Oscillating piston	Volumetric	Liquid	1.3 to 5 cm (½ to 2 in.)	2.8 to 600 L/min (0.75 to 160 gal/min.) Maximum of 4.3 to 480 m^3/hr (150 to 17,000 ft^3/hr)	None		±0.5% flow rate	Household water meter; low maximum flow rate
Bellows gas	Volumetric	Gas		Maximum of 4.3 to 480 m^3/hr (150 to 17,000 ft^3/hr)	None			Used for commercial and domestic gas service
Lobed impeller	Volumetric	Both	3.8 to 60 cm (1½ to 24 in.)	30 to 68,000 L/min (8 to 18,000 gal/min)	None	Low	±0.2% flow rate	Best used at high flow rates
Slide-vane rotary	Volumetric	Liquid	Up to 40 cm (Up to 16 in.)		None		±0.1 to 0.2% flow rate	
Retracting-vane rotary	Volumetric	Liquid	Up to 10 cm (Up to 4 in.)		None		±0.1 to 0.2% flow rate	
Helical gear	Volumetric	Liquid	3.8 to 25 cm (1½ to 10 in.)	19 to 15,000 L/min (5 to 4,000 gal/min)	None	Low	±0.1 to 0.2% flow rate	High viscous liquids only
Turbine	Volumetric	Both	0.64 to 60 cm (¼ to 24 in.)	190,000 L/min (50,000 gal/min) 65 scmm (230,000 scfm)	10 D up 5 D down	34 to 41 kPa @ 6.1 m/sec (5 to 6 psi @ 20 ft/sec) water flow	±0.5% flow rate	Straightening vanes Do not exceed maximum flow
Vortex shedding	Velocity	Both	2.5 to 30 cm (1 to 12 in.)	0.30 to 6.1 m/sec (1 to 20 ft/sec) 11 to 19,000 L/min (3 to 5,000 gal/min)	10 to 20D up 5D down	34 to 41 kPa @ 6.1 m/sec (5 to 6 psi @ 20 ft/sec) water flow	±1% flow rate (liquid) ±2% flow rate (gas)	Straightening vanes
Vortex precession	Velocity	Gas	2.5 to 20 cm (1 to 8 in.)	0.30 to 6.1 m/sec (1 to 20 ft/sec)	10 to 20D up 5D down	5x more than shedder	±2% flow rate	Straightening vanes

TABLE 4.4-1. (continued)

Type of flow meter	Type of measure-ment	Liquid, gas, or both	Applicable pipe diameter	Applicable flow rate	Straight pipe requirements[a]	Net pressure loss	Accuracy	Restrictions
Fluidic oscillating	Velocity	Liquid	2.5 to 10 cm (1 to 4 in.)	Up to 6.1 m/sec (20 ft/sec)	6D up 2D down	34 to 41 kPa @ 6.1 m/sec 5 to 6 psi @ 20 ft/s water flow	±1.25 to 2% flow rate	Carefully determine minimum flow rate
TOF ultrasonic	Velocity	Both	>0.32 cm (>⅛ in.)	Minimum 0.03 m/sec (0.1 ft/sec)	10 to 30D up 5 to 10D down	None	±0.5 to 10% full scale	Need clean fluid
Doppler ultrasonic	Velocity	Liquid	>0.32 cm (>⅛ in.)	Minimum 0.15 m/s (0.5 ft/sec); 0.38 L/min (0.1 gal/min)	Yes	None	As low as 1% flow rate	Fluid must have sufficient particles or bubbles
Thermo-anemometer	Velocity (mass)	Gas	>5 cm (>2 in.)		8 to 10D up 3D down	Very low	+2% flow rate	Critically positioned probes Highly fluid composition dependent
Colorimetric	Velocity (mass)	Gas	>5 cm (>2 in.)		8 to 10D up 3D down	Low	±4% flow rate	
Corrolis mass	Mass flow	Both limited gas	0.16 to 15 cm (1/16 to 6 in.)	Definitive max. + min. flow rate	None	High	±0.2 to 0.4% flow rate	Pressure drop across flow meter cannot exceed max. system pressure drop
Rotameter	Velocity	Both	1.3 to 10 cm (½ to 4 in.)	Up to 750 L/min (200 gal/min for liquid); unlimited for gas	None	Low	±1 to 2% full scale	Must be mounted vertically

[a]D = pipe diameters (e.g., 6D = 6 pipe diameters).

the flow rate is inferred by comparison to flow meters that have been carefully tested under laboratory conditions.

4.4.2.1 Measurement Principal[1]

If a constriction is placed in a closed channel carrying a stream of fluid, an increase in velocity will occur, and hence an increase in kinetic energy, at the point of the constriction. From an energy balance, as given by Bernoulli's theorem, a corresponding reduction in pressure must occur. The rate of discharge from the constriction can be determined from the change in pressure, the area available for the flow at the constriction, the density of the fluid, and the coefficient of discharge. The coefficient of discharge is defined as the ratio of the actual flow to the theoretical flow.

4.4.2.2 System Components and Operation[1-5]

Three types of differential pressure flow devices are commonly used in industrial applications: (1) Herschel-type venturi tubes, (2) flow nozzles, and (3) orifice plates. Figures 4.4-1, 4.4-2, and 4.4-3 present diagrams of the venturi tube, flow nozzle, and orifice plate, respectively. These devices are described in the following paragraphs. A fourth type of differential pressure flow device, the pitot tube, typically is not used for continuous measurements of fluid flow in industrial applications. Therefore, a discussion of the pitot tube is not presented.

4.4.2.2.1 Venturi tubes. The venturi tube consists of a converging cone, venturi throat, and diffuser. The inlet section to the venturi tube consist of a converging cone that has an included angle of roughly 21 degrees (°). The converging cone is joined by a smooth curve to a short cylindrical section called the venturi throat. Another smooth curve joins the throat to the diffuser, which consists of a cone with an included angle of roughly 7° to 8°. The diffuser recovers most of the pressure normally lost by an orifice plate.

The venturi tube can be used to measure fluid flow in pipes with diameters of approximately 5 to 120 centimeters (cm) (2 to 48 inches [in.]). The venturi has the following advantages over the orifice plate:

1. Handles more flow while imposing less permanent pressure loss--approximately 60 percent greater flow capacity;
2. Can be used with fluids containing a higher percentage of entrained solids; and
3. Has greater accuracy over a wider flow rate range.

4.4.2.2.2 Flow nozzles. The flow nozzle is similar to the venturi tube in that it has a throat; the primary difference is that the flow nozzle does not include a long converging cone and

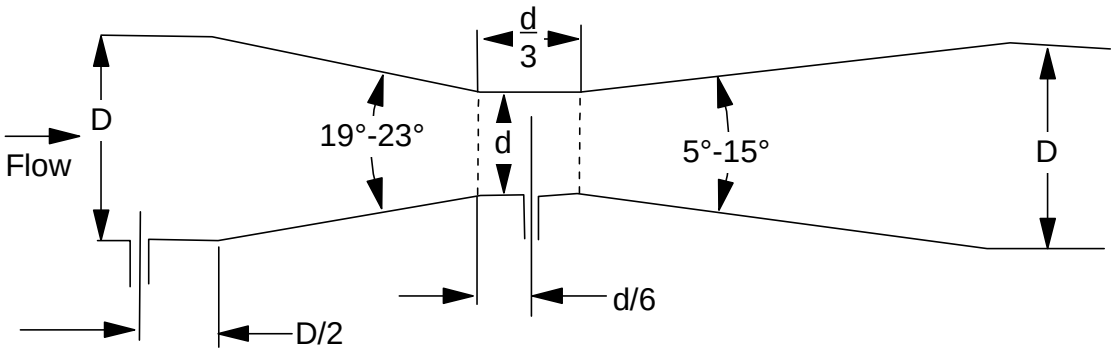


Figure 4.4-1. Venturi tube.[2]

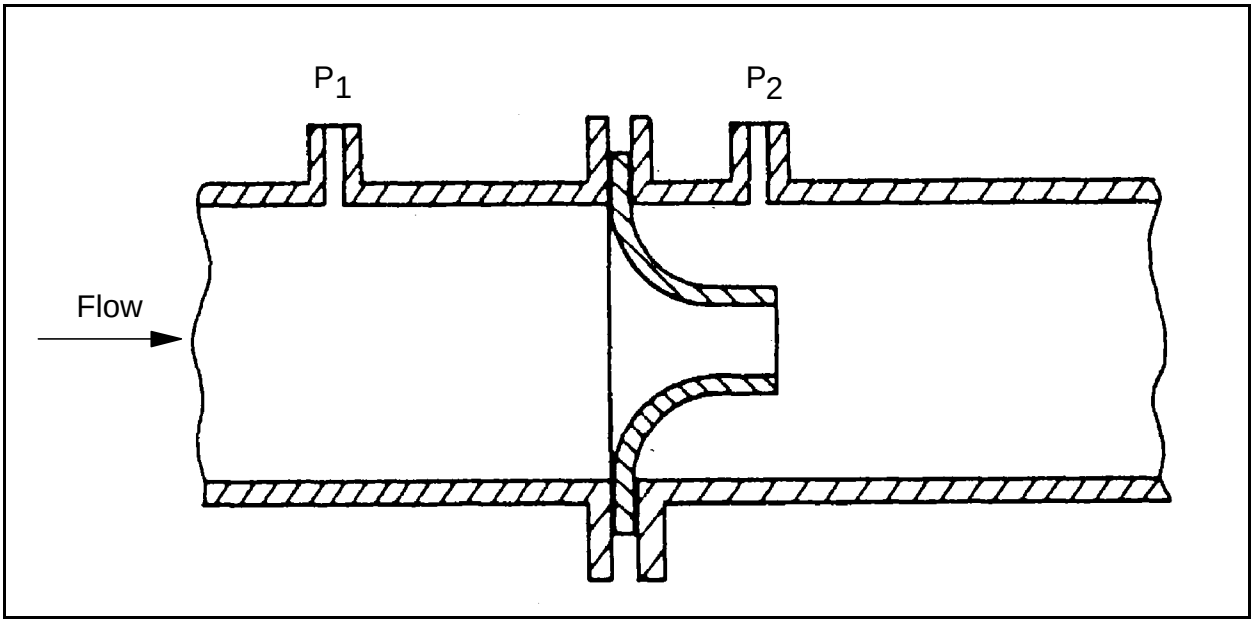


Figure 4.4-2. Flow nozzle.[1]

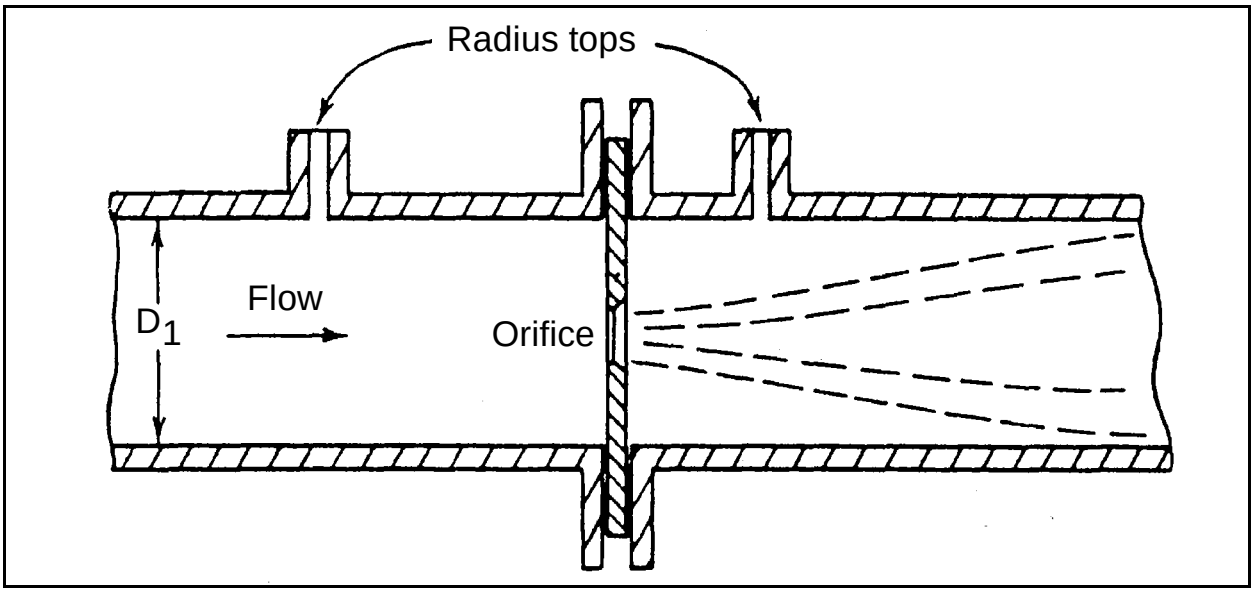


Figure 4.4-3. Orifice plate.[1]

diffuser. Flow nozzles are generally selected for high temperature, pressure, and velocity applications (e.g., measuring steam flow).

Flow nozzles, which can be used to measure fluid flow in pipes with diameters of approximately 7.6 to 61 cm (3 to 24 in.), have the following advantages:

1. Net pressure loss is less than for an orifice plate (although the net pressure loss is much greater than the loss associated with venturi tubes), and
2. Can be used in fluids containing solids that settle.

Flow nozzles have the following disadvantages:

1. More expensive than orifice plates, and
2. Limited to moderate pipe sizes.

4.4.2.2.3 <u>Orifice plates</u>. Orifice plates can be used to measure fluid flow in pipes with diameters of approximately 1.3 to 180 cm (0.5 to 72 in.). Orifice plates operate on the same principle as the venturi tube and the flow nozzle, but their design is quite different. An orifice plate consists of a square-edged or sharp-edged, thin opening in a metallic plate attached to a handle. The opening is of a predetermined size and shape and is machined to tight tolerances. The key dimensional information is usually stamped in the upstream side of the plate handle. The presence of the handle gives the orifice plate the appearance of a paddle. The opening in an orifice plate is either:

1. Concentric, with a circular center hole;
2. Eccentric, with an eccentric circular hole at the top (liquids) or bottom (gases) of the plate; or
3. Segmental, with a semicircular hole at the top (liquids) or bottom (gases) of the plate.

The differential pressure readings for an orifice plate are obtained from a pair of pressure taps, which are located in one of the following configurations:

1. Corner taps, which consist of static holes drilled as close as possible to the orifice plate, one in the upstream flange and one in the down-stream flange;

2. Radius taps, which consist of static holes located 1 pipe diameter upstream and 0.5 pipe diameters down-stream from the plate;

3. Pipe taps, which are static holes located 2.5 pipe diameters upstream and 8 pipe diameters downstream from the plate;

4. Flange taps, which consist of static holes located 2.5 cm (1 in.) upstream and 2.5 cm (1 in.) downstream of the plate; and

5. Vena contract, which are static holes located 0.5 to 2 pipe diameters upstream and at the minimum pressure point downstream from the plate. Corner taps and flange taps are advantageous because the pressure points can be tapped in the plate carrying the orifice. Pipe taps give the lowest differential pressure. Table 4.4-2 summarizes the advantages and disadvantages of orifice plate flow meters.

4.4.2.3 Accuracy[5-7]

Precision machining has led to increased accuracy of differential pressure flow meters. Typically, these devices meet ASME accuracy requirements without laboratory calibration. Each of the accuracy levels presented below can be increased, if needed, with laboratory calibration.

TABLE 4.4-2. ADVANTAGES AND DISADVANTAGES OF ORIFICE PLATE FLOW METERS

Advantages	Disadvantages
Low cost Available in numerous materials of construction Can be used with a wide range of pipe sizes Characteristics are well known and predictable from years of applicable experience	High net pressure loss--30 to 85 percent of the differential reading, depending on the opening to pipe diameter ratio (β) Tendency to clog; not useful for slurries or entrained particles Flow range limited to about 3:1 Characteristics tend to change with time due to erosion and corrosion of the opening Accuracy is dependent upon care during installation.

Venturi tube: ±0.75 percent of flow rate

Flow nozzle: ±1.0 percent of flow rate

Orifice plate: ±0.6 percent of flow rate.

4.4.2.4 Calibration Techniques[5]

4.4.2.4.1 Sensor. Differential pressure flow meters are inferential devices, so the physical condition of the throat, nozzle, or bore should be checked to ensure that dimensions are within tolerance. The most critical of these is the bore of the orifice plate. In addition, the appropriate ASME method for calibration should be used for calibration of these devices. For example, ASME MFC-3M-1989 could be used for venturi tubes, flow nozzles, and orifice plates.

4.4.2.4.2 System. The differential pressure transmitter can be calibrated by simulating inputs to the transmitter and making the required zero and span adjustments if the calibration error is outside the acceptable performance standard. Another system calibration that can be performed involves the determination of the energy or mass balance of fluid flow to process operations. If fluid flow energy or mass agrees (balances) within the performance specifications to actual production rates or heat input, then the flow rate system can be assumed to be in calibration. Additionally, comparisons of recent energy or mass balances to past data can be made.

4.4.2.5 Recommended QA/QC Procedures

Differential pressure flow measurement devices are extremely sensitive to swirling flow or abnormal velocity distributions caused by disturbances (e.g., pipe bends) upstream or downstream of the device. The presence of swirling flow and abnormal velocity distributions can be reduced or eliminated with sufficient straight piping or installing flow straighteners. Table 4.4-2 shows the recommended upstream and downstream disturbance distances from differential pressure meter orifices or nozzles.

Table 4.4-3 indicates the recommended locations both with and without straightening vanes. The criteria for straightening vanes (a set of smaller pipes arranged in a honeycomb configuration installed inside the fluid pipe) are as follows:

$d_v \leq D_p/4$ and $l_v > 8d_v$

where:

d_v = diameter of each straightening vane pipe;

D_p = fluid pipe diameter; and

l_v = length of each straightening vane pipe.

