Manual of Water Supply Practices

M33

Flowmeters in Water Supply

Third Edition

American Water Works Association

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Flowmeters in Water Supply

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Managing Editor: Melissa Valentine
Sr. Specialist, AWWA Manuals: Sue Bach
Cover Design: Melanie Yamamoto

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American Water Works Association

American Water Works Association
6666 West Quincy Avenue
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Contents

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Figures

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Tables

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Foreword

This manual provides information about the most common large flowmeters used in water treatment and in custody-transfer applications. Information on other meters can be obtained from AWWA Manual M6, *Water Meters—Selection, Installation, Testing, and Maintenance*. The flowmeters discussed in this manual include the Venturi, modified Venturi, orifice plate, electromagnetic (mag), turbine and propeller, transit-time ultrasonic, vortex, averaging Pitot, and averaging insertable electromagnetic (mag). The discussion of these meters covers basic theory, installation, maintenance, and advantages and disadvantages. General concepts applicable to flowmeters are also discussed, including flow characteristics, installation and performance issues, communications, information and signal outputs, and flowmeter selection.

The manual can be used as a bridge to other literature on flowmeters, to prepare the reader for further investigations into instrumentation design and applications. The Bibliography lists excellent information sources. For additional information, the reader should acquire the relevant manuals from the meter manufacturers. These manuals contain comprehensive information on meter specifications, theory, sizing, handling, installation, power and wiring, operation, maintenance, troubleshooting, and parts.

While this manual attempts to include recommended practice in the use of flowmeters, it is not intended as an AWWA standard.

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Michael J. Keilty, *Chair*

W. Ault, Kamstrup Water Metering LLC, Forest Park, Ill.
S. Carpenter, San Diego County Water Authority, Escondido, Calif.
G.H. De Jarlais, Badger Meter, Milwaukee, Wis.
D. Faber, Faber & Associates, Columbus, Ind.
J.J. Gemin, AECOM, Kitchener, Ont.
P.A. Hayes, Mammoth Community Water District, Mammoth Lakes, Calif.
A.M. Horbovetz, M.E. Simpson Company Inc., Valparaiso, Ind.
M.J. Keilty, Endress+Hauser Flowtec AG, Estes Park, Colo.
M.D. Kyser, Professional Engineering Consultants P.A., Tulsa, Okla.
G.G. Land, Master Meter Inc., Mansfield, Texas
E.J. Melanson, EJM Automation, Norfolk, Mass.
J.A. Olson, Badger Meter, Milwaukee, Wis.
J.F. Panek Jr., McCrometer Inc., Rowley, Iowa
J.A. Reiss, Elster AMCO Water, LLC, Ocala, Fla.
S.F. Sarrouh, T&M Associates, Columbus, Ohio
J.L. Smith, Primary Flow Signal Inc., Cranston, R.I.
J.S. Trofatter, JST Environmental, Land O' Lakes, Fla.
S.Y. Tung, City of Houston, Houston, Texas
D.C. Wyatt, Wyatt Engineering, Lincoln, R.I.

This edition of the manual was reviewed and approved by the AWWA Standards Committee on Rate-Type Flowmeters. The members of the committee at the time this manual was approved included:

Joseph J. Gemin, *Chair*

General Interest Members

J.A. Casados, Instituto Mexicano de Tecnología del Agua, Progreso, Mor.
A. Dabak, Texas Instruments, Dallas, Texas
D. Faber, Faber & Associates, Columbus, Ind.
J.J. Gemin, AECOM, Kitchener, Ont.
A.M. Horbovetz, M.E. Simpson Company Inc., Valparaiso, Ind.
F.S. Kurtz,* Standards Engineer Liaison, AWWA, Denver, Colo.
M.D. Kyser, Professional Engineering Consultants P.A., Tulsa, Okla.

* Liaison, nonvoting

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E.J. Melanson, EJM Automation, Norfolk, Mass.
R.A. Richter, National Institute of Standards and Technology, Gaithersburg, Md.
S.F. Sarrouh, T&M Associates, Columbus, Ohio
S. Thakurdesai,* Texas Instruments, Dallas, Texas
J.S. Trofatter, JST Environmental, Land O' Lakes, Fla.

Producer Members

R.A. Barillas,* Badger Meter, Milwaukee, Wis.
G.H. De Jarlais, Badger Meter, Milwaukee, Wis.
M.J. Keilty, Endress+Hauser Flowtec AG, Estes Park, Colo.
J.F. Panek Jr., McCrometer Inc., Rowley, Iowa
J.L. Smith, Primary Flow Signal Inc., Cranston, R.I.
D.C. Wyatt, Wyatt Engineering, Lincoln, R.I.

User Members

S. Carpenter, San Diego County Water Authority, Escondido, Calif.
W.F. Dunnill, Consolidated Utility District of Rutherford County, Murfreesboro, Tenn.
P.A. Hayes, Mammoth Community Water District, Mammoth Lakes, Calif.
A. Land, Dallas Water Utilities, Dallas, Texas
S.U. Mills-Wright,† Standards Council Liaison, Dallas Water Utilities, Dallas, Texas
S.Y. Tung, City of Houston, Houston, Texas
K. Whitaker,* San Diego County Water Authority, San Diego, Calif.

* Alternate
† Liaison, nonvoting

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Chapter 1

Characteristics of Flow

Flow is an important measurement made at treatment and distribution facilities, and flowmeters are used to measure this flow. Flowmeters measure product output of a plant, water distribution into a community, pacing of chemical feeds, and customer charges, to name just a few applications. Day-to-day operational decisions and long-term planning are based on measurements from flowmeters. To achieve proper flow measurement, the fluid must be homogeneous, with evenly dispersed solids or gases, acting as a single-phase fluid with no relative motion among its components. The fluids of main concern in water treatment generally meet these conditions.

FLUID PARAMETERS

The parameters and properties of fluids important to flowmetering are as follows:

- Density (ρ)—mass per unit volume.
  - Density is important when mass transfer measurements are needed.
  - It affects the nature of the flow and fluid behavior and is used to calculate many other fluid parameters.
- Electrical conductivity—ability of the fluid to conduct electricity.
  - This condition is typically met in the water industry.
- Flow area—area of unobstructed flow.
  - Accuracy of cross-sectional area measurement plays a major role in flow measurement accuracy. For example, a ⅛-in. deviation in the diameter of a 12-in. pipe will cause a 2 percent change in area. This is important because of the probable change of flow area caused by corrosion and erosion with time.
- Pressure—force per unit area.
  - Flow is driven by the difference in pressure.
  - Some flowmeters use the pressure differential across an obstruction to measure flow.
  - Pressure is a measure of the static component of the fluid's energy.

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- Temperature of the fluid
  - Change in temperature affects fluid viscosity, density, and pressure, which may cause measurement errors if not properly compensated for electronically or by recalibration.
- Sonic conductivity—ability of the fluid to conduct sound.
  - This condition is typically met in the water industry.
- Sonic velocity—speed of sound through the fluid.
- Velocity (V)—fluid's speed of flow.
  - V is the average velocity over the flow area.
- Viscosity (μ)—fluid's resistance to flow.
  - Viscosity affects the nature of the flow and fluid behavior and is used to calculate many other fluid parameters.
  - It causes shear forces to be dominant at lower velocities.
  - It causes a point of zero velocity at the pipe's surface.

MEASURING VELOCITY

One of the most common methods to determine rate of flow is to measure the fluid velocity and compute flow by the *continuity equation*, most simply presented as $Q = VA$. In this equation, Q is the rate of flow, V is the average velocity over the flow area, and A is the area occupied by flow. For custody transfer and other uses, flowmeters totalize the flow by integrating the rate of flow versus time. Positive displacement and other volumetric-type custody-transfer meters count and totalize the number of volumes of water that pass.

To date, fluid velocity is measured indirectly by quantifying its effect on an influenced parameter. Most meters are identified according to the physical parameter used to determine the velocity. One or more transducers are needed to detect such effect of liquid movement. The transducer is a device that, by its inherent nature, transforms energy from one form to another. Its output changes when it is influenced by flow. The transducer, in turn, allows detection of a change in flow, therefore indirectly identifying the velocity of a liquid. Examples are turbine, magnetic, and transit-time ultrasonic flowmeters. In turbine meters, the flow impinging on the turbine vanes imparts energy to the turbine and causes it to rotate. The rotation speed is proportional to the flow velocity, enabling the user to arrive at a value of velocity by counting the number of rotations per unit of time.

Flow is simply the volume of a moving fluid passing through a cross-sectional area per unit of time. To achieve a time rate of change of volume Q in most meters, which is also known as *volumetric rate of flow*, the average fluid velocity V and the cross-sectional area A must be known. Accurate rate of flow determination is directly related to the accuracy of cross-sectional area and velocity measurement.

The flowmeters considered in this manual are for closed-conduit, full flowing pipes, in which the flow cross-sectional area is that of the internal diameter of the pipe or the meter chamber. The basic continuity equation of flow is used to yield dimensions as gallons per minute, cubic meters per second, and million gallons per day. It is called the continuity equation because what goes in one end of a full length of pipe must go out the other end. Therefore, a reduction in the area somewhere along the length of the pipe results in a proportional increase in the velocity and vice versa, because the rate of flow remains constant. Various methods of flow measurement are described in Table 1-1.

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Table 1-1 Methods of flow measurement

Type	Measurement	Method
Coriolis	Vibration phase shift	Flow momentum distorts two specially shaped, resonating flow tubes, inducing Coriolis forces. This force causes a vibration phase shift, which is related to mass flow rate.
Differential pressure producers	Pressure	Differential pressure caused by flow-area reduction is measured and related to velocity through calibration.
Magnetic	Voltage	Induced voltage from changes in magnetic field flux is related to velocity through calibration.
Open channel	Level	The flow level is measured at the flume or weir, and flow rate is calculated based on the geometry of the channel cross section.
Optical	Light	The time it takes a particle to cross two light/laser beams is used to calculate flow velocity.
Positive displacement	Count	The flow is broken into packets of known volume, which are counted per unit time.
Sonar	Sound	The time it takes the sound emitted by turbulence to travel from one sensor to the other is related to flow.
Thermal	Temperature	Flow across heated elements causes a difference in temperature, which is related to velocity through calibration.
Turbine	Rotation speed	Flow causes the rotor to spin, and the speed of rotation is directly proportional to velocity related to flow through calibration.
Ultrasonic Doppler	Ultrasonic wave frequency shift	Relates the Doppler shift in a reflected ultrasonic wave to the velocity of the reflecting particle in the fluid.
Ultrasonic transit time	Ultrasonic wave pulse time	Relates the travel time of an ultrasonic pulse between two points and relates it to flow velocity through calibration.
Variable area	Level	Drag causes a vertically oriented float to rise with increased velocity. The increase in float height is related to velocity.
Vortex	Vortex shedding frequency	Relates the vortex shedding frequency induced by an obstruction to flow velocity through calibration.

TYPES OF FLOW

Laminar and Turbulent Flow

Regardless of whether there are disturbances in the flow caused by upstream conditions, the velocity across a pipe's cross section is not constant. As briefly discussed, the viscosity of the fluid causes the layer of the fluid at the pipe wall to have zero velocity. Layers of fluid have increasingly larger velocities the farther away they are from the pipe wall. Maximum velocity or free-stream velocity is reached at the pipe centerline. A plot of the velocity at various distances from the wall is what is called the *velocity profile* or *gradient*. An undisturbed velocity profile is symmetric along the pipe axis. As shown in Figure 1-1, pipe flow can assume two profiles, laminar flow and turbulent flow, with a transition phase between the two.

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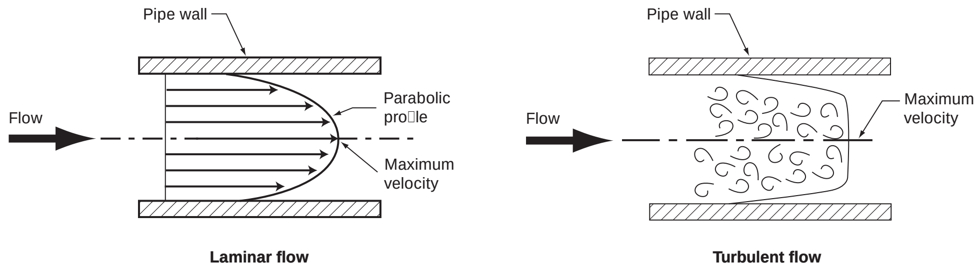

Figure 1-1 Velocity profiles

Laminar flow can result from low, average velocities. The fluid moves in smooth concentric, cylindrical layers or laminae, with the fastest-moving layers toward the central axis and the slowest-moving layers toward the pipe wall. A parabolic profile of flow exists across any diameter of the pipe. In laminar flow, shear stress is caused in the fluid by the sliding of one layer of fluid over another. A small disturbance in the flow is dampened by the viscous forces, which are dominant. Therefore, there are negligible velocity fluctuations normal to the flow directions, and adjacent fluid particles move along in essentially parallel paths.

When the average velocity increases above a certain value, some disturbances begin to appear because the inertial forces are becoming gradually more dominant than viscous shear forces. The flow appears to become more and more irregular. This is what is called *transition flow*. In the transition phase between laminar flow and turbulent flow, the change is gradual, with no distinct transition point.

As the average velocities continue to increase, turbulent flow is reached. Turbulent flow is characterized by velocities normal to the flow direction as individual fluid particles zigzag and gyrate in irregular, random motion. Adjacent particles are in a more or less random motion, not moving in parallel paths in turbulent flow, at which point flow layers practically disappear and the velocity across the stream is more uniform. This happens because the transverse movement of the fluid particles causes the flow in slower-moving layers to increase and the flow in faster-moving layers to decrease. The velocity profile is flattened, and the free-stream velocity is reached in layers closer to the pipe wall. Because turbulent velocity fluctuates, a time-averaged mean velocity is used to represent a turbulent steady flow.