The presence of fluid flow pulsations caused by piston pumps, reciprocating equipment, and the like will cause differential pressure readings to be high. Such pulsations in the differential pressure readings can be dampened in order to stabilize differential pressure readings for controlling process operations; however, doing so will not produce more accurate flow rate measurements. The most effective approach to minimizing the effect of fluid flow pulsations is to install a dampening chamber near the pulsating or reciprocating equipment.

TABLE 4.4-3. LOCATIONS OF ORIFICES AND NOZZLES RELATIVE TO PIPE FITTINGS[1]

Type of fitting upstream	D_2[a] / D_1	Distance, upstream fitting to orifice		Distance, vanes to orifice	Distance, nearest downstream fitting from orifice
		Without straightening vanes	With straightening vanes		
Single 90-deg. ell, tee, or cross used as ell	0.2 0.4 0.6 0.8	6 6 8 20	 10 12	 8	2 4
2 short-radius 90-deg. ells in form of "S"	0.2 0.4 0.6 0.8	7 8 13 25	 8 10 15	 6 11	 4
2 long- or short-radius 90-deg. ells in perpendicular planes	0.2 0.4 0.6 0.8	15 18 25 40	9 10 11 13	5 6 7 9	2
Contraction or enlargement	0.2 0.4 0.6 0.8	8 9 10 15	Vanes have no advantage		2
Globe valve or stop check	0.2 0.4 0.6 0.8	9 10 13 21	9 10 10 13	5 6 6 9	2
Gate valve, wide open, or plug cocks	0.2 0.4 0.6 0.8	6 6 8 14	Same as globe valve		2 4

[a]Distances in pipe diameters, D_1, D_2.

For best results, the proper device (i.e., venturi, nozzle, orifice) should be selected based on expected fluid temperature, pressure, density, velocity, percent of solids or entrained particles, viscosity, amount of straight pipe, and pipe size. Additionally, the proper differential pressure device and appropriate measurement range should be chosen.

The piping at least four diameters upstream and two diameters downstream of the device should have a smooth finish, free of mill scale, holes, bumps, grooves, pits, seam distortions, and the like. The pipe inside diameter should not depart from the average by more than 0.33 percent. Inside pipe distortions should be corrected by filling in, grinding, or filing.

In liquid flow applications, insulating or heat tracing the differential pressure lines will help ensure accuracy of the system measurements by preventing the liquid in the pressure lines from freezing. In some installations in which the differential pressure lines are subject to clogging, it may be necessary to install a purge system on the differential pressure lines to keep

them clean. In addition, the differential pressure lines should be checked periodically for leakage.

Orifice plate bore wear can be detected by a slow reduction of indicated flow rate with time. If the measured flow rate diverges from the expected flow rate over time, the orifice plate should be removed and inspected for bore wear, encrustation, or material buildup on the square edge of the orifice plate bore. Bore wear results in a measured flow rate that is lower than actual, and material buildup results in a measured flow rate that is higher than the actual flow rate.

4.4.2.5.1 Frequency of calibration. Calibration of differential pressure flow monitoring devices should follow a consistent pattern to allow for comparison of performance changes over time. The recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. The above calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or conditions are suspected of causing the loss of calibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.2.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include:

1. The recommended interval for zero and span calibration checks of the differential pressure transducer (Readings before and after adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;

4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);

5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position);

6. Designation of person to whom to report any failed calibration; and

7. Place to store calibration results.

4.4.2.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.3 Magnetic Flow Meters[2,4]

Magnetic flow meters are effective for monitoring the flow rate of fluids that present difficult handling problems, such as corrosive acids, rayon viscose, sewage, rock and acid slurries, sand and water slurries, paper pulp stock, rosin size, detergents, bleaches, dyes, emulsions, tomato pulp, milk, soda, and beer. Magnetic flow meters mainly are applicable to liquids that have a conductivity of 0.1 microsiemens per centimeter or greater. They are not applicable to petroleum products or gases.

4.4.3.1 Measurement Principal[4]

The basis of the magnetic flow meter is Faraday's Law of Electromagnetic Induction. In summary, a voltage induced in a conductor (i.e., the fluid flowing in the conduit) moving in a magnetic field is proportional to the velocity of the conductor. This relationship can be expressed mathematically as follows:

$$E = C \times B \times D \times v$$

where:

E = induced voltage;

C = constant;

B = magnetic flux density;

D = diameter of conduit; and

v = velocity of fluid.

4.4.3.2 System Components and Operation[2,4-5]

Two different types of magnetic flow meters are used in industrial applications; the difference between the two is the type of current used to generate the magnetic field. Alternating

current (ac) magnetic flow meters excite the flowing fluid with an ac electromagnetic field. Direct current (dc), or pulsed, magnetic flow meters excite the flowing fluid with a pulsed dc electromagnetic field. Figure 4.4-4 presents a diagram of a magnetic flow meter. Direct current magnetic flow meters are more common than ac magnetic flow meters.

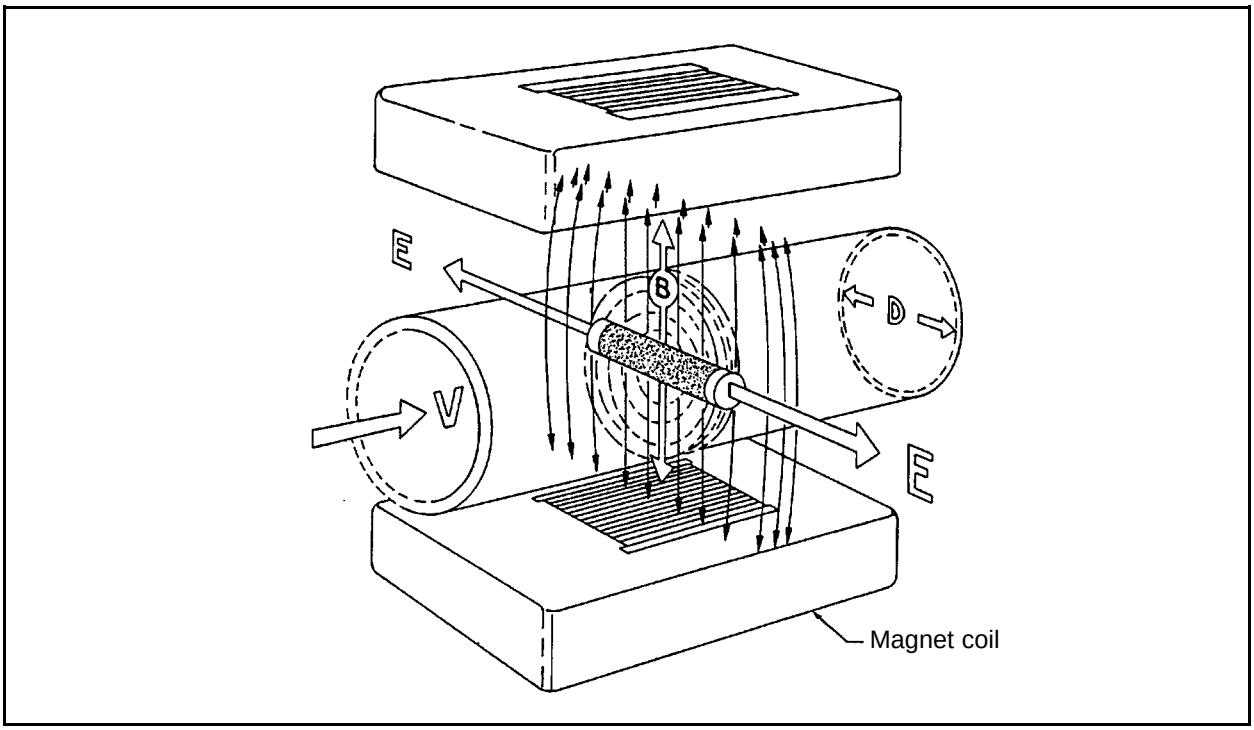


Figure 4.4-4. Magnetic flow meter.[5]

In principle, the fluid flowing through the pipe passes through the magnetic field. This action generates a voltage that is linearly proportional to the average velocity in the plane of the lectrodes. If the velocity profile changes due to swirl or helical flow patterns, the total measured velocity is unaffected as long as the velocity profile across the pipe is symmetrical. Nonsymmetrical flow profiles may cause flow rate measurement errors of several percent.

In operation, the magnetic coils create a magnetic field that passes through the flow tube and into the process fluid. When the conductive fluid flows through the flow meter, a voltage is induced between the electrodes, which are in contact with the process fluid and isolated electrically from the pipe walls by a nonconductive liner to prevent a short circuit in the electrode signal voltage. Grounding is required for magnetic flow meters to shield the relatively low voltage signal that is measured at the electrodes from the relatively high common-mode potentials that may be present in the fluid. If the pipe is conductive and comes in contact with the flow meter, the flow meter should be grounded to the pipe both upstream and downstream of the flow meter. If the pipe is constructed of a nonconductive material, such as plastic, or a

conductive material that is insulated from the process fluid, such as plastic-lined steel pipe, grounding rings should be installed in contact with the liquid.

Magnetic flow meters can be used in pipes that range in diameter from 0.25 to 240 cm (0.1 to 96 in.). Magnetic flow meters are available for flow rates in the range of 0.008 liters per minute (L/min) (0.002 gallons per minute [gal/min]) to 570,000 L/min (150,000 gal/min). Since magnetic flow meters do not place an obstruction in the pipe, the devices do not cause a loss in fluid pressure. Also, straight pipe requirements do not apply to this flow monitor device. Magnetic flow meters are insensitive to density and viscosity and can measure flow in both directions. In addition, because they cause no obstructions, magnetic flow meters often are used to measure the flow rate of slurries.

4.4.3.3 Accuracy[2]

If all components of a magnetic flow metering system are calibrated as a unit, system accuracies of ±0.5 percent of flow rate are possible. However, normal accuracy specifications are ±1.0 percent of flow rate. Higher accuracy systems match the primary flow meter with a transmitter in the factory.

4.4.3.4 Calibration Techniques[5]

Calibration of the electronics can be accomplished with a magnetic flow meter calibrator or by electronic means. Magnetic flow meter calibrators are precision instruments that inject the output signal of the primary flow meter into the transmitter, which effectively checks and calibrates all of the electronic circuits. An alternate calibration method, although not as accurate, is to make adjustments based upon test signals injected into the transmitter, circuit test measurements, or thumbwheel switches according to manufacturer's specifications.

Calibration of an ac magnetic flow meter must be performed at zero flow with the flow meter full of fluid. Zero adjustments to compensate for noise that may be present in the system also must be made with the flow meter full of fluid. Pulsed dc magnetic flow meters do not require this zero compensation for noise in the system because the flow signal is extracted regardless of the zero shifts that may occur due to noise.

4.4.3.5 Recommended QA/QC Procedures[5]

Magnetic flow meters can be affected adversely by electrode coating, liner damage, and electronic failure. Alternating current magnetic flow meters are most susceptible to nonconductive electrode coating, which causes a calibration shift due to changes in the conductivity that the electrodes sense. Device manufacturers should be consulted about electrode cleaning methods that do not require removal or replacement of the flow meter. If this is a

continual problem, an ultrasonic cleaner may be added or the ac flow meter could be replaced with a dc flow meter. Liner damage generally requires that the flow meter be replaced or sent back to the manufacturer for overhaul. Finally, most dc flow meters have a reference signal that checks about 90 percent of the electronic circuits. The reference signal can be used to check for a suspected malfunction.

The following recommended spare parts should be maintained: assortment of electrodes, liner, flow tube, and electronic components.

4.4.3.5.1 Frequency of calibration. Calibration of magnetic flow meters should follow a consistent pattern to allow for comparison of performance changes over time. The recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. These calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or conditions are suspected of causing the decalibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.3.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include the following:

1. The recommended interval for zero and span calibration checks of the electronics, and the recommended interval for reference (internal) signal electronics checks (Readings before and after any adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;

4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);

5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position);

6. Designation of person to whom to report any failed calibration; and

7. Place to store calibration results.

4.4.3.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.4 Positive Displacement Flow Meters

Positive displacement meters generally measure velocity as a function of how the fluid being measured produces a motion or rotation to a piston or vane. Examples of positive displacement meters used for measuring gas flow include vane anemometers, turbine meters, and propeller meters. These devices consist of blades, propellers, or cups, mounted on a rotating shaft; velocity is measured as a function of rotational speed of the shaft induced by the gas flow.

4.4.4.1 Measurement Principal[5]

Positive displacement type flow meters repeatedly entrap a known quantity of fluid as it passes through the flow meter. The number of times the fluid is entrapped is counted, and therefore the quantity of fluid passed through the flow meter is known. Because the measurements by a positive displacement meter are independent of time (a positive displacement of the meter occurs for each quantity or volume of fluid), positive displacement flow meters measure total flow and can be classified as volume meters.

4.4.4.2 System Components and Operation[2,4]

Seven types of positive displacement flow meters are commonly used. Four of these can be classified as rotating positive displacement flow meters: lobed-impeller meters, slide-vane rotary flow meters, retracting vane rotary flow meters, and helical gear flow meters. The other three types of positive displacement flow meters are nutating disk meters, oscillating disk meters, and bellows gas meters. Nutating-disk meters and oscillating piston meters generally are used as household water meters and can be used to measure flow rates up to a maximum of about 760 L/min (200 gal/min). The bellows gas meter is widely used in commercial and domestic natural gas service and has a maximum flow capacity range of 68 to 7,950 L/min (18 to

2,100 gal/min). For industrial applications, rotating positive displacement flow meters are the most commonly used type of positive displacement flow meter. The following paragraphs describe these flow measurement devices in greater detail.

4.4.4.2.1 Lobed-impeller meters. Lobed-impeller meters contain two fixed position rotors that revolve inside a cylindrical housing. The measuring chamber is formed by the walls of the cylinder and the surface of one half of one rotor. When the rotor is in the vertical position, a specific volume of fluid is contained in the measuring compartment. As the impeller turns, due to a slight differential pressure between the inlet and outlet ports, the measured volume is discharged through the bottom of the meter. This action occurs four times for a full revolution, with the impeller rotating the opposite direction at a speed proportional to the volume of the fluid. Figure 4.4-5 depicts a lobed-impeller flow meter.

Lobed-impeller meters can be used to measure fluid flow in pipes with diameters of approximately 3.8 to 61 cm (1.5 to 24 in.) Measurable maximum flow rates range from 30 to 66,000 L/min (8 to 17,500 gal/min). Table 4.4-4 summarizes the advantages and disadvantages of lobed-impeller flow meters.

4.4.4.2.2 Slide-vane rotary flow meters. Slide-vane rotary flow meters contain a cylindrical rotor that revolves on ball bearings around a central shaft and stationary cam. As fluid flows against an extended blade, the resulting rotation of the rotor and action of the cam cause the blades to act as cam followers, creating measuring chambers that measure fluid throughput. Figure 4.4-6 depicts a slide-vane rotary flow meter.

Slide-vane rotary flow meters can be used to measure fluid flow in pipes with diameters of up to 41 cm (16 in.). This type of flow measurement device can be used in temperatures to 204°C (400°F) and pressures up to 3,450 kPa (500 [psi]). Slide-vane rotary flow meters are characterized by high accuracy, but have the following limitations:

1. High costs;
2. Limited flow rate range--from 5:1 to 10:1; and
3. Moving parts that are subject to wear.

4.4.4.2.3 Retracting vane rotary flow meters. In retracting vane rotary flow meters, the vanes are jointed. As fluid enters the meter, it is deflected downward against the extended blade, causing rotation of the measuring element. Retracting vane rotary flow meters can be used to measure fluid flow in pipes with diameters up to four inches, at fluid temperatures up to 204°C (400°F) and pressures up to 6,200 kPa (900 psi). As is the case for slide-vane rotary flow meters, retracting vane rotary meters are characterized by high accuracy, but have the following limitations:

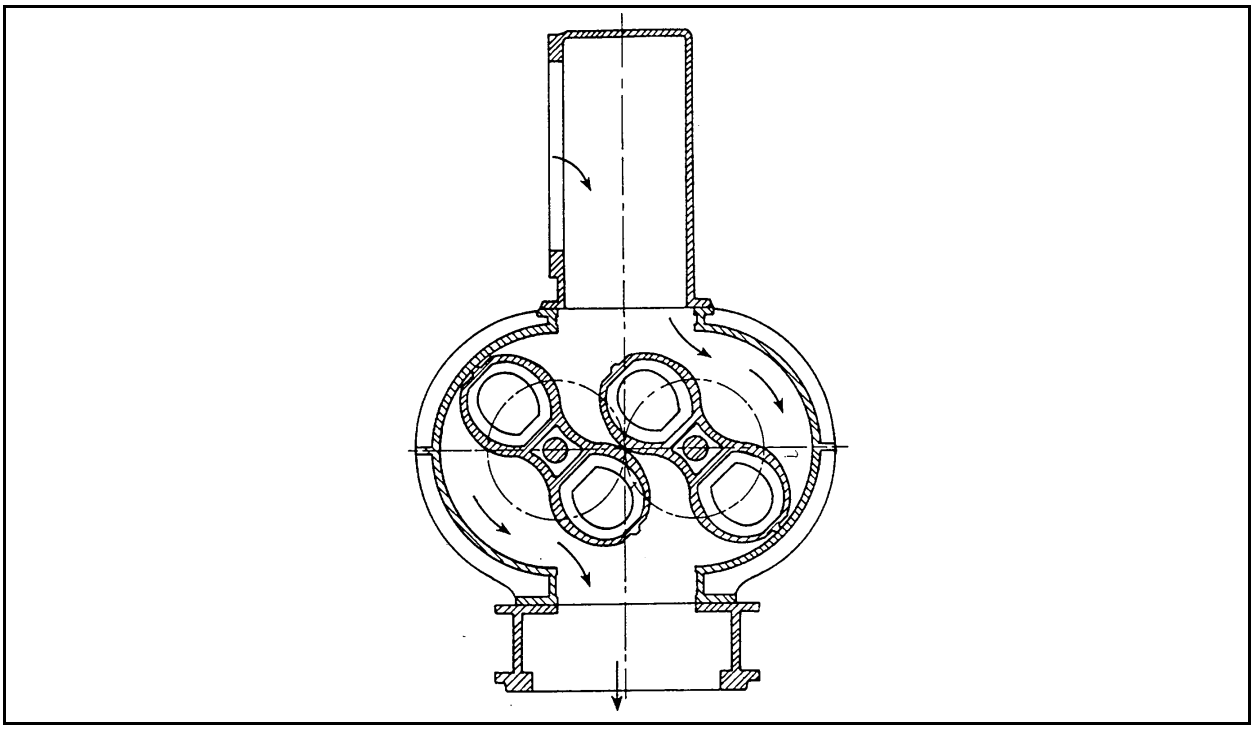


Figure 4.4-5. Lobed-impeller flow meter.[2]