Even though these fluctuations may be small, they have a large effect on flow characteristics as they cause mixing of the fluid. The motion of particles in directions normal to the main flow acts as an equivalent shear stress. This shear stress may be hundreds of times larger than the laminar viscous shear stress caused by the sliding of the layers. This results in a blunt, more uniform velocity profile. However, because of the friction and the lower velocities near the wall, a small laminar sublayer appears between the flattened velocity profile region and the wall. In the water industry, flows are typically turbulent.

Reynolds Number

Closely associated with flow properties is the Reynolds number, which is the ratio of inertial forces (from a pump or gravity) to viscous forces (the internal fluid resistance to flow) in a flowing liquid. As a ratio of force to force, the parameter is dimensionless. The Reynolds number (*Re*) indicates which forces dominate the flowing liquid. It can be easily calculated using

$$Re = \frac{\rho V D}{\mu} \qquad \text{(Eq 1-1)}$$

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where ρ is density, V is velocity, D is pipe diameter, and μ is viscosity. The type of flow, laminar or turbulent, is related to the Reynolds number. Low values (Reynolds numbers <2,000) indicate that the viscous forces are dominating the flow. Therefore, the flow is laminar. Flow with Reynolds numbers between 2,000 and 4,000 are in the transition phase. The velocity profile may fluctuate between laminar and turbulent. At Reynolds number values >4,000 (not a strict borderline value), the inertial forces begin to dominate. The flow becomes turbulent and the particles begin moving at the same velocity, except in the laminar sublayer at the walls. Reynolds numbers are noted in textbooks and vendor literature as having some impact on meter accuracy and the meter coefficient of discharge.

Distorted Velocity Profiles

Distorted velocity profiles occur downstream from fittings, valves, or other obstructions. Major disturbances to the velocity profile generally result in a skewed profile, swirl, or flow separation. In a skewed profile, velocities are asymmetrically higher in some sections than in others. Swirl means that the flow has random vortices with rotation along and/or normal to the flow direction. Crossflow may be a part of swirl; however, it involves flow with velocity vectors nonparallel to the pipe axis. When the fluid passes over a sharp edge or corner, the flow separates from the wall, possibly reattaching at a later point downstream.

All the previously mentioned conditions create what can be called *distorted profiles*, which make accurate flow measurement difficult because the average velocity is not uniform and steady throughout the pipe's cross-sectional area. The importance of this topic cannot be overstated. With all inferential flowmeters, the velocity profiles, both upstream and downstream, affect the flowmeter. This points out the importance of upstream and downstream undisturbed lengths of pipe, or the need for additional flow conditioning, or additional testing.

FLOW CONDITIONING

When the required undisturbed pipe length is unavailable, flow conditioners may be used to attempt to straighten the distorted velocity profiles shown in Figure 1-2 and return them to uniformity. This is an option if the fluid being measured, such as finished water, contains no solids or other material that can plug the conditioner and if the additional head loss can be tolerated. Flow conditioners include such devices as tube bundles, vanes, and other proprietary devices that are placed in the flow to create an obstruction. These devices cause a quick return to the normal turbulent profile shown in Figure 1-1 by inducing pressure gradients and redirecting velocities normal to the main flow direction. However, they still require some downstream straight lengths before the flowmeters.

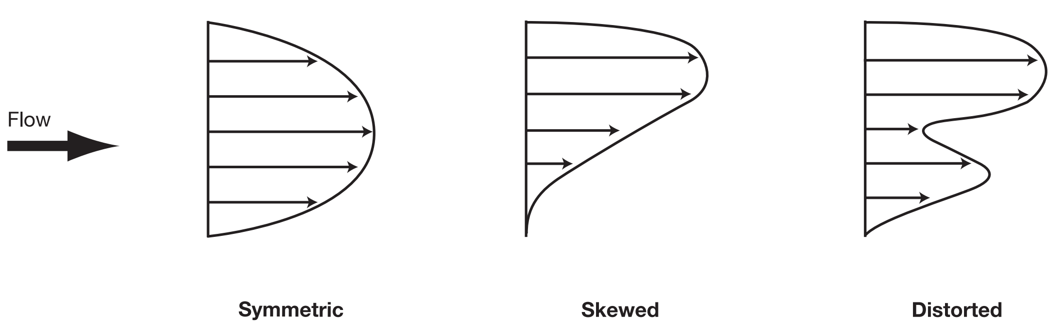

Figure 1-2 Distorted velocity profiles

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Consulting with flowmeter and flow conditioner manufacturers regarding applicability and installation data is highly recommended. A detailed discussion of the effect of velocity profiles on flow measurement is provided in chapter 4.

METER COEFFICIENT OF DISCHARGE

The coefficient of discharge C_d is used to account for deviations from the true average velocity and the cross-sectional area of the pipe and is used primarily with differential pressure meters. The ratio of actual rate of flow (determined by high-accuracy measurement) to the theoretical flow (calculated from a mathematical model published by the manufacturer) defines the meter's discharge coefficient.

A flow coefficient K_{CD} (or K_{CD} factor) is sometimes used that effectively combines C_d with the geometric and conversion parameters. The K_{CD} factor $= Q / (\sqrt{\Delta P})$ where Q is in gallons per minute and ΔP is in inches of water.

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Chapter 2

Types of Flowmeters

This manual describes the more common types of flowmeters used in water treatment and custody-transfer applications. Information on other meters can be obtained from AWWA Manual of Water Supply Practices, M6, *Water Meters—Selection, Installation, Testing and Maintenance*, and from the respective manufacturers. Table 2-1 lists various types of meters used in the water industry. Meters described in this manual for use in water treatment and custody-transfer applications are highlighted in **bold letters** in Table 2-1. Criteria for the selection of flowmeters for various water treatment and custody-transfer applications are provided in Chapter 3.

Some meters described in this manual, as well as other meters used in applications for revenue billing (such as displacement, multijet, single-jet, compound, and fire service meters), are described in AWWA Manual M6.

Among flowmeter types, several numerical values are presented for accuracy, repeatability, and rangeability. These are provided as representative or typical values, specifically for meters used in water treatment and custody-transfer applications. These values have been reported by one or more manufacturers of the meter type based on their laboratory testing and are illustrated in Table 2-2. Some metering technologies (turbine, propeller, magnetic, and transit-time ultrasonic) are also used in products designed for the retail sales of water to individual customers within a utility service area. For these applications, meter performance requirements are often quite different from those in water treatment and custody-transfer applications. For example, a turbine meter designed for retail water sales may have substantially wider rangeability and wider accuracy limits than one designed for a process control application. The authors of this document cannot make any warranty as to the accuracy of data in Table 2-2. It is included to provide useful background for the reader.