TABLE 4.4-4. ADVANTAGES AND DISADVANTAGES OF LOBED-IMPELLER FLOW METERS

Advantages	Disadvantages
Can be used at relatively high temperatures (204°C [400°F]) and pressure (8,200 kPa [1,200 psi])	Susceptible to damage from entrained vapors
Low net pressure loss	Larger sizes are bulky and heavy
Available in numerous materials of construction	High cost
No upstream or downstream pipe diameter requirements	Moving parts subject to wear
Applicable for gases and a wide range of light to viscous liquids	Best used at high flow rates because of possible slippage at low flow rates
Wide range of flow rates	

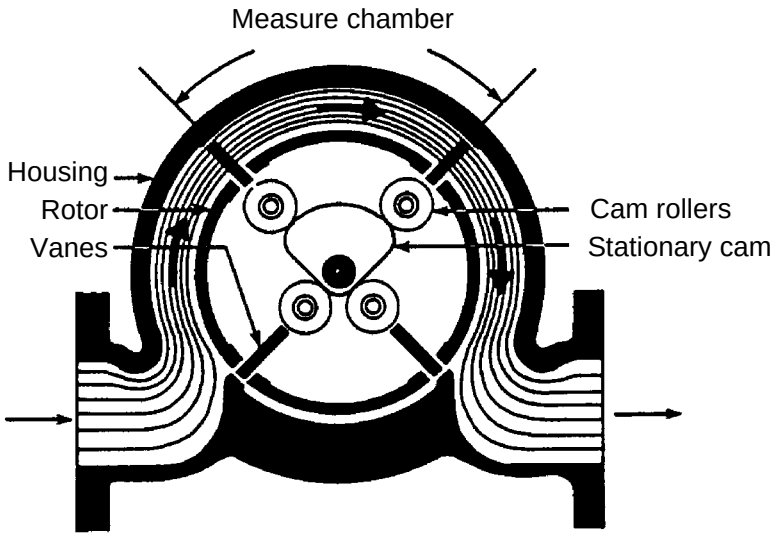


Figure 4.4-6. Slide-vane rotary flow meter.[2]

1. High costs;
2. Limited flow rate range--from 5:1 to 10:1; and
3. Moving parts that are subject to wear.

Figure 4.4-7 depicts a retracting vane rotary flow meter.

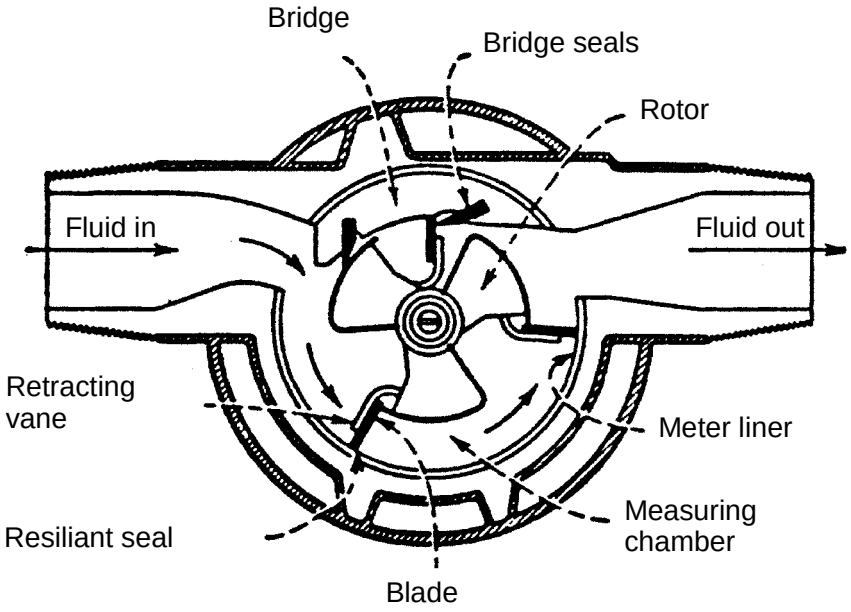


Figure 4.4-7. Retracting vane rotary flow meter.[4]

4.4.4.2.4 <u>Helical gear flow meters</u>. Helical gear meters use two radially-pitched helical gears to continually entrap liquid as it passes through the flow meter, causing the rotors to rotate

in a longitudinal plane. Flow is proportional to the rotational speed of the gears. System components include the rotor, bearings, and sensing system. Magnetic or optical sensing systems monitor the speed of the gears. In a magnetic sensor, the gear teeth are sensed by a magnetic pickup and amplified. An optical sensor uses a magnetically driven, optically encoded disc. Rotation of the disc is sensed by an optical pickup that senses a pulse each time a portion of a revolution occurs. Figure 4.4-8 depicts a helical gear flow meter.

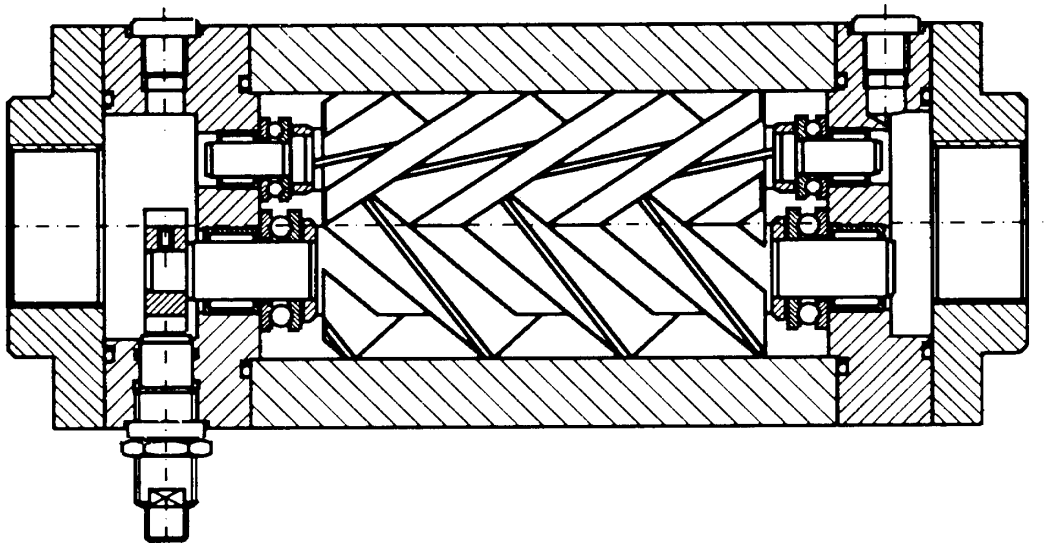


Figure 4.4-8. Helical gear flow meter.[11]

Helical gear meters can be used to measure highly viscous liquid flow in pipes with diameters of approximately 3.8 to 25 cm (1.5 to 10 in.). Measurable flow rates range from 19 to 15,100 L/min (5 to 4,000 gal/min). Table 4.4-5 summarizes the advantages and disadvantages of helical gear flow meters.

4.4.4.3 Accuracy[4,5]

The following accuracies apply to the four rotating positive displacement flow meters:

Lobed-impeller: ±0.2 percent of flow rate

Slide-vane rotary: ±0.2 percent of flow rate

Retracting vane rotary: ±0.2 percent of flow rate

Helical gear: ±0.2 to 0.4 percent of flow rate.

4.4.4.4 Calibration Techniques[5]

4.4.4.4.1 Sensor. The meter constant (K-factor), which establishes the relationship between the frequency output of the flow meter, the volumetric flow, and the output of the converter, is fixed by design and cannot be calibrated.

TABLE 4.4-5. ADVANTAGES AND DISADVANTAGES OF HELICAL GEAR FLOW METERS

Advantages	Disadvantages
Applicable to highly viscous liquids	Moving parts subject to wear
Low net pressure loss	Only applicable to liquids
Good accuracy	

4.4.4.4.2 System. To calibrate positive displacement flow meter systems, a frequency signal that corresponds to the output of the primary flow meter device at a known flow is injected into the converter so as to verify operation of the converter and set zero and span. Another system calibration that can be performed involves energy or mass balance calculation of fluid flow to process operations; if fluid flow energy or mass agrees (balances) within the performance specifications to actual production rates or heat input, the flow rate measurement system can be assumed to be in calibration. Additionally, comparisons of recent energy or mass balances to past data can be made.

4.4.4.5 Recommended QA/QC Procedures[5]

Positive displacement flow meters are subject to deterioration due to wear, corrosion, exposure to a dirty liquid, and abrasion. Pluggage can occur if the flow meter is exposed to a dirty liquid. Excessive slippage usually results from corrosion or abrasion. Line cleaning before commissioning a new unit is recommended. Additionally, the meter should not be exposed to steam, which is often used to clean pipes. The following recommended spare parts should be maintained: rotor, sensor, bearings, and electronic components.

4.4.4.5.1 Frequency of calibration. Calibration of the positive displacement flow meter converter should follow a consistent pattern to allow for comparison of performance changes over time. If slippage is suspected, appropriate procedures should be undertaken, and the meter should be sent back to the manufacturer for repair. The recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. These calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or conditions are suspected of causing the

decalibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.4.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include:

1. The recommended interval for zero and span calibration checks of the converter (Readings before and after adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;
4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);
5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position);
6. Designation of person to whom to report any failed calibration; and
7. Place to store calibration results.

4.4.4.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.5 Turbine Flow Meters

4.4.5.1 Measurement Principal

Unlike positive displacement flow meters, which physically capture a discrete volume of fluid, turbine flow meters infer the total quantity of flow from the reaction of the fluid on the turbine flow meter.

4.4.5.2 System Components and Operation[2,4-5]

A turbine flow meter consists of a rotating device (i.e., rotor) that is positioned in the flow stream in such a manner that the rotational velocity of the rotor is proportional to the fluid velocity and hence the flow through the device. The flowing fluid reaction with the turbine blades imparts a force to the blade surface and sets the rotor in motion. The steady-state speed is proportional to the fluid velocity.

The rotor speed may be transmitted through the meter housing by a mechanical shaft, with magnetic coupling to an external shaft, or through a suitable gland in the housing. In another type of turbine flow meter design, a signal is generated by means of a magnetic pickup coil, consisting of a permanent magnet with coil windings, mounted in close proximity to the rotor but external to the fluid channel.

Like some other flow rate monitoring devices, the turbine meter is sensitive to swirling and perturbed flows. Therefore, all turbine flow meters use a section of straightening vanes upstream of the rotor to ensure that the fluid entering the rotor is free from swirl. Standard requirements for turbine flow meters are 10 diameters of straight pipe upstream and 5 diameters of straight pipe downstream of the rotor with straightening vanes.

Turbine flow meters for measuring gas flow are characterized by a central hub that is larger than the hub in turbine flow meters used for liquid flow measurement. A diagram of the turbine flow meter is presented in Figure 4.4-9. Other turbine flow meter designs are the paddle wheel, propeller, and tangential turbine.

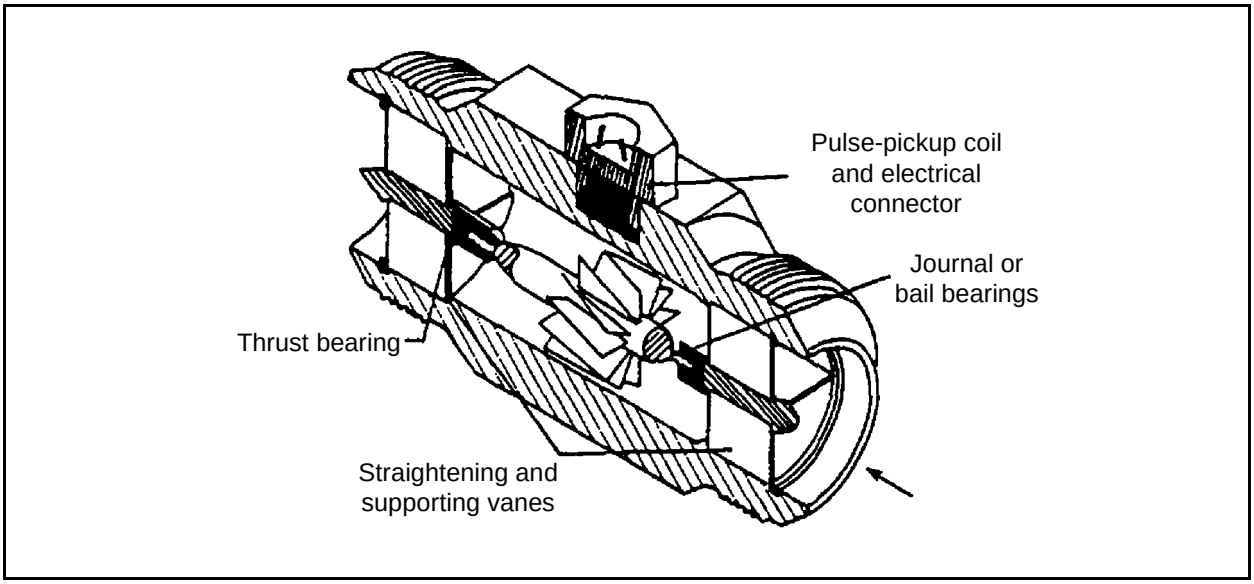


Figure 4.4-9. Turbine flow meter.[2]

Turbine flow meters can be used to measure fluid flow in pipes with diameters of approximately 0.64 to 61 cm (0.25 to 24 in.). The turbine flow meter can measure liquid flow rates from 0.23 to 189,000 L/min (0.06 to 50,000 gal/min) and gas flow rates from (100 to 230,000 standard cubic feet per minute [scfm]). Table 4.4-6 summarizes the advantages and disadvantages of turbine flow meters.

TABLE 4.4-6. ADVANTAGES AND DISADVANTAGES OF TURBINE FLOW METERS

Advantages	Disadvantages
Sensitive to fluctuations in flow and can more accurately detect changes in fluid velocity	Exhibit a larger amount of slip than do positive displacement flow meters
Rotor stoppage does not totally block the flow of fluid as would be the case for positive displacement flow meters	Contain many moving parts
Available for a wide range of flow rates	Require straight pipe and flow straightening vanes
	Cannot operate at flows greater than recommended; overspinning the rotor can destroy the bearings

4.4.5.3 Accuracy[5]

Although the trend in flow rate measurement has been toward flow meters than have few or no moving parts, the turbine flow meter often is used when high accuracy is desired. The accuracy of liquid-flow turbine flow meters is approximately ±0.5 percent over a 10 to 1 flow rate range. Accuracy typically is not as high in turbine flow meters used for gas flow applications.

4.4.5.4 Calibration Techniques[5]

4.4.5.4.1 Sensor. The primary flow meter device is factory calibrated.

4.4.5.4.2 System. Turbine transmitter calibration is performed by adjustment to properly interpret the frequency output of the primary device. Zero and span adjustments are made by simulating the frequency that the primary device would transmit at zero flow or maximum flow and adjusting the transmitter output as appropriate.

Another system calibration that can be performed involves energy or mass balance calculation of fluid flow to process operations. If fluid flow energy or mass agrees (balances) within the performance specifications to actual production rates or heat input, the flow rate system can be assumed to be in calibration. Additionally, comparisons of recent energy or mass balances to past data can be made.

4.4.5.5 Recommended QA/QC Procedures[5]

Turbine flow meters should not be subject to sudden surges of liquid flow, such as the starting of a pump or opening of a valve when the flow meter or piping is empty. Diagnosis of sensor failure, as opposed to rotor, bearing, or electronic failure, is important in order to avoid unnecessary work. Sensor failure should be suspected when flow is known to exist in the pipe but zero flow is indicated at the transmitter output. In such cases, the transmitter should be checked in the same manner as performance of a span calibration. If the transmitter functions electrically, then the fault likely lies in the rotor, the bearing, or the sensing element.

Bearing wear can be detected by applying a low flow of fluid to the turbine and checking for rotor drag. Excessive wear can cause the rotor to eventually stop rotating and fail completely. The following recommended spare parts should be maintained: rotor, sensor, bearings, and electronic components (transmitter).

4.4.5.5.1 Frequency of calibration. Calibration of the turbine flow meter transmitter should follow a consistent pattern to allow for comparison of performance changes over time. If slippage or bearing wear is suspected, appropriate procedures should be undertaken to correct the problem. The recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. These calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or conditions are suspected of causing the decalibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.5.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include:

1. The recommended interval for zero and span calibration checks of the transmitter (Readings before and after adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;
4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);
5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position);
6. Designation of person to whom to report any failed calibration; and
7. Place to store calibration results.

4.4.5.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.6 Vortex Formation Flow Meters

4.4.6.1 Measurement Principal

Vortex formation flow meters detect vortices in the fluid flow downstream of their generation.