In any application, for any meter type, it is incumbent on the user to determine what their accuracy needs are, whether conditions of installation fall within the range represented by any manufacturer's data, and whether their specific installation requirements may require additional laboratory testing to determine expected performance.

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Table 2-1 Types of flowmeters for the water industry

		Usual Size Range	
	Type	*in.*	*(mm)*
1	Displacement meters		
	a. Nutating disc	½–2	(13–50)
	b. Oscillating piston	½–2	(13–50)
	c. Oval gear	¼–3	(6–80)
	d. Rotary vane	½–2	(13–50)
2	Nondisplacement meters		
	a. Velocity		
	Impeller/paddle-wheel	½–4	(13–100)
	Insertable impeller/paddle-wheel	>2½	(>65)
	Magnetic pickup turbine	**¼–12**	**(6–300)**
	Mechanical register turbine	**¾–20**	**(20–500)**
	Multijet	½–2	(13–50)
	Propeller	**2–72**	**(50–1,800)**
	Single jet	½–6	(13–150)
	b. Differential pressure		
	Fixed opening, variable differential		
	Orifice	**>1**	**(>25)**
	Venturi, flow nozzle, flow tube, other profile modifiers	**1–120**	**(25–3,000)**
	Pitot tube	**Unlimited**	**Unlimited**
	Variable area, fixed differential		
	Rotameter	**1⁄16–12**	**(1½–300)**
	c. Electronic velocity		
	Clamp-on ultrasonic (transit-time)	**Unlimited**	**Unlimited**
	Coriolis	**1⁄24–16**	**(1–400)**
	Electromagnetic (mag)	**1⁄10–120**	**(2½–3,000)**
	Insertable electromagnetic (mag) (averaging)	**4–120**	**(100–3,000)**
	Insertable vortex	**>4**	**(>100)**
	Fluidic oscillator	½–2	(13–50)
	Ultrasonic (transit-time)	**¼–360**	**(6–9,000)**
	Vortex	**¼–10**	**(6–250)**
	d. Level measurement		
	Weir, flume	(Suitable for open-channel flow only)	
3	Compound meters		
	a. Standard compound	2–8	(50–200)
	b. Fire service	3–12	(80–300)

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Table 2-2 Representative characteristics of various types of flowmeters

Type	Accuracy*	Repeatability*	Rangeability	Relative Head Loss
Coriolis	±0.10%	0.05%	20:1	Medium
Electromagnetic (mag)	±0.50%	0.25%	20:1	None to low
Insertable electromagnetic (mag)	±0.50%	0.25%	20:1	Low
Orifice	±1%	0.25%	10:1	Medium to high
Pitot tube	±1%	0.50%	4:1	Low
Propeller	±2%	0.20%	15:1	Low to medium
Rotameter	±0.50%	0.25%	10:1	Low
Turbine	±0.50%	0.20%	10:1	Low to medium
Ultrasonic (transit-time)	±0.50%	0.25%	20:1	None to low
Venturi	±0.75%	0.25%	10:1	Medium
Vortex	±0.75%	0.50%	25:1	Medium

* Accuracy and repeatability values may vary within a specific meter type depending on the accuracy limits and rangeability the meter was designed for. These values are used as examples only and are not indicative of all meter types defined.

TURBINE AND PROPELLER FLOWMETERS

In turbine and propeller flowmeters, flowing water strikes rotor blades that rotate at a rate proportional to the flow velocity. The rotor (turbine wheel) of a turbine meter generally fills the cross section of the pipe and is mounted to spin freely between two central bearings supported in the pipe wall (Figure 2-1, left). The rotor (propeller) of a propeller meter (Figure 2-1, right) is mounted on bearings, or a ceramic sleeve, at the downstream end of the pipe and occupies up to 80 percent of the meter cross-sectional area. The tapered propeller nose faces upstream into the flow and is mounted to spin freely in line with the pipe axis.

Within given limits of flow rate and fluid viscosity, the rotor speed and volumetric flow rate maintain a linear relationship. Most turbine meters and propeller meters used in the water industry have mechanical registers. For turbine meters and propeller meters that use electronic registers, a magnetic proximity sensor in the meter detects the rotor velocity and converts it to a frequency signal. Therefore, the rotation of the rotor blades causes a known number of cycles per unit volume. The meter coefficient is the calibration K-factor, which is a known number of pulses for a given volume measured. The K-factor is typically constant over a 10:1 flow range within a linearity tolerance of ±0.25. For identical turbine meters, the K-factor may vary as a result of manufacturing tolerances. Therefore, each meter with an electronic register may be calibrated for its own specific K-factor value.

Turbine meter accuracy varies from manufacturer to manufacturer. Depending on the application the meter is designed for, ±0.5 percent is a typical representation of accuracy. For specific operating characteristics, refer to ANSI/AWWA C701, *Cold-Water Meters—Turbine Type, for Customer Service*. Manufacturers of propeller meters agree on an accuracy of ±2 percent of the actual flow rate within the normal flow limits of the meter. At low flow rates, accuracy is reduced. For specific operating characteristics, refer to ANSI/AWWA C704, *Propeller Type Meters for Waterworks Applications*.

The orientation and configuration of the meter blade profile are important to the application of the turbine meter. Straight-bladed meters may be less affected by variations in velocity, while helical-bladed meters, as the propeller meter, are generally less affected by variations in viscosity.

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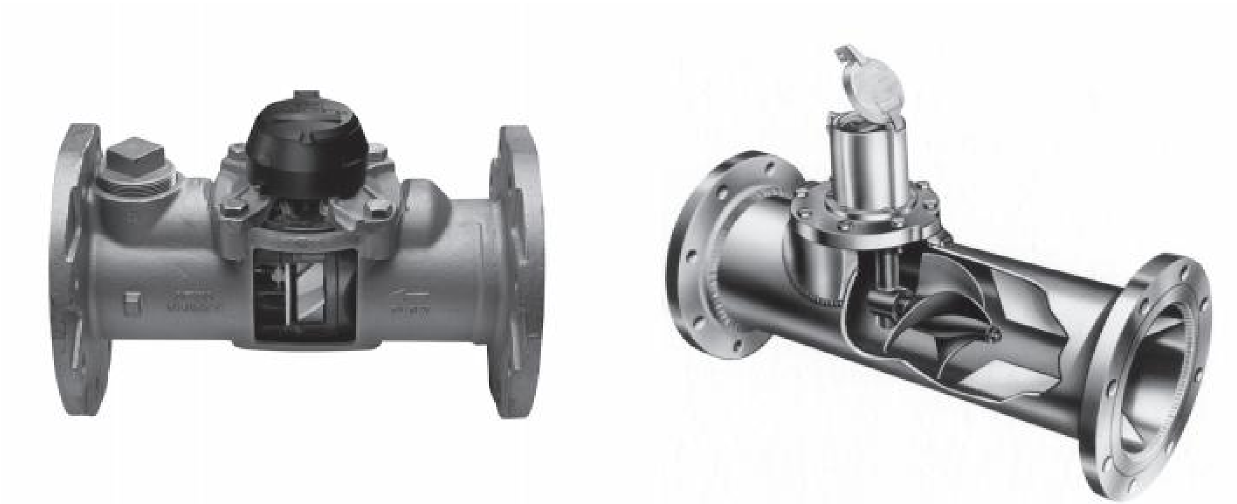