4.4.6.2 System Components and Operation[2,5]

Vortex formation flow meters can be classified based on design as either vortex shedding or vortex precession. In a vortex shedding device, vortex generation is induced by the means of a blunt, typically flat-faced, body placed perpendicular to the flowing fluid. As fluid passes the vortex generating element, the sharp corners cause a fixed point of fluid separation that forms a shear layer. At a specific distance downstream, the fluid in the shear layer breaks down into well-formed vortices. These vortices are formed and shed with a frequency that is linearly proportional to the fluid velocity. Sensing of the vortices is accomplished either by sensing the fluctuating pressure in the wake of the vortex generator or by sensing local velocity fluctuations around the body. Figure 4.4-10 depicts a vortex shedding flow meter.

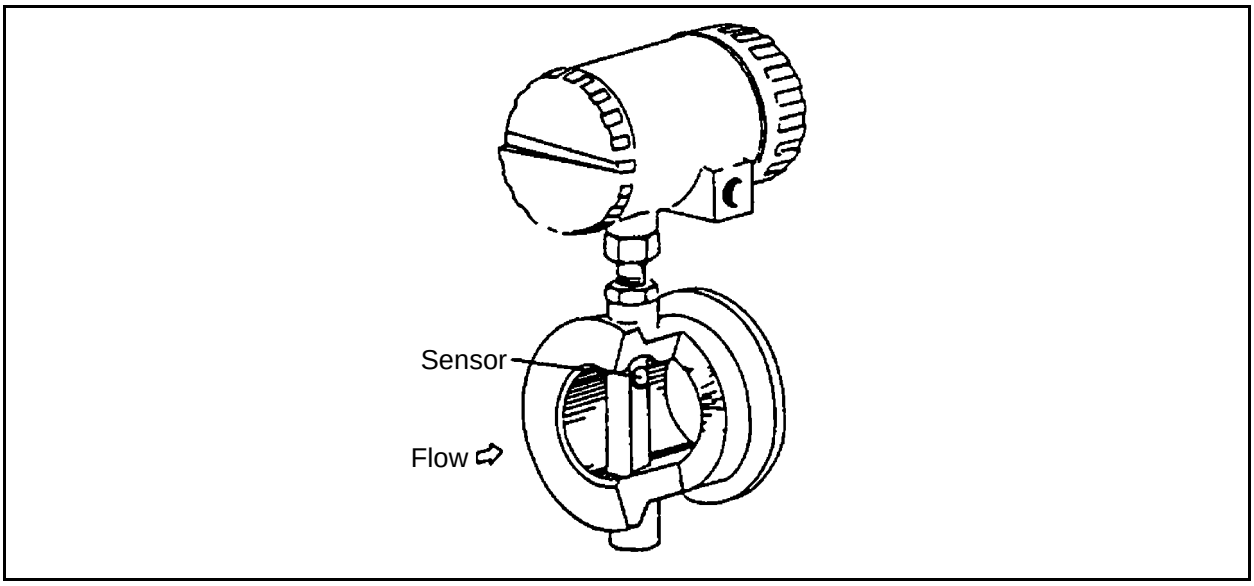


Figure 4.4-10. Vortex shedding flow meter.[2]

Vortex shedding flow meters are generally comprised of the following three basic parts: a vortex generating element, a sensor to convert vortex energy into electrical pulses, and a transmitter. The primary differences in vortex shedding flow meter designs are the shape of the generating element and the type of sensor used.

Vortex shedding flow meters are applicable to low viscosity liquids and to pressurized gases with sufficiently high densities and momentum to operate the flow meter.

In a vortex precession flow meter, the fluid entering the meter is forced into a swirl condition along the axis of flow by swirl-blade, guide vanes. The swirl is a vortex filament that is produced continuously, rather than periodically as is the case for shed vortices. At the exit of the swirl blades, the flow is contracted and expanded in a venturi-like passage, causing the vortex filament to adopt a helical path. The helical path results in a precession-like motion of the vortex filament at a fixed downstream station. A sensor placed at the downstream station relays the frequency of precession, which is linearly proportional to flow rate. Vortex precession flow meters are comprised of the following parts: swirl blades and deswirl blades, a vortex filament, a sensor, and a transmitter. The vortex precession flow meter is basically obsolete, and has yielded to the shedder device. A vortex precession flow meter is depicted in Figure 4.4-11.

Vortex formation flow meters can be used to measure fluid flow in pipes that range in diameters from 2.5 to 30 cm (1 to 12 in.) for shedding devices and from 2.5 to 20 cm (1 to 8 in.) for precession devices. The linear flow rate range for a vortex shedding flow meter is 20 to 1 for liquid and 100 to 1 for gases with the minimum flow rate of approximately 60 scfm. The applicable liquid flow rate range (for the shedding device) is 11 to 18,900 L/min (3 to 5,000 gal/min).

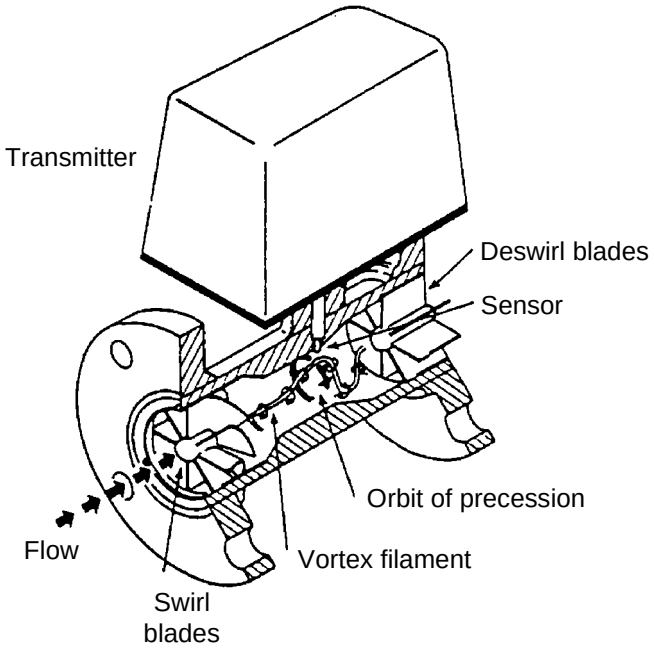


Figure 4.4-11. Vortex precession flow meter.[2]

The vortex precession flow meter is applicable only to gases with a flow rate range comparable to the vortex shedding flow meter.

Vortex formation flow meters are sensitive to swirling flow. Typical straight pipe requirements to reduce the amount of swirl in the fluid are 10 to 20 pipe diameters upstream and 5 diameters downstream. Tables 4.4-7 and 4.4-8 summarize the advantages and disadvantages of vortex shedding and vortex precession flow meters, respectively.

4.4.6.3 Accuracy[8]

The accuracy of vortex formation flow meters is approximately ±1 percent of flow rate for liquid applications and ±2 percent of flow rate for gas applications.

4.4.6.4 Calibration Techniques[5]

4.4.6.4.1 Sensor. The primary flow meter device is factory calibrated.

4.4.6.4.2 System. Calibration of the vortex formation transmitter is performed by injecting frequency signals into the transmitter and making the appropriate adjustments. This allows verification of the thumbwheel adjustments as well as fine adjustment of the zero and span analog circuit. Another possible system calibration involves energy or mass balance calculation of fluid flow to process operations. If fluid flow energy or mass agrees (balances) within the performance specifications to actual production rates or heat input, the flow rate

TABLE 4.4-7. ADVANTAGES AND DISADVANTAGES OF VORTEX SHEDDING FLOW METERS

Advantages	Disadvantages
No moving parts	Sensitive to upstream flow disturbances
Insensitive to density changes	Pulsed signal output
Linear over a wide velocity range	Limited pipe diameters
	Somewhat high net pressure loss (35 to 50 percent of the differential pressure)

TABLE 4.4-8. ADVANTAGES AND DISADVANTAGES OF VORTEX PRECESSION FLOW METERS

Advantages	Disadvantages
No moving parts	Sensitive to upstream flow disturbances
Insensitive to density changes	High net pressure loss (five times higher than for the vortex shedding device)
Continuous output	Limited pipe diameters
Linear over a wide velocity range	Limited to gas applications only

system can be assumed to be in calibration. Additionally, comparisons of recent energy or mass balances to past data can be made.

4.4.6.5 Recommended QA/QC Procedures[5]

Vortex shedding flow meters do not require zero adjustment. The span adjustment is typically performed with field changeable links or thumbwheel switches. When an analog output is used, both zero and span of the analog circuit should be performed. Normal shedder wear usually has no effect on the performance of the instrument. The following recommended spare parts should be maintained: sensor, shedder, and electronic components (transmitter).

4.4.6.5.1 Frequency of calibration. Calibration of the flow meter transmitter should follow a consistent pattern to allow for comparison of performance changes over time. The recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. These calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or

conditions are suspected of causing the decalibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.6.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include:

1. The recommended interval for zero and span calibration checks of the transmitter (Readings before and after adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;
4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);
5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position);
6. Designation of person to whom to report any failed calibration; and
7. Place to store calibration results.

4.4.6.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.7 Fluidic Oscillating Flow Meters

4.4.7.1 Measurement Principal[2,5]

The operation of fluidic flow meters is based on the Coanda Effect, which causes a liquid to attach itself to a surface, and fluidics, which is typified by feedback action of the liquid on itself.

4.4.7.2 System Components and Operation[2,5]

When flow is initiated, the flowing stream attaches itself to one of the two sidewalls in the flow meter (i.e., by means of the Coanda Effect). A small portion of the flow is diverted through a recycle, feedback passage to a control port. The feedback flow, acting on the main flow, diverts the main flow to the opposite side wall where the feedback action is repeated on the opposite side of the flow meter. A continuous self-induced oscillating flow results between the meter body side walls. As the main flow oscillates between the side walls, the velocity of the flow in the feedback passages cycles between zero and a maximum velocity. The feedback passages thereby contain a region of substantial flow rate change where the frequency of the oscillating fluid is detectable by a thermal sensor. The oscillating frequency is linearly proportional to the fluid velocity.

The main components of the fluidic oscillating flow meter are: the feedback passage, side wall, control port, and sensor. A diagram of the fluidic oscillating flow meter is presented in Figure 4.4-12. The figure shows both stages of flow through this type of flow meter. Fluidic oscillating flow meters can be used to measure liquid flow in pipes with a diameter range of 2.5 to 10 cm (1 to 4 in.), with a maximum velocity of 4.6 to 7.6 meter per second (m/sec) (15 to 25 feet per second [ft/sec]). The application of fluidic oscillating flow meters is limited to liquids with less than 2 percent solids such as acids, bases, water, fuel oils, and chemicals, provided the Reynolds number is greater than the minimum for flow meter operation (typically 500 to 3,000). Table 4.4-9 summarizes the advantages and disadvantages of fluidic oscillating flow meters.

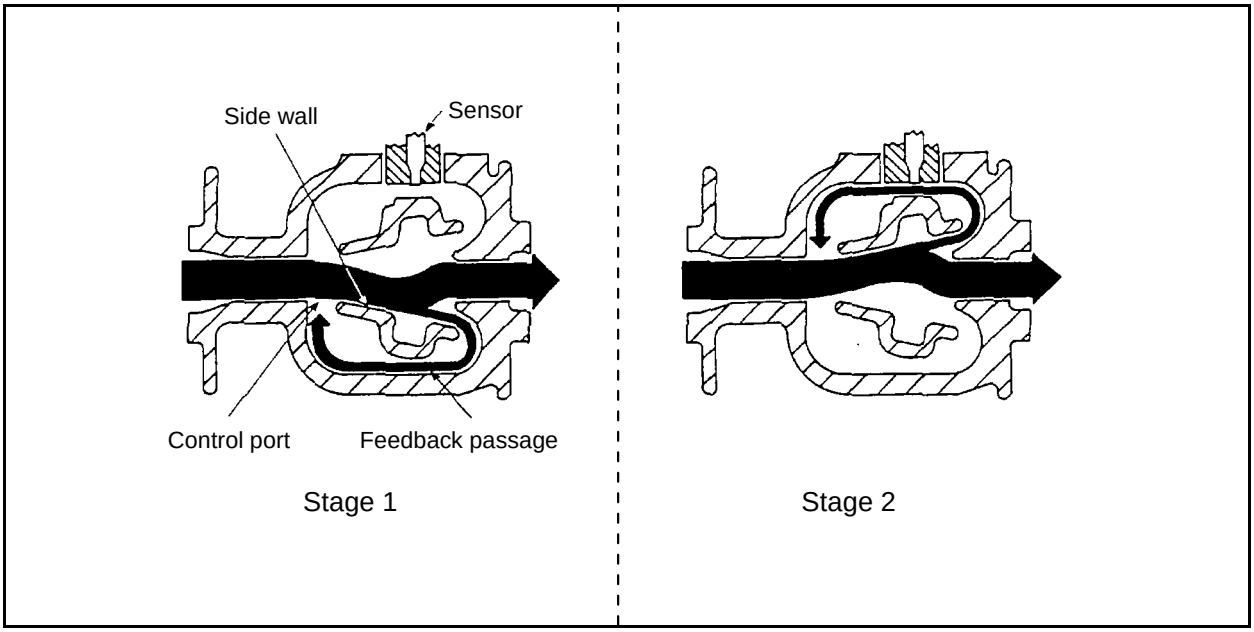


Figure 4.4-12. Fluidic oscillating flow meter.[2]

TABLE 4.4-9. ADVANTAGES AND DISADVANTAGES OF FLUIDIC OSCILLATING FLOW METERS

Advantages	Disadvantages
Lower installed cost compared to more traditional techniques	Sensitive to upstream flow disturbances (suggest following orifice installation practices)
Insensitive to density changes	Pulsed signal output
Accurate over a wide velocity range (up to 50:1)	Limited pipe diameters
Operates at velocities up to 4.6 to 7.6 m/s (15 to 25 ft/sec)	Applicable only to liquids

4.4.7.3 Accuracy[5]

Fluidic oscillating flow meters have accuracy statements that range from ±1.25 to 2.0 percent of flow rate.

4.4.7.4 Calibration Techniques[5]

4.4.7.4.1 Sensor. The primary flow meter device is factory calibrated.

4.4.7.4.2 System. Calibration of the electronics is performed by adjusting the zero with no flow through the flow meter and adjusting the span by injecting a frequency signal that simulates the maximum flow. Another system calibration that can be performed involves energy or mass balance calculation of fluid flow to process operations. If fluid flow energy or mass agrees (balances) within the performance specifications to actual production rates or heat input, the flow rate system can be assumed to be in calibration. Additionally, comparisons of recent energy or mass balances to past data can be made.

4.4.7.5 Recommended QA/QC Procedures[5]

If the liquid has a tendency to coat the thermal sensor, the sensor should be cleaned regularly. If sporadic operation of the flow meter occurs, the sensor is probably coated. A deflection type sensor usually does not suffer from coating effects. The recommended spare parts that should be maintained include the sensor and electronic circuit boards.

4.4.7.5.1 Frequency of calibration. Calibration of the flow meter transmitter should follow a consistent pattern to allow for comparison of performance changes over time. The recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. These calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or

examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or conditions are suspected of causing the decalibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.7.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include:

1. The recommended interval for zero and span calibration checks of the transmitter (Readings before and after adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;
4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);
5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position);
6. Designation of person to whom to report any failed calibration; and
7. Place to store calibration results.

4.4.7.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.8 Ultrasonic Flow Meters

Ultrasonic flow meters can be applied to pipes of all sizes. Since the flow meter element is virtually the same independent of the pipe diameter, this technology has economic advantages over other flow meter technologies in large pipe applications.

4.4.8.1 Measurement Principal[2]

Electrical energy excites a piezoelectric crystal type of material to a state of mechanical resonance. As the crystal resonates, a sound wave, traveling at the speed of sound of the media, is generated. Ultrasonic flow meters determine flow rate based on the characteristics of the sound wave generated by the crystal. Piezoelectric crystals are placed either in contact with the fluid (wetted transducers) or mounted on the outside of the pipe containing the fluid (clamp-on transducers).

4.4.8.2 System Components and Operation[2,5]

Two types of ultrasonic flow meters are available: time-of-flight (TOF) and Doppler. In TOF ultrasonic flow meters, sound waves are introduced into the flowing fluid, one wave traveling with the flow and one wave traveling against the flow. The difference in transit time of the waves is proportional to the fluid flow rate, because the sound wave is accelerated when traveling with the flow and slowed when traveling against the flow. Therefore, if the sound wave velocity of the fluid (speed of sound) is known, the transit distance is known, and time difference is known, then the fluid flow rate can be determined. Time-of-flight ultrasonic flow meters can be classified as one of the following: axial transmission, multibeam (transverse or longitudinal) contra-propagating, cross beam, sing around, and reflected beam. Figure 4.4-13 depicts a TOF ultrasonic flow meter.

In wetted transducer TOF meter setups, a 45° transmission angle normally is chosen to save on needed pipe length while optimizing amplitude of the velocity vector along the sound path. Time-of-flight ultrasonic flow meters require a clean fluid so that sound pulses are not diverted (reflected) from the intended path. Any velocity profile change outside the transmission path is not felt by the sonic beam. Therefore, for greater accuracy, multiple beams may be used. To avoid swirling flow, straight runs of 10 to 30 pipe diameters upstream and 5 to 10 diameters downstream are required.