Figure 2-1 Turbine flowmeter (left) and propeller flowmeter (right)

Installation

Turbine flowmeters may be installed with a strainer to prevent solids from interfering with the rotor mechanism, which is not usually the case with propeller meters. Because these meters are affected by upstream configurations that cause swirls or velocity fluctuations, manufacturers frequently provide or recommend built-in straightening vanes upstream in the pipe. These minimize the effect of profile irregularities and smooth flow entering the meter. Straight pipe lengths of at least five pipe diameters upstream and two pipe diameters downstream are a minimum recommendation in applications where the actual types and degrees of flow profile disturbances are assumed to be fairly minor, and the degree to which the specific meter design is able to accommodate these disturbances is unknown. Larger flow-profile disturbances (e.g., those caused by throttling valves, check valves, or paired elbows that are out of plane) could require increased lengths of straight piping or the addition of flow-conditioning elements. On the other hand, some meter designs may be relatively insensitive to various flow-profile disturbances.

When selecting a meter for a specific application, one should take care to ensure that the maximum flow rate will not be exceeded, except for short periods. Running over the maximum flow rate for extended periods increases bearing wear and shifts the meter's calibrated accuracy.

Location downstream from a chemical injection point should be avoided, and the electronic mechanisms that provide digital outputs should be protected from electromagnetic influence.

Maintenance

Periodic mechanical maintenance prolongs the life of a turbine or propeller flowmeter. Factory maintenance programs are available for meter testing, maintenance, and recalibration. Periodic inspection, calibration, and service should be performed at least annually.

Propeller meters are generally manufactured for ease of disassembly and extraction of the metering unit from the pipe body. According to many manufacturers, no special tools are required for maintenance. When the metering unit is removed, a cover plate is commonly available for installation, so line service can continue. During service and disassembly, the complete metering assembly should be examined for wear and corrosion.

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Parts should be cleaned, while worn or damaged parts should be replaced. Manufacturers provide troubleshooting procedures covering problems, causes, and recommended corrective actions. An example of a troubleshooting checklist for mechanical meters can be found at the end of this chapter.

Advantages and Disadvantages

Advantages of turbine and propeller flowmeters are as follows:

- The very large sizes have good repeatability and can be very accurate with periodic calibration.
- Output flow signal is directly proportional to a pulse train with high linearity over a broad range of flow rates, at least 10:1 for large meters.
- Head loss is low to moderate, decreasing with larger sizes.
- Meter size is the same as the diameter of pipe in which it is installed.
- Flow is restricted but not blocked if the meter seizes up.
- No external power source is required.

Disadvantages of turbine and propeller flowmeters are as follows:

- Systematic mechanical maintenance and lubrication are required to maintain meter accuracy.
- Gradual deterioration of meter surfaces via wear or fouling makes periodic recalibration necessary to maintain high accuracy. Corrosive liquids, liquids of poor lubricating quality, and liquids with a high proportion of suspended solids cause bearing problems.
- The calibration factor is sensitive to changes in viscosity of the flowing liquid.
- These meters are sensitive to flow disturbances and swirls.
- Bearing friction is detrimental to meter performance; the effect is more pronounced in smaller meters.
- Accuracy decreases significantly at low flows.

ORIFICE PLATE FLOWMETERS

The orifice plate flowmeter uses a differential pressure created through a restriction in the pipe. Measurement of the differential pressure between points upstream and downstream of this restriction is used to calculate flow in the conduit. The orifice plate flowmeter consists of a thin plate with a hole in it (Figure 2-2). The standard plate is a circular disc that fits snugly in the pipe, usually of stainless steel ⅛–½ in. (3–13 mm) thick, that contains an orifice with a sharp leading edge. The hole is usually concentric with the pipe into which the plate is inserted and perpendicular to the axis of flow. The plate is typically installed in a pipeline between two flanges, and the differential pressure across the plate is measured. Because of its simplicity, low cost, ease of installation, and reasonable accuracy, the orifice plate is among the most common primary elements for measuring flow.

Most orifice plate flowmeters for clean water are made with a circular orifice concentric with the pipe. In special applications, notably for flowing solids, the orifice may also be eccentric or segmental. Passage of entrained solids is permitted if the hole is tangent to the inside surface of the bottom of a horizontally laid pipe.

As in a typical differential-pressure flowmeter, the pressure upstream (approximately one pipe diameter from the plate) is compared with the pressure downstream where the flow converges to the point of narrowest stream flow. The narrowest section of flow, the

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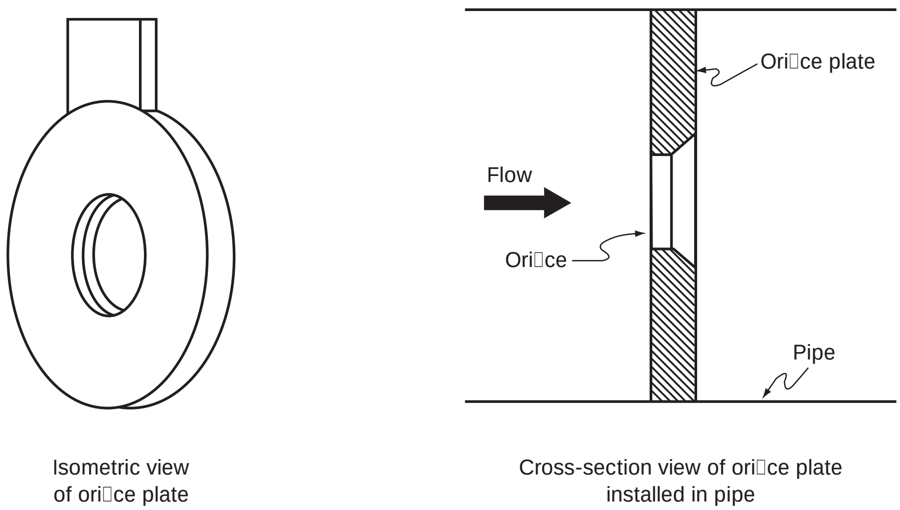

Figure 2-2 Schematic of an orifice plate flowmeter

vena contracta, occurs one-half pipe diameter downstream from the plate. These points define where to locate the pressure taps.