The basis of operation of Doppler ultrasonic flow meters is that, when an ultrasonic beam is projected into an inhomogeneous fluid, some acoustic energy is backscattered toward the transducer. Because the fluid is in motion relative to the fixed transducer, the scattered sound moving with the fluid is received by the transducer at a different frequency than the frequency at

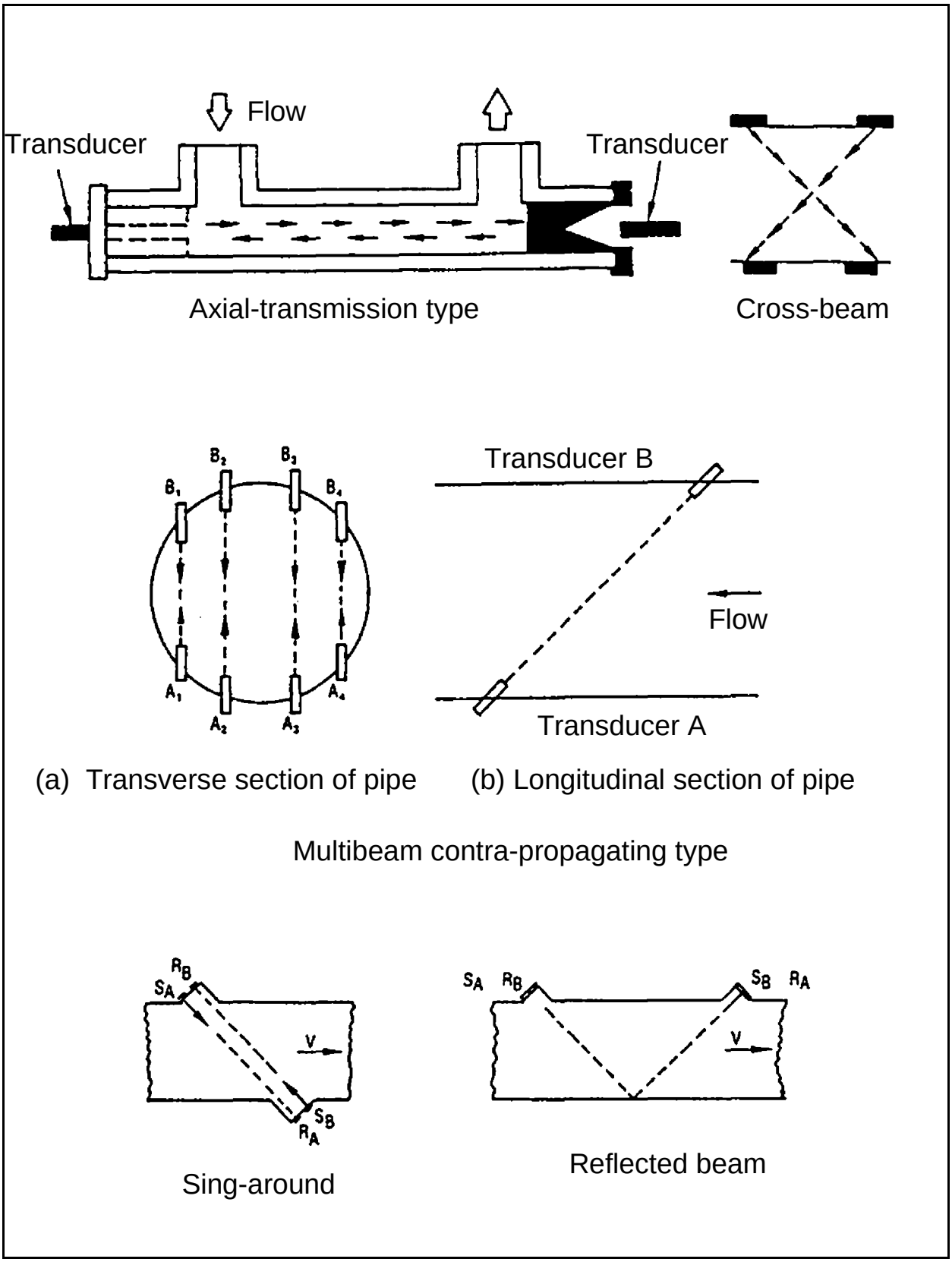


Figure 4.4-13. Time of flight ultrasonic flow meter.[2]

which it was sent. The difference between the outgoing and incoming frequencies is directly proportional to the fluid flow rate.

Most common Doppler flow meter configurations use the clamp-on arrangement, and several manufacturers offer portable clamp-on Doppler ultrasonic flow meters for field measurements. To operate well, Doppler ultrasonic flow meters require sufficient particles or bubbles in the fluid to reflect signals toward the sensor. Performance is affected by velocity profile changes because the receivers normally detect multiple frequencies, low frequencies from particles near the wall and high frequencies from particles in the center of the pipe. Signal processing techniques are used to weight each frequency to arrive at an integrated velocity. If particle concentration varies, severe errors may be incurred. Performance also is affected by particle concentration distribution.

Ultrasonic flow meters are comprised of the following basic parts: the transducer, receiver, timer, and temperature sensor. Figure 4.4-14 depicts some of the transducer arrangements used in Doppler ultrasonic flow meters. Ultrasonic flow meters can be used to measure fluid flow in pipes with a diameter greater than 0.32 cm (0.125 in.) with a minimum flow rate of approximately 0.38 L/min (0.1 gal/min). Time-of-flight ultrasonic flow meters are applicable to liquids and gases flowing at velocities greater than 0.03 m/sec (0.1 ft/sec). Doppler ultrasonic flow meters are applicable only to liquids flowing at a velocity greater than 0.15 m/sec (0.5 ft/sec). Tables 4.4-10 and 4.4-11 summarize the advantages and disadvantages of TOF and Doppler type ultrasonic flow meters, respectively.

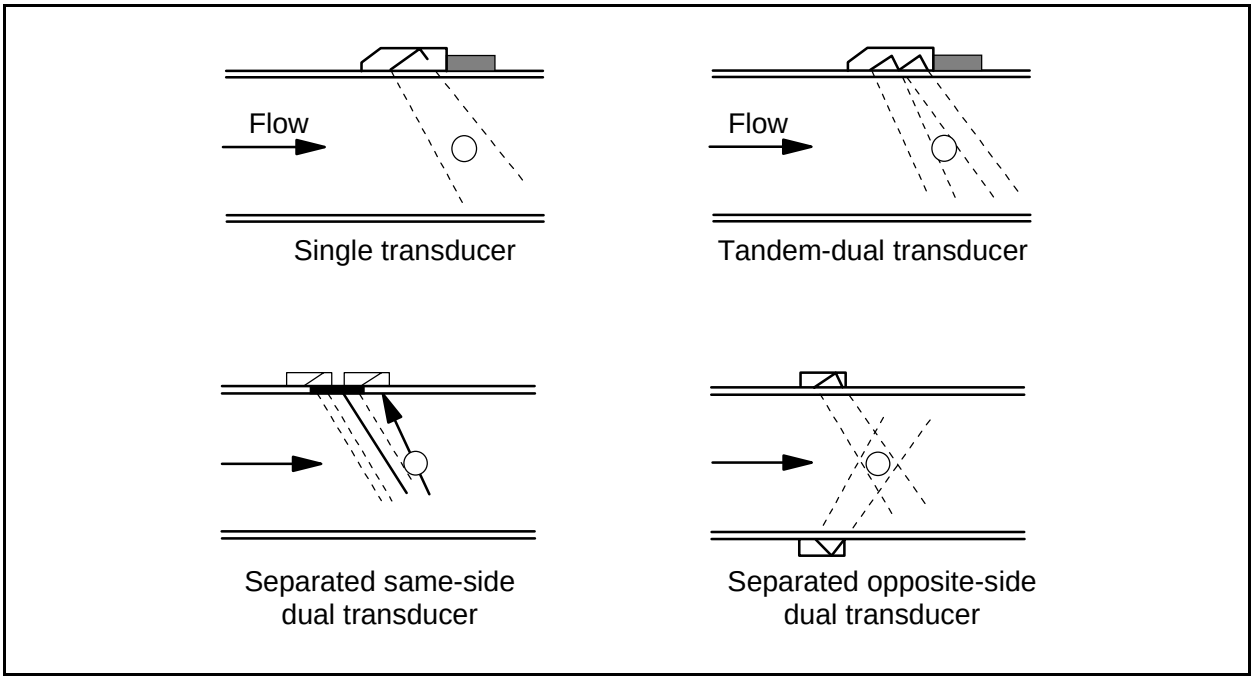


Figure 4.4-14. Doppler ultrasonic flow meter transducer arrangements.[2]

TABLE 4.4-10. ADVANTAGES AND DISADVANTAGES OF TIME-OF-FLIGHT ULTRASONIC FLOW METERS

Advantages	Disadvantages
Device does not protrude into the fluid	Sensitive to upstream flow disturbances
No moving parts	Fluid must be relatively clean
Wide range of pipe diameters	Must compensate for speed of sound changes in the fluid
Low-velocity detection limit	Need long length of straight pipe.

TABLE 4.4-11. ADVANTAGES AND DISADVANTAGES OF DOPPLER ULTRASONIC FLOW METERS

Advantages	Disadvantages
Ease of installation for clamp-on devices	Sensitive to upstream flow disturbances
Wide range of pipe diameters	Performance is highly variable--uncertainty of the depth of penetration, the velocity profile, or fluid composition changes can result in errors of greater than 30 percent
Low-velocity detection limit	Requires entrained gases or particles in the fluid
	Limited to liquid applications only

4.4.8.3 Accuracy[2,5]

Generally, wetted transducer devices are considered more accurate than clamp-on devices. Additionally, TOF ultrasonic flow meters are usually more accurate than doppler ultrasonic flow meters. The accuracy of TOF ultrasonic flow meters ranges from ±0.5 to 10 percent of full scale. The accuracy of Doppler ultrasonic flow meters can be as low as 1 percent of flow rate.

4.4.8.4 Calibration Techniques[5]

Calibration of ultrasonic flow meters is performed by electronically simulating the signals that would be present under flow conditions and making the necessary adjustments to the transmitter. Another possible system calibration involves energy or mass balance calculation of fluid flow to process operations. If fluid flow energy or mass agrees (balances) within the performance specifications to actual production rates or heat input, the flow rate system can be assumed to be in calibration. Additionally, comparisons of recent energy or mass balances to past data can be made.

4.4.8.5 Recommended QA/QC Procedures

The intensity of the ultrasonic signal should be checked periodically to ensure it is within manufacturer's specifications. The following recommended spare parts should be maintained: transducer, and mounting hardware such as gaskets or O-rings.

4.4.8.5.1 Frequency of calibration. Calibration of the flow meter transmitter should follow a consistent pattern to allow for comparison of performance changes over time. The recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. These calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or conditions are suspected of causing the decalibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.8.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include:

1. The recommended interval for zero and span calibration checks of the transmitter (Readings before and after adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;
4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);
5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position);

6. Designation of person to whom to report any failed calibration; and
7. Place to store calibration results.

4.4.8.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.9 Thermal Flow Meters

Thermal flow meters measure flow rate either by monitoring the cooling action of the flow on a heated body placed in the flow or by the transfer of heat energy between two points along the flow path. Since thermal flow meter output is dependent upon thermal (not physical) properties of the fluid, it is applicable to fluids that are not dense enough to be sensed by technologies that use mechanical devices.

4.4.9.1 Measurement Principal[2]

The general equation for determining the amount of heat given up by a heated sensor to a fluid in terms of the current supplied and the resistance can be expressed as:

$$q = 0.24I^2R$$

where:

- q = amount of heat released;
- I = current supplied; and
- R = resistance.

In terms of fluid properties and fluid velocity:

$$q = (t_s - t_g)[C_t + (2\pi dC_v\rho V)^{1/n}]$$

where:

- t_s = sensor operating temperature;
- t_g = fluid temperature;
- C_t = thermal conductivity of fluid;
- C_v = thermal capacity (specific heat at constant volume for a gas;
- ρ = density of fluid;
- d = diameter of wire;
- V = velocity of fluid; and
- n = usually close to 2.

When considering thermal balance in a flowing system, assuming the absorption of heat by anything other than the flowing fluid (i.e., pipe wall) is negligible, the flow rate can be determined by the difference between two temperature readings as:

$$q = \rho V C_p (t_b - t_a)$$

where:

C_p = thermal capacity (specific heat at constant pressure for a gas);

t_b = temperature of fluid before the heater; and

t_a = temperature of fluid after the heater.

4.4.9.2 System Components and Operation.[2]

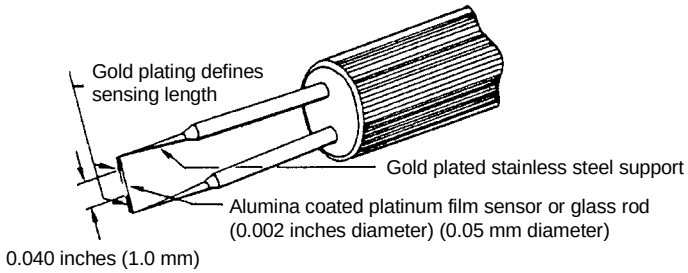
Two types of thermal class flow meters are available: thermal anemometers (thermo-anemometers) and calorimetric flow meters. Thermo-anemometers measure flow rate by monitoring the cooling action of the flow on a heated body placed in the flow. The thermo-element may be held at a constant temperature or variable temperatures (constant current). Rate of flow is measured by the variation in the magnitude of the current for an element with its resistance (temperature) held constant or by the variation in the element resistance for a supplied current of constant magnitude. Constant temperature circuits are used more often because they have the following advantages over constant current circuits:

1. Superior performance in both noise level and frequency response;
2. Compatibility with complex frequency characteristics of hot-film probes;
3. Increased probe life;
4. Prevention of sensor burnout due to velocity changes;
5. Linearization of constant-current system is not possible; and
6. Easy temperature compensation.

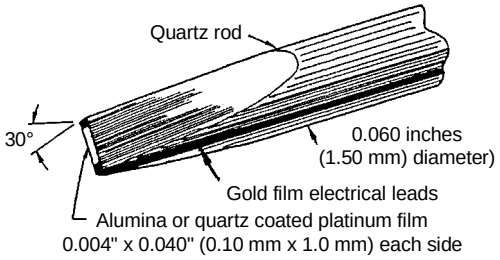
Thermo-anemometers can be either a hot-wire anemometer or a hot film anemometer. In hot-wire anemometers, the thermo-element is a fine metal wire (0.00038 cm [0.00015 in.] in diameter) made of tungsten with a thin platinum coating on the surface. The thin, metal wire element is connected as one of the arms of a balanced measuring bridge. In hot-film anemometers, the thermo-element consists of a metallic film made of alumina or quartz deposited on a vitreous or ceramic substrate (usually platinum). Hot-film anemometers come in a variety of shapes such as wires, wedges, cones, and flat surfaces. Figure 4.4-15 depicts four of these shapes.

The hot-film probe has the following advantages over the hot-wire probe:

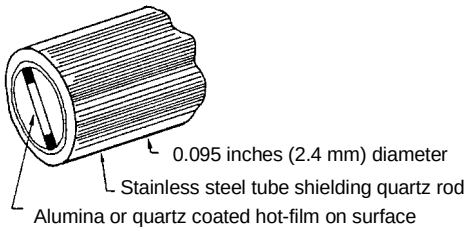
1. More rugged;
2. Less susceptible to accumulation of foreign materials;
3. Easier to clean;
4. Better frequency response over a wider frequency range; and
5. Adapted to a variety of probe shapes.



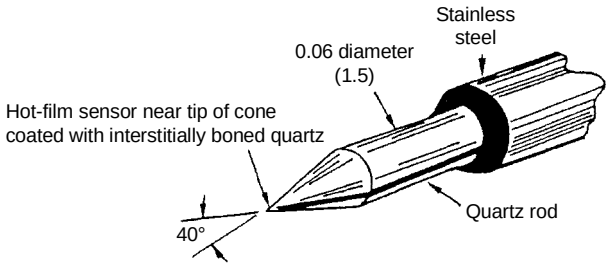
Cylindrical hot-film sensor and support needles
0.002" diameter (0.05 mm)



Hot-film wedge probe



Hot-film flush mounted probe



Hot-film cone probe

Figure 4.4-15. Thermo-anemometers in various shapes.[2]

However, in some applications, a hot-wire probe is superior. Other important characteristics of thermo-anemometers are as follows:

1. Inherently mass flow sensitive;
2. Highly dependent upon fluid composition; and
3. Probe output is nonlinear in terms of current or voltage, requiring a linearizing circuit.

Calorimetric flow meters work on the principle of heat transfer by the flow of fluid. A calorimetric flow meter consists of three elements: a temperature measurement device upstream of a heater; a heater; and a temperature measurement device downstream of a heater. The flow rate is determined by the difference in the two temperature readings. As is the case for thermo-anemometers, calorimetric flow meters are inherently sensitive to mass flow. However, unlike thermo-anemometers, calorimetric flow meters are linearly proportional to heat transfer. Figure 4.4-16 is a diagram of a calorimetric flow meter.

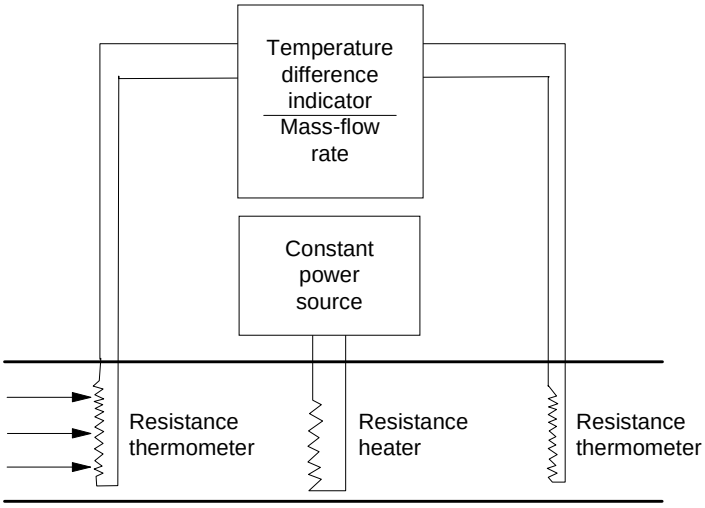


Figure 4.4-16. Calorimetric flow meter (heated grid).[2]

Calorimetric flow meters operate by one of three techniques:

1. Devices that draw constant power to the heater with simultaneous measurement of the amount of heat transferred to the flow;
2. Devices that heat the flow to a constant temperature with simultaneous measurement of the energy supplied to the heater; or
3. Devices that vary the heater temperature sinusoidally with time; in these, the flow rate is measured by the signal phase shift at the sensor compared to the input signal at the heater.

Thermal flow meters can be used to measure fluid flow in pipes with diameters of 5.1 cm (2 in.) or larger. Thermal flow meters are applicable to fluids that have known heat capacities, that is, mostly gases, with very limited liquid applications because of heat transfer problems.

Thermal flow meters are susceptible to swirling flow and require straight pipe sections of 8 to 10 diameters upstream and 3 diameters downstream of the device. Table 4.4-12 summarizes the advantages and disadvantages of thermal flow meters.

TABLE 4.4-12. ADVANTAGES AND DISADVANTAGES OF THERMAL FLOW METERS

Advantages	Disadvantages
No moving parts	Require temperature and pressure compensation
Low net pressure loss	Require temperature and pressure measurement devices
Accurate over a wide flow range (300 to 1)	Point measurements require critically positioned probes
Can be used on a variety of pipe sizes	Mostly applicable to gases
	Require straight pipe upstream of the device

4.4.9.3 Accuracy.[2]

Thermo-anemometer accuracy ranges from ±1.5 to 2 percent of flow rate. Calorimetric flow meter accuracy is approximately ±4 to 5 percent of flow rate.

4.4.9.4 Calibration Techniques.[9]

Calibration is done by the manufacturer and cannot be adjusted unless correction factors are applied to the output. Sensors are calibrated in an NIST- traceable wind tunnel in air and referenced to standard temperature and pressure. When calibrating thermal flow meters, electronic zero and span calibrations of the transmitter should be checked by injecting the appropriate signal level to the transmitter input points. Another system calibration that can be performed involves energy or mass balance calculation of fluid flow to process operations. If fluid flow energy or mass agrees (balances) within the performance specifications to actual production rates or heat input, then the flow rate system can be assumed to be in calibration. Additionally, comparisons of recent energy or mass balances to past data can be made.

4.4.9.5 Recommended QA/QC Procedures

Routine maintenance should include a program to keep the thermally conductive surfaces clean. Additionally, replaceable sensor tips enhance repair of failed sensors. The following recommended spare parts should be maintained: replaceable probes or entire flow meter assembly, and electronic circuit boards.

4.4.9.5.1 Frequency of calibration. Calibration of the flow meter transmitter should follow a consistent pattern to allow for comparison of performance changes over time. The

recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. These calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or conditions are suspected of causing the decalibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.9.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include:

1. The recommended interval for zero and span calibration checks of the transmitter (Readings before and after adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;
4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);
5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position); and
6. Designation of person to whom to report any failed calibration; and
7. Place to store calibration results.

4.4.9.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.10 Mass Flow Meters (Coriolis)[5]

A Coriolis mass flow meter consists of a U-shaped tube that deflects or vibrates as the fluid flows through it. The operation of this type of mass flow meter is based on the conservation of angular momentum as it applies to the Coriolis acceleration of a fluid. Coriolis acceleration is that tangential force experienced when one walks radially outward on a rotating platform. The force is only experienced when one changes position in relation to the center of rotation.

4.4.10.1 Measurement Principal[10]

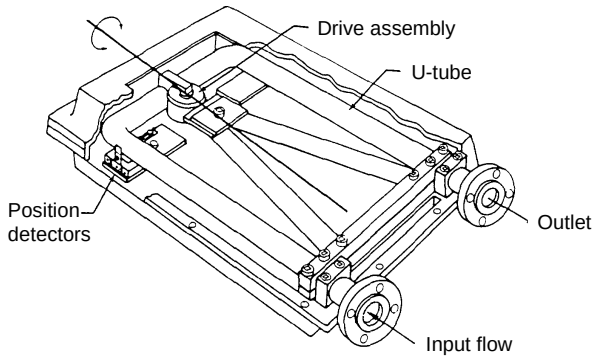
As fluid enters the U-shaped tube, it is forced to take on the vertical movement of the vibrating tube. When the tube is moving upward, the fluid flowing into the meter resists being forced up by pushing down on the tube. Having been forced upward, the fluid flowing out of the meter resists having its vertical motion decreased by pushing up on the tube. The two opposing forces on the tube cause it to twist. The amount of twist is directly proportional to the mass rate of fluid flowing through the tube.

4.4.10.2 System Components and Operation[5]

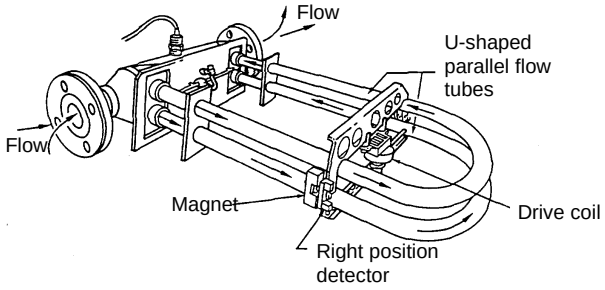
A mass flow meter consists of a vibrating U-shaped tube in which the Coriolis acceleration is created and measured. In place of the rotational motion described above, the inlet and outlet of the tube are held fixed while the tube is vibrated sinusoidally about an axis formed between the inlet and outlet, typically by a magnetic device located in the bend. In most devices, magnetic sensors located on each side of the flow tube measure the respective velocities, which change as the tube twists. Newer models have two U-shaped tubes to measure fluid flow.

Coriolis mass flow meters have specific minimum and maximum operating flow rates. High-temperature sensors can operate up to 430°C (800°F). The pressure drop across the flow meter cannot exceed the maximum allowable pressure drop that the total system will accept, otherwise the fluid will not flow into the U-tube. A diagram of a Coriolis mass flow meter is presented in Figure 4.4-17.

Mass flow meters can be used to measure fluid flow in pipes with a diameter range of 0.16 to 15 cm (0.0625 to 6 in.). Coriolis mass flow meters are generally used in the following liquid applications: harsh chemicals, low to medium viscosity, foods, slurries, and blending systems. Gas applications are somewhat limited since the density of low-pressure gases is usually too low to accurately operate the flow meter. Typically, thin walled tubes are used for gas applications. However, when applicable, the mass flow meter eliminates the need for pressure and temperature compensation and the hardware necessary to implement these functions. Table 4.4-13 summarizes the advantages and disadvantages of Coriolis mass flow meters.



(A) Single U-tube design



(B) Dual U-tube design

Figure 4.4-17. Coriolis mass flow meter.[5]

TABLE 4.4-13. ADVANTAGES AND DISADVANTAGES OF CORIOLIS MASS FLOW METERS

Advantages	Disadvantages
Have no Reynolds number constraints	Limited applicability to gases
Applicable to virtually any liquid	Relatively expensive
Excellent accuracy	High-net pressure loss
Not affected by swirling flow; therefore, no need for straight pipe	
No need for temperature compensation	
Provide direct mass flow measurement	

4.4.10.3 Accuracy[5]

Coriolis mass flow meters have an accuracy of 0.2 to 0.4 percent of flow rate (within ±28°C [±50°F] of calibrated temperature) to a mass flow rate of 0.45 kilogram per hour (kg/hr) (1 pound per hour [lb/hr]).

4.4.10.4 Calibration Techniques[5]

Zero and span calibration of most flow meters is performed digitally under zero flow conditions at operating temperature. Variations of more than about 28°C (50°F) from the temperature at which the zero adjustment was performed result in reduced accuracy. Another possible system calibration involves energy or mass balance calculation of fluid flow to process operations. If fluid flow energy or mass agrees (balances) within the performance specifications to actual production rates or heat input, the flow rate system can be assumed to be in calibration. Additionally, comparisons of recent energy or mass balances to past data can be made.

4.4.10.5 Recommended QA/QC Procedures[5]

Excessive coating of the inside of the tube can cause the tube to become restricted. This will result in a loss of accuracy if the flow is less than the minimum accurately measurable flow of the flow meter. The recommended spare parts that should be maintained include sensors and electronic circuit boards.

4.4.10.5.1 Frequency of calibration. Calibration of the flow meter transmitter should follow a consistent pattern to allow for comparison of performance changes over time. The recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. These calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or conditions are suspected of causing the decalibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not

necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.10.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include:

1. The recommended interval for zero and span calibration checks of the transmitter (Readings before and after adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;
4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);
5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position);
6. Designation of person to whom to report any failed calibration; and
7. Place to store calibration results.

4.4.10.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.11 Rotameters[5]

Rotameters can be classified as a type of area flow meter. In the past, rotameters were one of the mainstays in flow meter technology because they provide economical local readouts and control of gases and nonviscous liquids. Although rotameters have been displaced to some degree by other technologies, the rotameter has maintained its place in some applications due to its design simplicity and its ability to be tailored to each application by careful selection of its components.

4.4.11.1 Measurement Principal[5]

Rotameters operate on the principle of generating a condition of dynamic balance within the flow meter, in which a float is positioned in accordance with the flow through the flow meter. The float remains in dynamic balance when the sum of the forces acting on the float are zero. Therefore, when the weight of the float less the weight of the fluid that it displaces is equal to the upward force on the float due to fluid velocity, the float is in dynamic balance.

4.4.11.2 System Components and Operation[1,4,5]

A rotameter consists of a plummet, or "float," which is free to move up or down within a slightly tapered tube, with the small end down. Fluid enters the lower end of the tube and causes the float to rise until the annular area between the float and the wall of the tube is such that the pressure drop across the constriction is just sufficient to support the float. The tapered tube, which typically is made of glass, is etched with a near linear scale on which the position of the float may be visually noted as an indication of flow. Rotameters are available with pneumatic, electric, and electronic transmitters for actuating remote recorders, integrators, and automatic flow controllers. A diagram of a rotameter is presented in Figure 4.4-18. Rotameters can be used to measure fluid flow in pipes with a diameter range of 1.3 to 10 cm (0.5 to 4 in.). Liquid flow measurement range is approximately 0.19 to 760 L/min (0.05 to 200 gal/min) for liquids with a viscosity less than about 30 centipoise. Gas flow measurement is virtually unlimited depending on float material. Rotameters require no straight runs of pipe upstream or downstream of the meter. Pressure losses are consistent over the flow range. Table 4.4-14 summarizes the advantages and disadvantages of rotameters.

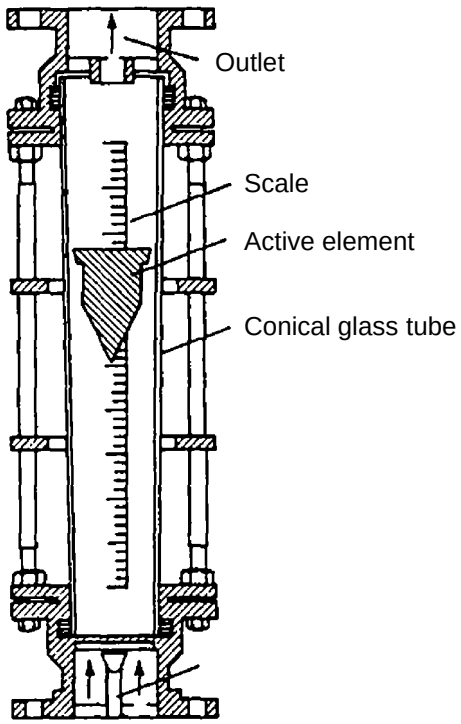


Figure 4.4-18. Rotameter.[12]

TABLE 4.4-14. ADVANTAGES AND DISADVANTAGES OF ROTAMETERS

Advantages	Disadvantages
Easily equipped with magnetic, electronic, induction, or mercury-switch transmitters	Must be mounted vertically
Viscosity-immune bobs are available	Limited to relatively small pipe sizes and capacities
Several rotameters mounted side-by-side provide convenient flow comparisons	Relatively low temperature and pressure limits
Relatively low cost	Sensitive to fluid temperature changes
Handle a wide variety of corrosive materials	
No need for straight pipe	
Extremely effective for low flows	

4.4.11.3 Accuracy.[5]

Rotameters have an accuracy of ±1 to 2 percent of full scale from 10 to 100 percent of the calibrated range. Some rotameters can be calibrated to ±0.5 percent of full scale.

4.4.11.4 Calibration Techniques.[5]

Rotameter system transmitters can be calibrated for zero and span by manipulating the float to the zero and full scale positions and making the necessary zero and span adjustments. The scale on a rotameter can be calibrated to the exact metering fluid by utilizing a bubble flow calibrator at several values along the scale. The results of the bubble calibration can be used to generate a calibration curve. Generally, rotameter calibration scales are for a specific gas (e.g., air, nitrogen, etc.) at standard temperature and pressure. Therefore, some correction to actual conditions is required for accurate measurements.

Another possible system calibration involves energy or mass balance calculation of fluid flow to process operations. If fluid flow energy or mass agrees (balances) within the performance specifications to actual production rates or heat input, the flow rate system can be assumed to be in calibration. Additionally, comparisons of recent energy or mass balances to past data can be made.

4.4.11.5 Recommended QA/QC Procedures[5]

Periodic cleaning of the flow tube is required to prevent a buildup on the inside of the tube. If a residue builds up on the inside of the tube, the float will stick and a reduction of accuracy will occur. The following recommended spare parts should be maintained: metering tube, floats, and electronic circuit boards.

4.4.11.5.1 Frequency of calibration. Calibration of the flow meter transmitter should follow a consistent pattern to allow for comparison of performance changes over time. The recommended frequency of calibration depends largely on site-specific conditions and facility standard operating procedures. Moreover, specific regulations may require a specific calibration frequency (e.g., annually). In general, calibration frequency should be within the manufacturer's recommendations. These calibration intervals should not be relied on indefinitely; they are starting points. At the end of the initial calibration period, the system should be calibrated or examined, as appropriate, and the data obtained should be charted. If the system is near or beyond the limit of accuracy (80 percent of acceptable error) and no process excursions or conditions are suspected of causing the decalibration, the calibration interval probably is too long. In such a case, the system should be recalibrated to the center of the acceptance band, and the calibration interval should be shortened. At the end of the second calibration period, calibration should be checked to determine if the system is drifting. If the system is near or beyond the limit of acceptable accuracy, similar steps should be taken, and the calibration period should be further shortened. This process should be repeated until the system is within the acceptable limit of accuracy at the end of the calibration interval. If, at the end of the initial calibration period, the system is determined to be within acceptable tolerance, adjustment is not necessary. The results should be recorded and the same calibration interval should be maintained for another calibration period. A log of all calibration check results should be maintained at the facility. Any corrective actions or adjustments should be recorded. Calibration data should be reviewed annually in order to spot significant deviations from defined procedures or tolerances.

4.4.11.5.2 Quality control. Written procedures should be prepared for instrument calibrations. These procedures should include:

1. The recommended interval for zero and span calibration checks of the transmitter (Readings before and after adjustment should be recorded.);
2. The reference zero and span values to be applied;
3. Step-by-step written procedures;
4. Blank field calibration forms (Records should include identification of the instrument component calibrated, the date of calibration, and initials of the person who performed the calibration.);
5. Designation of responsibility to perform the calibration (i.e., name of person(s) or position);
6. Designation of person to whom to report any failed calibration; and
7. Place to store calibration results.

4.4.11.5.3 Quality assurance. The calibration logs should be reviewed to confirm that calibrations were completed and performed properly. The person performing this review and the

frequency of review should be specified. The written calibration procedures should be reviewed and updated to reflect any changes (e.g., system modifications or instrument changes).

4.4.12 References for Flow Measurement

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4.5 pH AND CONDUCTIVITY MEASUREMENT SYSTEMS

4.5.1 pH Monitoring

A pH measurement system consists of three components: a pH sensing electrode, the pH meter, which is an amplifier for translating the signal, and a reference electrode. A pH sensing electrode is a small battery displaying a voltage that varies depending upon the pH of the solution in which it is immersed. The reference electrode is also a battery, but unlike the pH sensing electrode, its voltage does not vary with the pH of the solution. In a pH measurement system, the pH electrode delivers a varying voltage to the pH meter while the reference electrode delivers a constant voltage to the meter. Although a pH measurement system consists of both types of electrodes, some electrodes, known as combination electrodes, are designed to incorporate both functions.

Selecting the appropriate pH and reference electrodes for the application for which it is to be used is critical to proper pH measurement. Section 4.5.1.1 presents a discussion on selecting the proper electrodes for a particular application. Section 4.5.1.2 describes the different types of pH measurement stations, Section 4.5.1.3 presents a discussion of pH control system components, and Section 4.5.1.4 presents a discussion on electrode maintenance, and Section 1.1.5 discusses calibration procedures.

4.5.1.1 Electrode Selection[1,2]

The factors to be evaluated in selection of pH sensing and reference electrodes include where the electrodes will be used, for example, in the laboratory or in an industrial process environment, the accuracy required, the components in the sample, and the pH of the sample. The key variables in electrode selection are: (1) combination or electrode pair, (2) gel-filled or refillable, (3) reference electrode configuration, and (4) body construction.

4.5.1.1.1 Combination electrodes or electrode pair. In a combination electrode, the reference electrode surrounds the glass pH electrode. Combination electrodes are used for most laboratory and industrial applications because they are easier to use than electrode pairs. Combination electrodes can be used to monitor smaller volumes and are also more convenient in areas where access is restricted. One drawback with combination electrodes is that the pH measuring system has to be equipped with a temperature compensation system for accurate measurements. As discussed later, the output of a pH electrode is temperature sensitive. This sensitivity is magnified in a combination electrode. Combination electrodes are also not suitable for use with colloidal suspensions, samples containing iodides, samples with high solids content, viscous solutions, specific ion determinations, and high purity water. Electrode pairs should be used for these applications.