To obtain an electrical flow measurement signal, the pressure at the ports is transferred to a differential-pressure transducer. The transducer is typically a flexible diaphragm with a small chamber where the two pressure lines from the meter tube are connected to the two sides. The pressures exert opposing forces on the diaphragm, causing deflection of the sides. To sense the diaphragm's deflection, a strain gauge or a variable-capacitance or variable-reluctance device is built into the transducer to generate an electrical signal proportional to the pressure difference. Direct reading of differential pressure is possible using a U-tube manometer or double-bellows gauge.

The combination of all the components associated with the measurement of flow in an orifice plate flowmeter is referred to as the *orifice plate flowmeter system*. For an orifice plate flowmeter to operate adequately, all system components associated with the measurement of flow must operate adequately.

Numerous eddies form downstream from the plate between the pipe wall and the *vena contracta,* causing kinetic energy to be dissipated as heat. This dissipation accounts for the medium to high relative head loss associated with the orifice plate flowmeter.

The orifice plate can be fabricated to accommodate any pipe size. Inherent accuracy, independent of pipe diameter errors and the differential-pressure sensor, may be ±1 percent.

Orifice plates are also available as part of integrated pipe assemblies, which include the plate, pipe length, pressure taps, and, in some cases, the differential pressure sensor and signal transmitter.

Installation

The orifice plate is usually mounted between two flanges. Manufacturers may extend the plate to include a tab above the edge of the pipe flange. The tab, suitable for a nameplate, may contain pertinent data on the specific installation and may identify the upstream side. To prevent errors in flow measurement, the gaskets should not protrude across the plate face beyond the inside pipe wall. Typically, the orifice plate flowmeter also requires a straight run of smooth flow before and after the plate. Pressure taps must be installed

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perpendicular to the pipe wall. For horizontal pipe runs, the pressure taps should be in the horizontal plane of the pipe centerline. Burrs and intrusions at the taps must be removed.

Maintenance

As a differential-pressure flowmeter with no moving parts, the orifice plate flowmeter requires maintenance similar to that of the Venturi. The orifice should be visually checked periodically to be sure its dimensions and sharp leading edge are unaffected by the flow. Degeneration of the sharp edge can result in significant measurement errors. Solids may collect behind the plate at the bottom, and gases may be trapped at the top. These may be easily cleared by removal of the plate. Some manufacturers provide special mounting devices to allow the orifice plate to be inserted and removed without interrupting the flow, which simplifies maintenance.

The pressure taps should also be examined for possible obstruction. The pressure-differential measurement assembly should be periodically checked.

Advantages and Disadvantages

Advantages of orifice plate flowmeters are as follows:

- Lowest-cost differential-pressure meter.
- Economically manufactured to very close tolerances.
- Easy to install and replace.
- No moving parts.

Disadvantages of orifice plate flowmeters are as follows:

- High permanent pressure loss through orifice plate can cause significant power costs.
- Volume flow is nonlinear.
- Rangeability is lower than with linear-output flowmeters.
- Longer upstream and downstream straight pipe runs are required than with other types of meters.
- Field calibration is usually required.

VENTURI FLOWMETERS

The Venturi (Figure 2-3) is a type of differential-pressure flowmeter. In the Venturi, a defined constriction (throat) in the meter body causes an increase in flow velocity at the constriction, resulting in a corresponding decrease in pressure in the throat. The ratio of throat diameter to pipe diameter (where the two pressure measurements are taken) is called the *beta ratio*. The difference in pressure between the connections upstream and at the constriction (throat) is proportional to the square of the flow. Flow is calculated from the square root of the measured pressure differential multiplied by a meter factor that accounts for dimensional units and discharge coefficient. The discharge coefficient takes into account contraction characteristics and pressure-tap location for a fully developed velocity profile within a range of Reynolds numbers.

To obtain an electrical flow measurement signal, the pressure at the ports is transferred to a differential-pressure (ΔP) transducer. The transducer is typically a flexible diaphragm with a small chamber; two pressure lines from the meter tube are connected to the two sides of the diaphragm. The pressures exert opposing forces on the diaphragm, causing deflection of the sides. To sense the diaphragm's deflection, a

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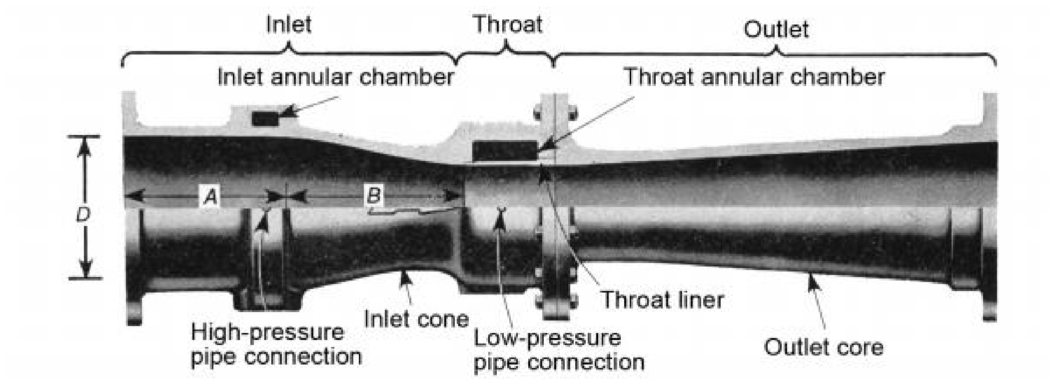

Figure 2-3 Schematic of one type of Venturi meter

strain gauge, or a variable capacitance or a variable reluctance device, is built into the transducer to generate an electrical signal proportional to the pressure difference. Direct reading of differential pressure is possible using a U-tube manometer or double-bellows gauge. The combination of all components associated with the measurement of flow in a Venturi flowmeter is referred to as the *Venturi system.* For a Venturi meter to operate adequately, it is important that all system components associated with the measurement of flow operate adequately.

The theoretical flow equation calculates the actual rate of flow only when all assumptions used to develop the flow equation are met. How closely the actual rate of flow can be calculated depends directly on the geometry of the reduced area. For a Venturi where the reduction is gradual, the agreement is roughly 1–3 percent if the velocity profile is uniform and the Reynolds numbers are high. At lower Reynolds numbers or with increasing viscosity, the velocity profile becomes one dimensional, expansion approaches adiabatic, and unless the effects are well modeled, inaccuracies will exist. The major distinction between the Venturi and many modified forms of this device is that the Venturi discharge coefficient is well known and well documented.

Venturis are normally not used when meters operate at low velocities. The Venturi has no theoretical range limitations up to the speed of sound. However, the flowmetering system, which includes the ΔP device, has definite limits. With the increased use of smart transmitters, the rangeability of the Venturi may be increased. Some Venturi meters provide a rangeability of 10:1 depending on the selection of the ΔP device.

The Venturi meter has a low permanent head loss and does not obstruct the flow of suspended matter. However, caution is urged when the device is used in applications conveying solids, and the manufacturer should be consulted for application assistance.