4.5.1.1.2 Gel-filled or refillable electrodes. Gel-filled electrodes require little or no maintenance. Most gel-filled electrodes have polymer bodies and are therefore very durable. Refillable electrodes require greater maintenance and are less durable. As the name suggests, they have to be refilled with electrolyte solution periodically. The body of refillable electrodes is typically made of glass. However, refillable electrodes are more accurate (± 0.01 pH unit) than gel-filled electrodes (± 0.05 pH unit) and have a longer life span (typically more than 1 year) than gel-filled electrodes (6 months to 1 year). Gel-filled electrodes are typically used in industrial environments; because of their durability and lower maintenance requirements refillable electrodes are used primarily for laboratory applications because of their accuracy.

4.5.1.1.3 Reference electrode configuration. The reference electrode consists of three primary parts: an internal element, electrolytic filling solution, and a permeable junction through which the filling solution flows. The internal element may be a silver wire coated with silver chloride, that is, an Ag/AgCl electrode, or a platinum wire covered with a mixture of mercuric chloride, commonly referred to as calomel (Hg_2Cl_2). Silver chloride electrodes are used for most laboratory and industrial applications. However, some samples react with the silver in the Ag/AgCl electrode. For example, strong reducing agents can reduce the silver ion to silver metal, thereby silverplating the junction. Calomel electrodes should be used for solutions containing proteins, sulfide or heavy metal ions, or strong reducing agents. However, calomel electrodes should not be used for applications in which the electrode will be exposed to temperatures above 65°C (150°F) because the electrode breaks down at higher temperatures.

Junction type is also an important factor in selecting a reference electrode. The function of the liquid junction is to allow small quantities of the filling solution from the reference electrode to leak into the sample being measured. The four most common forms of junctions are ceramic or other frit material, a fibrous material such as quartz, sleeve junctions, and double junctions.

The fritted junctions are usually white and consist of small particles pressed closely together. The filling solution moves through the open cells between the particles. The flow rate across the surface of the material is variable because the size of the cells is variable. In general, fritted junctions clog relatively easily and should not be used with samples containing small particulate that may clog the junction.

There are two basic types of fibrous material junctions, those with woven fibers and those with straight fibers. The cells of the woven fiber junctions vary in size because of the structure of the woven material. As with the fritted junctions, this leads to variability in flow rate across the junction. The flow rate is high where the fibers are loosely woven and low where the fibers are more tightly woven. Straight fiber junctions made of quartz are preferable to the woven fiber junctions. These junctions have straight fibers of quartz laid next to each other. The filling

solution passes uniformly through the straight channels between the fibers. The junctions made of straight fibrous material are easier to clean and are better for dirty samples.

A sleeve junction is similar to a fritted junction in that some areas of the junction have a higher flow rate than other areas. However, the sleeve junction has a much higher flow rate than the fritted material junction and is easier to clean. Because of the high flow rate, sleeve junction electrodes are suitable for dirty viscous samples. They also provide better precision than other junction types.

Double junctions are required for applications in which the electrolytic filling solution and the sample solution should not come in contact. Contact between the filling solution and sample solution can cause precipitation of salts with low solubility, precipitation of the potassium chloride or silver chloride in the filling solutions as a result of the diffusion of water or organic solvent from the sample solution, and contamination of the sample solution by the reference filling solution. To prevent this contact an electrolyte bridge is inserted between the reference electrode and the sample solution.

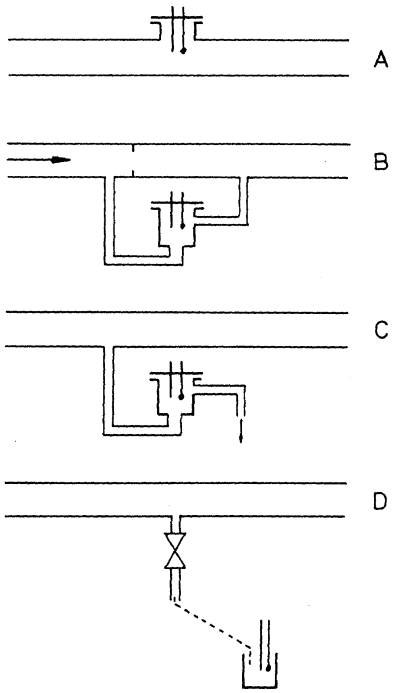
4.5.1.1.4 Body construction. Polymer body electrodes are more durable than glass body electrodes and are used more often for field or industrial applications. Electrodes with glass bodies are most often used for laboratory applications. Glass body electrodes are also the best choice for solutions containing proteins and other compounds with high surface tension, highly corrosive materials, and organics that might attack a polymer body. Samples with a very high pH, >12, require a special glass to minimize error caused by sodium ions. This special glass can be used over the entire pH scale, but it has a higher resistance than the standard glass used in most glass electrodes.

4.5.2 pH Measurement Stations[2]

There are three types of measurement stations that are typically used for inline process pH measurement: immersion electrode assemblies, built-in electrode assemblies, and flow-through electrode assemblies. Figure 4.5.1 shows a diagram of the three types of inline electrode assemblies and an offline laboratory measurement. In addition, pH measurements of a solution can be done offline by withdrawing a sample at a sample vent and taking the sample to the pH meter.

4.5.2.1 Immersion Electrode Assemblies

These electrode assemblies are used for measuring the pH of a sample in open vessels. In order to compensate for the hydrostatic pressure resulting from the immersion of the electrodes below the surface of the sample, the vessel containing the electrolyte must be raised. The reference electrode can also be installed in the electrolyte reservoir. Contact with the sample



Application of electrode assemblies. A in line, B in line with bypass, C on line, D offline.

Figure 4.5-1. Applications for electrode assemblies.

solution is made via a tube with a separator. However, a reservoir is unnecessary if the assembly is equipped with a sealed reference electrode. Immersion electrode assemblies are often mounted loose, so they can be deflected by strong currents. The electrode assemblies are moved from their holders for maintenance, which should be conducted at least every 4 weeks.

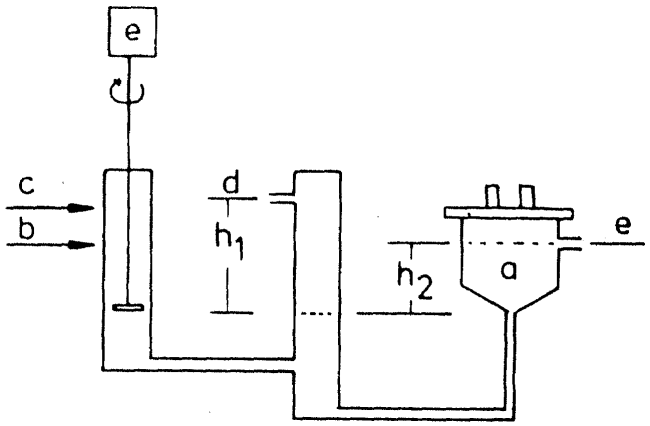
4.5.2.2 Built-In Electrode Assemblies

Built-in electrode assemblies are used in closed containers. These have a mounting plate similar to that used for an immersion assembly or a screw adaptor fitted with a male or female thread. Built-in electrode assemblies that are installed in the side of the vessel should have an angle of at least 15 degrees to ensure that the reference electrolyte and internal buffer will collect in the lower portions of the electrodes. The head of the built-in electrode must be made of material compatible with the material used for the piping and vessel. Enamel electrodes are often used to ensure compatibility. Because it is not possible to remove the electrode for maintenance during normal operations if the vessel is pressurized or the site is below the sample solution, an exchangeable unit should be available at all times in case removal is necessary.

4.5.2.3 Flow-Through Electrode Assemblies

Flow-through electrode assemblies are typically used for vessels with an inflow and side outflow. For most applications, flow-through units are the easiest to maintain. The electrode assemblies are mounted in pipelines, and the sample solution flows past them. The assemblies may be straight-through or angled. The sample should pass freely after the electrode so that pressure compensation is unnecessary. If a flow-through electrode assembly is used in a closed system, a bypass is needed. The electrode then can be removed for maintenance by closing the valves without having to remove the electrode housing. One potential problem with horizontal flow-through units is that impurities in sample streams with sediment or floating particles can settle out. Therefore, the units must be cleaned out regularly. Flow-through electrode assemblies can be used with piping up to 25 mm. If the diameter of the piping is larger than 25 mm, the assembly should be equipped with a bypass. In addition, pressure compensation should be used if the outflow from the unit is not free.

Flow-through units are also useful for pH measurements in nonaqueous solutions. Although most pH measurements are done in aqueous solutions, a facility may need to know whether a solvent contains excess acid or base. An extraction electrode assembly with a flow-through cell is needed for these applications. With extraction electrode assemblies, the solvent is extracted with water, which preferentially absorbs the inorganic acids and bases. The pH of the aqueous solution is then monitored. Figure 4.5.2 depicts an extraction electrode assembly.

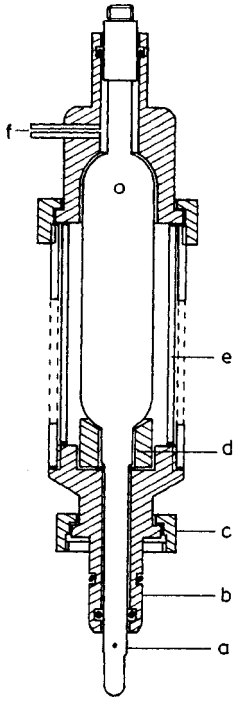


Measurement of the pH of an extract of a solvent, from Shinskey (7-13), (a) flow through cell, (b) inlet for organic solvent, (e) inlet for water, (d) outlet for organic solvent, (e) outlet for aqueous solution, h_1 static lead of organic solvent, h_2 static head of aqueous solution, R stirrer.

Figure 4.5-2. Extraction electrode assembly.

4.5.2.4 Pressurized Chamber Electrode Assemblies

Pressurized chamber electrode assemblies may be built-in assemblies or flow-through assemblies. They should be used when the pressure is greater than 300 kPa (3 bar). Figure 4.5.3 shows a sectional view of a pressurized chamber electrode assembly. In order to conserve space, combination electrodes are typically used with pressurized assemblies. The electrolyte reserve is stored in the enlarged stem. The assembly can be constructed in a range of lengths for built-in assemblies in pressurized vessels. It can also be used as a flow-through assembly when it is installed as a T-piece. Pressurized electrode assemblies can be used at pressures greater than 1 Mpa, but the unit must be enclosed in steel casing for these applications.



Section through a pressure chamber electrode assembly, (a) combination electrode, (b) fitting shank *d* = 19 or 25 mm, (c) sleeve, nut (d) support, (e) viewing glass, (f) pressurization connection.

Figure 4.5-3. Pressurized chamber electrode assembly.

4.5.3 pH Control Systems[1]

For some industrial processes, monitoring the pH is all that is required. In other processes, parameters may be adjusted if the pH is not within the expected range, but the focus of these is not on achieving a particular pH. Some industrial processes, however, based on achieving a particular pH or maintaining a specific pH. This section focuses on selecting the appropriate pH control system for different types of processes that may require pH control.

There are three basic types of pH control systems: batch processing system, continuous system with tank, and continuous system with on-line control.

4.5.3.1 Batch Processing System

This is a simple system in which the process solution is pumped into a tank until it is full, the solution is agitated and mixed, chemical is added to the solution until the desired pH is reached, and the solution flows out or is pumped out of the tank. A relay controller is used to turn the chemical addition pump on and off. Figure 4.5.4 presents an example diagram of a batch processing system.

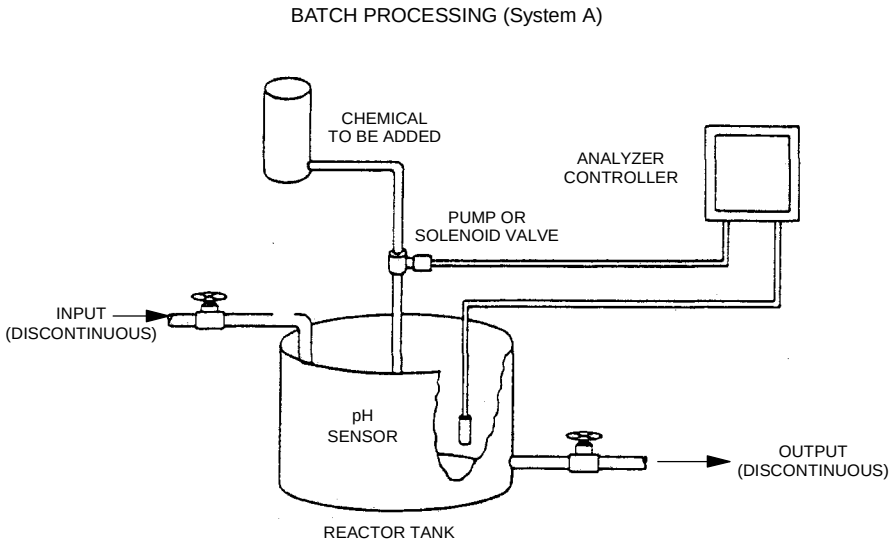


Figure 4.5-4. pH control system for batch process.

While not essential, it is desirable to have a level sensing device to monitor the amount of fluid in the tank and to signal when the tank is full or empty. The sensing device should also shut off operation of the mixer and pH controller when the solution is not at the proper level. It is important to note that the system will not reach equilibrium immediately. After the chemical addition, there will be some delay before the pH stabilizes and can be accurately measured. The actual time period before equilibrium is reached will depend upon the mixing system. The faster the mixing, the sooner the system will reach equilibrium and the pH of the system will stabilize.

4.5.3.2 Continuous System with Tank

Unlike the batch processing system, the continuous system with tank allows for continuous input. Level control and monitoring is not as important as it is with the batch system because the tank outlet can be of sufficient size to make tank overflow unlikely. A pump or an on/off valve controls chemical additions. The sizing of the control element is critical. In some

cases, two control elements are needed. For example, one valve delivers the chemical used to adjust the pH at a higher rate when the pH is at a particular level and another valve delivers the chemical at a lower rate when the pH approaches the desired endpoint. Again, good mixing is critical with this type of system. The mixer should not be undersized.

4.5.3.3 Continuous System with On-Line Control

This system is used for pH control of a process sample moving through a pipe. The system consists of a pH sensor, an analyzer/controller for receiving input from the pH sensor and converting this to a signal that controls the valve or pump regulating chemical additions, and a static mixer. The static mixer provides good mixing quickly. Chemicals are injected just upstream of the mixer and the pH sensor is just downstream of the mixer. With a good mixer, the delay time, that is, the time between when the chemical is added to the sample and the pH sensor can detect the change in pH, should not be more than a few seconds.

4.5.4 Operation and Maintenance of the pH Measuring System[1,2]

Proper operation and maintenance of the pH measuring system is just as important in achieving accurate pH measurements as selecting the correct electrode and assembly. In particular, care and maintenance of the electrodes is critical. More than 80 percent of the errors encountered in pH measurements are due to electrode problems. Of these electrode problems, most are associated with the reference electrode.

4.5.4.1 Operation, Maintenance and Troubleshooting of the Reference Electrode

Reference electrodes contain a reference half-cell consisting of a sealed glass tube surrounding a piece of wire that is immersed in a mixture of crystals. For a silver chloride electrode, the wire is silver and the crystals are silver chloride. For a calomel electrode, the wire is platinum and the crystals are Hg_2Cl_2. The end of the glass tube is sealed with a wad of cotton, glass wool, or a frit. In order to provide electrical continuity, the crystals must be wet. Therefore, the glass tube and the body of the reference electrode are filled at the factory with a potassium chloride solution. Before shipment, the electrode is sealed at the filling hole and the junction.

The filling solution in the reference electrode completes the circuit with the pH electrode. Before using the reference electrode, the filling hole should be unsealed so that the filling solution can flow into the sample and complete the circuit. The filling hole should remain open as long as the reference electrode is in the sample solution. When not in use, the reference electrode should be stored at all times in an acidic solution with a low salt content. These

solutions are available commercially or they can be made by adjusting a potassium chloride solution to a pH of 4.0.

Typically, the first sign that there is a problem with the reference electrode is a long stabilization time. The pH reading may vary for some time before finally reaching a stable point. The increased stabilization time may be caused by changes in temperature, reactions taking place in the sample, a sample that is not well mixed, or by absorption of CO_2 from the reference electrode. However, the most likely causes are that the reference electrode is not compatible with the sample or the reference electrode is faulty. Usually, it is possible to determine if the problem is with the electrode or if the long stabilization time is caused by other factors such as a change in temperature. If you move a hand quickly toward and then away from the electrode and the pH reading changes significantly in response to the hand movement and then reverses when the hand is retracted, it is likely the reference electrode is either partially blocked or defective. If the drift continues as before when you move your hand toward and away from the electrode, the problem is probably with the sample.

While moving a hand towards and away from the reference electrode is one method of determining if a reference electrode is faulty, there are two other methods that can better predict a problem with the reference electrode. Both of these methods involve the use of a magnetic stirrer. If stirring the sample with a magnetic stirrer causes unstable readings, then turn the stirrer off. If the reading changes significantly (0.1 to 0.2 pH units), there is a problem with the reference electrode. Another check can be done with the stirrer operating. If the pH readings fluctuate with the stirrer on and turning the stirrer down to a slower speed reduces the fluctuations, the problem is probably with the reference electrode.

If the pH readings drift continuously without ever stabilizing, the problem may be a completely blocked reference electrode or it may be an electrical problem. For example, the electrode may not properly connected to the meter, the wires within the reference or pH electrodes may be broken, the lead wire from the pH or reference electrode may be broken, or there may be an open circuit within the meter. The easiest and quickest way to determine if the problem is with the electrodes or the meter is to replace each of the electrodes. Another method is to use a wire, paper clip, or shorting plug, to short between the reference electrode input and the pH electrode input on the meter. If shorting the electrode inputs eliminates the drift, substituting the pH electrode and then the reference electrode if necessary should identify which electrode is the open circuit.

If the reference electrode dries out, there is no pH reading even though the pH electrode may be operating correctly. When the body of the electrode dries out, the fluid in the half-cell tube leaks out through the junction at the end of the tube. There is then no continuity through the crystals. To prevent the electrode from drying out, it should be stored in solution at all times.