Commonly constructed from cast iron or plastic, the Venturi requires the greatest laying length of all differential-pressure meters and is, therefore, the heaviest flow tube as well. Fabricated-steel and insert-type Venturi meters are also available.

Installation

Consider the following factors in the selection process before installation:

- Select a meter that generates a high differential pressure (therefore, a small throat size), taking into account how much head loss can be tolerated. A good rule of thumb is to size the tube to provide at least 1 in. (25 mm) of differential pressure at

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the minimum anticipated flow. A high differential pressure provides the greatest energy to drive the instrumentation and improve the range and accuracy. Throat size is defined in terms of the beta ratio.

- Review the upstream piping configuration with respect to manufacturer's requirements. A Venturi is not strongly affected by the downstream configuration except for a slight increase in head loss.
- Consider future expansion of the facility, which may increase required flow.

The installation of a Venturi is critical to the accuracy of the differential-pressure measurement. Errors in computing flow may become unacceptable if distorted flow is present. Swirls or vortices in the flow that affect meter accuracy can be produced by a projecting gasket, misalignment, or a burr on a pressure tap.

The Venturi should be installed with its axis horizontal, and the fluid entering the tube should have a fully developed velocity profile free from swirls and vortices. In a horizontal installation, the pressure port taps must not be at the bottom (subject to clogging) or the top (subject to air-bubble trapping). The preferred location is on the side in the horizontal plane of the centerline. Two pressure lines of equal length should be installed and routed to prevent air or solids accumulation in the connection piping to the differential-pressure measuring device.

Maintenance

Having no moving parts, the Venturi would normally require less attention than, for example, a turbine meter. However, the pressure-differential assembly can have significant piping, fittings, and valves. Lines may clog and corrosion can appear, and so periodic disassembly, inspection, and cleaning should be practiced. The pressure sensors, in particular, should be removed and inspected. While the throat of the Venturi must be inspected for debris or deposits, the high fluid velocity usually scours the throat.

Manufacturers provide step-by-step instructions for checking the meter components. The procedures include disassembly, inspection and testing, parts replacement, and reassembly, with emphasis on the differential-pressure unit and electrical housing. Instructions for zero and span adjustment are also included. A troubleshooting guide may be provided with symptoms, potential sources, and recommended corrective action. To aid the user, illustrated drawings, schematic diagrams, and parts lists are provided in the manufacturer's manual. An example of a troubleshooting checklist for differential-pressure meters can be found at the end of this chapter.

Advantages and Disadvantages

Advantages of the Venturi meter are as follows:

- Life expectancy of a Venturi body, excluding the instrumentation, can be greater than 50 years.
- Simple construction; no moving parts.
- No sudden change in contour; no sharp corners.
- Relatively high pressure recovery in the outlet cone, yielding a low head loss and substantial power savings for large flows.
- Well documented in the literature as an acceptable type of flowmeter.

Disadvantages of the Venturi meter are as follows:

- Costlier to purchase and install larger units.
- The largest and heaviest of the differential-pressure meters.

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- Differential pressure is not linear with flow rate and requires square root extraction, which reduces rangeability.
- The coefficient of discharge becomes nonlinear (varies) for low Reynolds numbers (below 125,000 for an ASME-type Venturi; threshold varies for other Venturi types). The deviation is often predictable, however, and can be calculated using a linearizing device added to the output signal loop.
- If the Venturi is exposed to cold ambient temperatures, there is the potential for plugging of static lines with dirty fluids or freezing of static lines.

MODIFIED VENTURIS

Several flowmeters are derived from the Venturi and operate on the same principle. Classified as differential-pressure producers, they include flow tubes and a vast array of proprietary designs such as cones and wedges. The objective of any modification to the Venturi is to achieve shorter laying length, less cost, and higher head recovery. The length of the throat in the flow tubes is much shorter than in Venturi meters, which may result in a less stable flow pattern through the throat and reduce accuracy.

Flow Tubes

Although similar to the Venturi, the flow tube has a relatively short transition section from the inlet to the throat (see Figure 2-4) and a recovery cone of gradually increasing diameter. The flow tube causes significantly less pressure drop than the orifice plate flowmeter, but it is costlier. With its shortened inlet section, the flow tube is usually less expensive than the Venturi for the same line size. The body structure does not provide hydraulic profile conditioning and is therefore more sensitive to upstream flow disturbances.

A very low head loss, one lower than that of a comparable Venturi with the same beta ratio, has been achieved by the low-loss flow tube design. The head loss of the tube is a percentage of the differential pressure, based on throat size.

Flow tubes are typically proprietary designs, and the user should be careful to apply the meter within the calibrated ranges. Supporting application data are generally available only from the manufacturer.

Because construction materials for the flow tube are the same as those for the Venturi, long life may be anticipated. The accuracy is ±0.75 percent of the flow rate, and the range, like that of the Venturi, is limited only by the associated instruments. The coefficient of discharge also varies with low Reynolds numbers. If that variability is not accounted for, measurement accuracy is less certain.

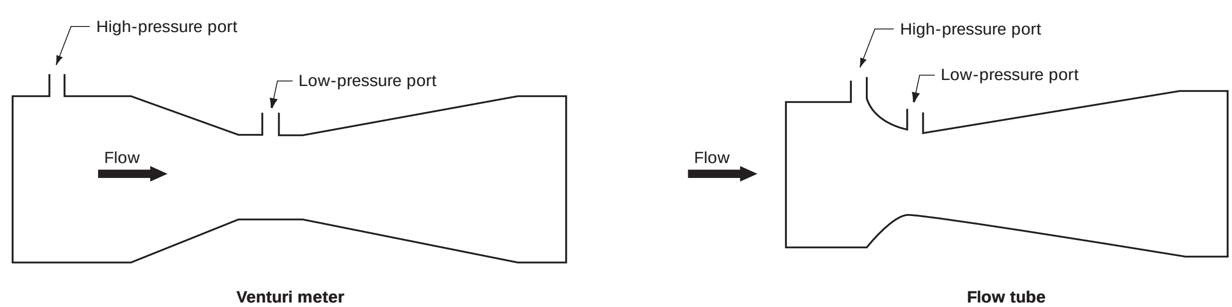

Figure 2-4 Location of pressure ports in Venturi meter and flow tube

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Insert Flow Tubes

Another variation of the Venturi meter is the insert flow tube. The convenience of the unit is based on its short laying length, single mounting flange with no inlet cone upstream of the flange, and low head loss. Most often the high-pressure and low-pressure metering taps are built into the flange, with the high-pressure (upstream) tap being a modified design known as a *corner tap*. This is done for convenience when installing the tube, but it does alter the performance characteristics somewhat. To correct this, the high-pressure (upstream) tap in the uniform pipe section is often installed just upstream from the tube. If this is done according to the manufacturer's instructions, it can produce a performance comparable to the flanged-end Venturi type from which the design was modified. It also allows both the low-pressure and high-pressure taps to be cleaned out (if they plug) without removing the tube from the line.