However, a dry electrode can be restored and reused. In order to properly restore the electrode and avoid an air bubble in the tube, the electrode should be filled with filling solution, the junction plugged, and the electrode body evacuated with a laboratory aspirator. The vacuum should be maintained until no more bubbles emerge from the end of the inner glass tube. When the inner glass tube is free of air, the vacuum should be slowly released. The filling solution will then be drawn into the tube and will saturate the crystals.

In some cases, the reference electrode contains the correct amount of filling solution, but the filling hole is completely blocked. If the filling hole is blocked, the filling solution cannot flow into the sample. The electrode will not establish a consistent electrical connection with the sample, and the pH readings will vary considerably. If the filling hole is partially blocked, the solution may not flow into the sample at the proper rate. In addition, sample ions will migrate into the junction and establish new potentials. These voltages will be measured by the system and interpreted as changing pH readings.

Just as it is possible to restore a reference electrode that has dried out, it is also possible in many cases to restore a blocked or partially blocked reference electrode. There are a series of increasingly severe procedures that may be tried to restore an electrode to proper function. These procedures are presented below.

1. The first and easiest method to try to restore the electrode is simply soaking the junction in a solution of ten percent potassium chloride and 90 percent distilled or deionized water. This helps to dissolve the crystals at the end of the electrode. The reference electrode should be filled with filling solution and then soaked in the potassium chloride solution that has been slightly warmed. The electrode should soak at least 20 minutes.

2. The junction of silver chloride electrode often becomes clogged with silver chloride. Ammonium hydroxide can be used to remove the silver chloride. The first step is to remove the filling solution from the reference electrode. Next, immerse the end of the electrode (do not put ammonia inside the electrode) in the concentrated ammonia for 10 to 20 minutes. Remove the electrode, rinse the outside and inside of the electrode thoroughly with deionized or distilled water. Finally, refill the electrode with filling solution.

3. Protein can also cause a problem with the reference electrode if it penetrates the junction. The protein can be removed by soaking the electrode in 8 M urea for about 2 hours. As with the concentrated ammonia, the electrode should be rinsed well after soaking. Also, empty and rinse the filling solution and refill with fresh filling solution.

4. The reference electrode can also be cleaned with a vacuum. Connect a piece of flexible tubing to an aspirator at one end, to the reference electrode at the other end, and turn on the water. This should draw the filling solution through the junction and remove any obstruction.

5. Boiling the junction may remove obstructions that are not removed using any of the other methods. However, this method should only be used for silver chloride reference electrodes. As mentioned previously, calomel breaks down at about 65°C (150°F), so a calomel reference electrode should not be boiled. A silver chloride electrode can be immersed in boiling water for up to 30 seconds. Even with a silver chloride electrode, however, boiling the junction should be one of the last measures attempted because the glass may break.

While it is possible to restore a damaged reference electrode, proper operation and maintenance can make such measures unnecessary. The electrode should always be used in a vertical position. If the electrode is horizontal, the filling solution will leak out. Between samples, the electrode should be rinsed with distilled or deionized water. After rinsing, the end of the electrode should be blotted with lint free paper. Wiping the electrode can result in static charges that will cause variable pH readings. For accurate readings, the level of filling solution should be higher than the level of the sampling solution. In general, the electrode should be kept at least two thirds full of filling solution. With these simple measures, the reference electrode should last for several years.

Although these manual cleaning procedures work well for laboratory situations, they are not as suitable for online pH measurements. Although the electrodes used for online pH monitoring of a process can be removed and cleaned using these procedures, this requires either an interruption in the process or, a more likely scenario, an interruption in data gathering. For online pH monitoring, automatic cleaning systems are preferred.

Although the focus of manual cleaning of the electrodes is on removing contaminants and deposits from the electrode, the focus of automatic cleaning systems is frequent cleaning to prevent the deposits from ever forming. This can be done using hydraulic, chemical, or mechanical cleaning.

Because deposition of contaminants on the electrode is a greater problem with stagnant solutions, one of the simplest methods of preventing such deposits is to install the electrode in a region of high flow velocity and preferably in a turbulent zone. If flow through the area to be monitored is slow, a baffle plate can be installed to create turbulence. If the sample solution contains small particles or fibers, the electrode assembly should be installed at an angle to the flow so that the particles and fibers will not be trapped.

Chemical cleaning uses a variety of chemicals, including hydrochloric acid, detergents, and caustic soda. There are several methods that can be used for on-line chemical cleaning. The first is a bypass system with an additional feed line. Cleaning solution can be directed to the electrode by rotating a valve. This method is simple, but chemical consumption can be high. A rinsing jet or ring is more economical than a bypass system. With this system, solvent and rinsing agent are applied in the presence of the sample. The cleaning fluid is applied at regular

intervals, from one to several hours, and rinsing only requires a fraction of a minute. A small pump is used to raise the pressure and force the cleaning fluid through the sample solution. A spring-loaded valve prevents the cleaning fluid from leaking out when the pH is being determined. During cleaning, the recorder is switched off so that inaccurate readings are not recorded.

Mechanical cleaning has the advantage that pH monitoring is not interrupted during cleaning. A rotating brush or a wiper is typically used, and an electric motor drives the brush or wiper. Although mechanical cleaning is effective for soft precipitates, hard crystals scratch the tube and fatty deposits are not removed but merely smeared over the electrode. Because the moving parts are immersed in the sample stream, mechanical cleaning of corrosive sample streams is not advised. The sample stream will corrode the moving parts.

4.5.4.2 Maintenance of the pH Sensing Electrode[1-3]

Before a new electrode or an older electrode that has been stored dry is used, it should be hydrated in a suitable solution. The electrode should first be soaked for at least 24 hours in a dilute solution of hydrochloric acid. After rinsing with distilled water, the electrode should then be soaked for at least 12 hours in a buffer with a pH value between 4 and 8.

With earlier glass electrodes, which were less stable than the electrodes used today, it was necessary to keep the pH electrode immersed in an aqueous solution to maintain proper function. Newer formulations are more stable and do not require immersion. However, to avoid surface contamination of the electrode, it is still a good idea to keep the pH electrode covered or immersed in a liquid. Contamination on the surface of the electrode can cause a barrier between the ions in solution and the surface of the glass. This barrier leads to inaccurate pH readings. Storing the pH electrode in liquid prevents airborne contaminants from settling on the electrode and forming this barrier. The storage solution should be somewhat acidic so that the contaminants in the pH glass are exchanged out for hydrogen ions, thereby keeping the electrode more sensitive to pH. The slightly acidic potassium chloride solution used as the filling solution for the reference electrode is a good solution for storing the pH electrode.

The pH electrode should be checked periodically to ensure that it has the required responsiveness and sensitivity. In general, an electrode is in good working order if the response is fast (<1 minute), the response during stirring is stable, and the sensitivity as determined from buffers is better than 95 percent. This last indicator of electrode performance can be tested using a series of standard buffers. The measured pH of the buffers is plotted versus the output in millivolts (mV). The resulting plot should be a straight line that approximates the theoretical slope. If the slope falls to approximately 95 percent of the theoretical slope, the electrode should be discarded or regenerated. In some cases, the electrode can be regenerated with hydrofluoric

acid. However, this process shortens the life of the electrode and should only be used as a last resort.

4.5.4.3 Maintenance of the Combination Electrode[1,2]

Most combination electrodes are based on a silver chloride reference half-cell. These electrodes should not be soaked in any solution that will cause precipitation of the silver in the junction of the electrode. Solutions of low chloride concentration can cause precipitation of the silver and should not be used for electrode storage. Solutions of high chloride concentration can reduce the electrode's sensitivity to hydrogen ion. Therefore, when storing a combination electrode overnight or for a weekend, the electrode should be stored in air with the protective cap over the end of the electrode and the filling hole covered. For longer term storage, the filling solution should be removed from the electrode and the electrode stored completely dry.

4.5.5 Calibration of the pH Meter[1,2]

Proper operation and maintenance of the pH and reference electrodes are critical components of accurate pH measurements. The other critical component is calibration of the pH meter. Meter calibration in the laboratory is a simple and straightforward process that should be done routinely. Online calibration of the electrode assemblies that are used for continuous pH monitoring can be more difficult. The basic procedures are the same for laboratory and online calibration, but to avoid having to take the pH electrodes offline for calibration, self calibration systems are required.

4.5.5.1 Laboratory Calibrations

The pH meter should be calibrated at least once every 8-hour shift. Standard buffer solutions used for calibration can be prepared in the laboratory, but they are also available commercially, usually in three pH values, 4.00, 7.00, and 10.00. The buffers should be stored in tightly sealed containers away from heat and poured just before calibration. Only fresh samples of buffer should be used for a calibration.

The calibration can be one point, two point, or multipoint, with multipoint calibrations providing the most accurate pH readings. However, two point calibrations are the most common and are sufficient for most applications. One point calibrations are often useful for quick, intermediate checks during the day.

A two point calibration uses two buffers. One of the buffers should have a pH value of 7.00 and the other should be closest to the value anticipated for the sample. For example, if the sample is acidic, the buffer with a pH value of 4.00 should be used. If the sample is basic, the

buffer with a value of 10.00 should be used. Actual calibration procedures vary according to pH meter. However, the following is a summary of the basic steps for a two point calibration:

1. Set the temperature setting on the meter to the temperature of the buffers, typically room temperature or 25°C. If meter is equipped with automatic temperature compensation, make sure it is activated before calibrating.

2. Turn the pH meter to "pH" or to "ATC" if automatic temperature compensation is available.

3. Place the clean electrodes into the container of fresh pH 7.00 buffer.

4. Adjust the pH reading to 7.00 using either the "zero offset," "standardized," or "set" knob.

5. Rinse the electrodes with distilled or deionized water.

6. Place the electrodes in the second buffer (with a pH value of 4.00 or 10.00).

7. Adjust the pH reading to display the correct value using either the "slope," "calibrate," or "gain" knob.

The basic procedure is the same for a one point calibration and a multiple point calibration. For a one point calibration, use the buffer that is closest in value to the expected pH of the sample. For a multiple point calibration, calculate the calibration curve using the least squares method.

Many pH meters in use today are controlled by microprocessors. These pH meters are able to calculate the pH directly from the calibration and sample results using the appropriate equations and the stored results obtained from the calibration solution. Typically, only one calibration solution, one with a pH near that of the sample, is needed. A 7.00 buffer is not required.

4.5.5.2 Temperature Compensation

As discussed earlier, the output of the pH electrode will vary with temperature. The amount of variation depends upon the temperature and the pH of the solution. There are only two scenarios in which this variation does not occur. If the pH of the solution is 7.0, no matter the temperature of the solution, there is no temperature error. Likewise, there is no temperature error if the sample solution is at ambient temperature, 25°C (78°F). For all other scenarios, the temperature error can be calculated as follows:

0.03 pH error/pH unit/10°C (18°F)

The error factor calculated using this equation is added to the pH reading in some cases and subtracted from the reading in other cases. Table 4.5-1 demonstrates how to use the error factor for calculating the correct pH.

TABLE 4.5-1. USING THE ERROR FACTOR TO CALCULATE pH CORRECTED FOR TEMPERATURE

	Solution temperature	
pH	Above 25°C	Below 25°C
Above 7	Subtract error factor	Add error factor
Below 7	Add error factor	Subtract error factor

The need for temperature compensation is based on the accuracy required for a particular application and the pH and temperature of the sample solution. To determine whether or not temperature compensation is required for a particular operation, use the equation to develop the error factor for the operation and compare this value to the accuracy required. If the error factor is greater than the target accuracy value, temperature compensation should be used. For example, if the error factor is 0.1 and the target accuracy value for the operation is $\pm$0.01, temperature compensation is required.

Temperature compensation can be done with an automatic or manual compensator. Automatic temperature compensation should be used if the temperature of the sample solution fluctuates. If the temperature of sample is fairly stable and only varies a few degrees, a manual compensator can be used. If an automatic temperature compensator is used, it should always be located with the electrodes. During calibration, the compensator should be in the buffer with the electrodes. With a manual compensator, the temperature should be adjusted to the same temperature of the sample solution or buffer.

4.5.5.3 Self Calibration Systems for Online pH Measurements

Online calibration of the electrode assemblies used for continuous pH monitoring as discussed earlier is typically more difficult than calibration in the laboratory. In order to avoid having to disassemble the electrodes and remove them to the laboratory for calibration, some electrode assemblies are equipped with a self calibration system. The type of calibration system depends upon the type of electrode assembly that is used.

There are two types of calibration systems used for immersion electrode assemblies. One option is to surround the electrode assembly with a porous plastic membrane. During routine pH measurement, the membrane is flush with the electrode. The sample penetrates the porous membrane to the electrodes. For calibration, the system is equipped with an inlet and an outlet for the buffer solution. During calibration, the buffer solution is fed through the inlet and forced through the membrane. The membrane expands and forms a pocket around the electrode for the buffer solution. Another self calibration system used with immersion electrode assemblies uses air pressure to displace the sample solution during calibration.

The self calibration system using air pressure is also used for built-in electrode assemblies. The cylinder with the electrodes has an upper and lower position. One is used for monitoring and one for calibrations. Compressed air moves the cylinder into the upper or lower position. For calibrations, the cylinder is lowered into a chamber containing buffer solution.

Self calibration systems were first used for flow-through electrode assemblies. A four-way ball valve acts as the flow-through electrode assembly with the electrode mounted in the bore. The system converts from measurement mode to calibration mode by rotating the valve 90°.

4.5.6 Conductivity Measurement[1,2,4]

The ability of a solution to conduct electricity is called conductance and its reciprocal is called resistance. As electrolytes, for example, salts, bases, and acids, are added to a solution of pure water, the conductance increases and the resistance decreases. A conductivity measurement system measures the conductance of a solution with a sensor that is immersed in the solution.

For strong acids and bases, pH values are not very meaningful indicators of the concentration. The measurement uncertainty is large because pH is a logarithmic scale. Conductivity measurements are more suitable than pH measurements for producing accurate and reproducible estimates of the concentrations of free acids and bases because the relationship between conductivity and concentration is almost linear over a range of concentrations. Because of this relationship, conductivity measurements are often used to determine the total dissolved solids content of water samples.

The standard unit for conductivity measurement in the past has been mho/centimeter (mho is the reciprocal of ohm). This conductivity value can then be converted to a total dissolved solids concentration value (in parts per million) using a standard conversion chart. The mho/cm unit is now being replaced with an interchangeable unit of measurement called the Siemen/cm. Conductivity is expressed in millionths of a Siemen, that is microSiemens/cm. Many conductivity meters provide the option of conductivity measurements in each measurement unit.

4.5.6.1 Conductivity Sensors

There are two primary types of conductivity sensors, contacting-type sensors and electrodeless-type sensors. The contacting type sensor consists of two electrodes that are insulated from each other. The electrodes may be made of 316 stainless steel, titanium-palladium alloy or graphite and are specifically sized and spaced to provide a known cell constant. The spacing of the electrodes is critical and is an important factor in selecting a conductivity sensor. A sensor with the electrodes placed closely together is used for solutions

with low conductivity and a sensor with the electrodes further apart is used for solutions with high conductivity. Because all contacting-type sensors cannot be used for all solutions, it is important to have some idea of the conductivity of the solution before purchasing a sensor. There are sensors available that cover multiple ranges and can therefore be used for samples with low conductivity and high conductivity, but these sensors are typically more expensive than those designed for a specific range of conductivity. Some of the meters equipped to measure multiple conductivity ranges automatically select the most suitable range for maximum resolution.

Electrodeless-type sensors induce an alternating current in a closed loop of solution and measure the magnitude to determine the conductivity. Electrodeless-type sensors eliminate some of the problems associated with contacting-type sensors. Polarization, oily fouling, process coating or nonconducting chemical plating, all of which can affect the performance of contact-type sensors, do not affect the performance of electrodeless-type sensors unless the fouling is excessive.

The temperature of the solution can have a dramatic effect on the conductivity of the solution. The conductivity may vary as much as four percent per degree centrigrade, and the conductivity of common solutions may vary from 1 to 3 percent per degree centigrade. Therefore, no matter what type of sensor is used, the conductivity meter should be equipped with automatic temperature compensation.

4.5.6.2 Conductivity Meters

As with pH meters, there are many conductivity meters available. They range from small pocket-sized meters that can be used for a selected conductivity measuring range to micro-processor controlled meters that are set up for as many as five conductivity measuring ranges. Some meters are suitable only for laboratory measurements and others are suitable for industrial applications. Conductivity sensors, like pH measuring systems, are available in flow-through, submersion, and insertion mounting styles for continuous in-line conductivity measurements of a process stream. Flow-through sensors are threaded on the electrode end of the body and submersion sensors are threaded on the cable end. Convertible style sensors are threaded on both ends so that they can be used for flow-through or submersion applications. The conductivity sensors are equipped with an integral temperature sensor to automatically adjust conductivity values to a 25°C reference.

4.5.6.3 Meter Calibration

The calibration process for a conductivity meter is similar to that for a pH meter. As with the pH meter calibration, the standard solutions used for calibration should have a conductivity similar to that of the sample. Standard solutions covering a wide range of conductivity values are

available commercially. Some meters that provide multiple units of measurement, for example, ppm, total dissolved solids, mho/cm, allow the operator to choose the measurement unit and create a specific calibration curve for that unit by measuring up to four concentration standards.

As with the buffer solutions used to calibrate pH meters, the standard solutions for calibration of the conductivity meter should be stored in closed containers and poured fresh each time the meter is calibrated. Both the standard calibration solution and the sample are easily contaminated by air. Process samples that are not analyzed inline, that is, samples that are collected from the process stream for analysis, should be analyzed immediately to avoid contamination.

4.5.7 References for pH and Conductivity Measurement

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4.6 ELECTRICAL

(Reserved)

4.7 LEVEL INDICATOR

(Reserved)

4.8 MOTION AND ROTATION

(Reserved)