Additional meters derived from the Venturi operate on the same principle but use substantially different flow geometries. Meters in this category would include those with cones suspended within the flow stream and tapered protrusions forming an asymmetric *necking-down* of the flow stream.

AVERAGING PITOT FLOWMETERS

An averaging Pitot flowmeter operates on the principle of differential pressure. The averaging Pitot flowmeter consists of an insertion tube, or probe, that is placed along a diameter through the pipe cross section (Figure 2-5). Multiple ports face upstream into the flow to provide sampled pressures at selected points along the vertical pipe diameter. The multiple pressures are sensed as an interpolated average by the internal tube to provide an averaged pressure over the pipe cross section. A port or ports facing downstream register static pressure. The device produces a differential pressure between the averaged velocity head ports and the static head port(s). As with the Venturi flowmeter, the fluid velocity is proportional to the square root of the differential between the resultant upstream pressure and the static pressure.

Accuracy for a Pitot meter is ±1 percent of full scale. The meter's range is greatly limited by the sensitivity of the differential-pressure sensor and the results obtainable for low differential. The meter, by nature, is velocity-profile sensitive. If the meter is placed

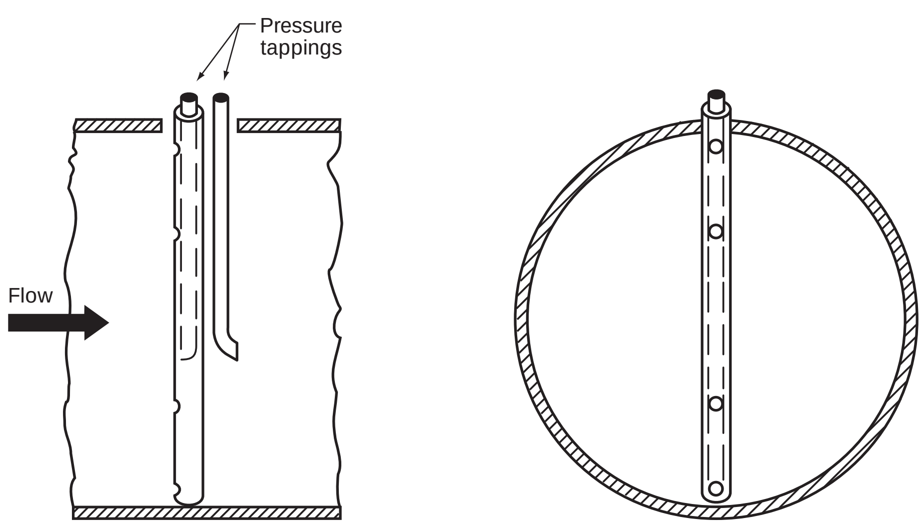

Figure 2-5 Schematic of an averaging Pitot flowmeter insertion tube

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in different planes at the same point in a pipe, different readings may result. Laboratory calibration is not valid for field conditions unless the pipe configuration is duplicated.

According to manufacturers, the shape of the insertion tube causes most foreign material to flow around the probe rather than accumulate on it. Ordinarily, material that does affect the probe does not significantly affect meter performance unless, in extreme cases, the ports are completely obstructed or buildup changes the outside shape.

Installation

The insertion tube must be installed in the pipe according to the manufacturer's instructions. Deviation from perpendicular to the axis of the pipe in any direction affects the sensed pressures. Misalignment of the tube from the diameter beyond 3° in the pipe cross-sectional plane or 5° upstream or downstream out of the cross-sectional plane causes significant error. Rotation of the tube beyond 3° from a strict upstream–downstream orientation also causes errors in the sensed pressure.

The correct size insertion tube must be installed in the correct size pipe. The location of the ports on the insertion tube is based on the pipe's inside diameter and wall thickness. If the tube is installed in the proper size line with the proper fittings, its sensing ports will be at their correct locations, and the meter will respond with the designed accuracy. If the tube is inserted in an incorrect line size, it can be expected to provide a repeatable signal, but it must be recalibrated to yield accurate flow measurements.

The location of tube ports is based on a fully developed turbulent flow, with a velocity profile that is consistent across the pipe in all directions. The averaging of pressures will be incorrect in an inconsistent flow profile, and errors in flow measurement will result. Upstream conditions, such as changes in pipe diameter and the presence of valves or elbows, influence the flow profile. Therefore, as with other meters, sufficient lengths of pipe must be provided upstream of the insertion tube to allow the turbulent flow profile to develop. Flow straighteners may be used to reduce the necessary length of straight pipe upstream. Tables of recommended upstream and downstream straight pipe lengths are provided by manufacturers. Upstream lengths vary from 7 to 24 pipe diameters without a straightener and 3 to 9 pipe diameters with a straightener. Downstream straight pipe lengths vary from 3 to 4 pipe diameters.

Maintenance

The probe should be removed and cleaned periodically. Probe removal does not require shutting down the system. Sensing ports and internal passages can be cleaned using external pressure without being removed. The manufacturer's recommendations should be followed in cleaning the probe. The sensor design will handle most flow conditions without clogging. Nevertheless, if the fluid is contaminated, periodic purging of the internal passages may be necessary. Designs can be provided to facilitate purging.

Advantages and Disadvantages

Advantages of averaging Pitot flowmeters are as follows:

- They can be removed without shutting down the system (hot tap option).
- Nonconstricting design produces low head losses.
- Meter cost is low.
- They are easily installed at any time by making a wet tap in the pipeline.
- Materials of construction and the nature of the parts provide for long life.

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Disadvantages of averaging Pitot flowmeters are as follows:

- Any leaks in the instrument lines or connections will significantly affect the meter accuracy, because the flow measurement depends on the comparison of two pressures generated by the flow past the device, and the pressure change may be small.
- Potential exists for calibration error caused by misalignment of the insertion tube.
- Flow rate calculations require square root extraction.

VARIABLE AREA FLOWMETERS

The variable area meter, also known as the *rotameter*, is a variation on the differential-pressure meter. The area through which the liquid flows is permitted to vary so that a constant differential pressure is maintained. This is achieved through the construction and application of the meter. The basic elements of the rotameter are a tapered (conical) tube, vertically oriented, and a cylindrical float, free to rise and fall in the tube. The metering tube is mounted in a vertical position with the tapered end at the bottom where the fluid to be measured enters. The fluid rises, filling the tube, and passes through an annulus of area around the float and out the top of the tube (see Figure 2-6). The greater the entering volumetric flow, the larger the required annulus area and the higher the float rises. Therefore, the rise is proportional to the rate of flow. In a simple rotameter, the tube body is properly tapered to provide a linear flow scale to reflect the position of the float.

Figure 2-6 Variable area flowmeter

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Typically, the tube is transparent, of glass or plastic, engraved with a scale calibrated in the selected units of flow.

Under the no-flow condition, the float rests at the bottom of the tube. During flow, the forces acting on the float are its weight, buoyant force of the liquid on the float, and the pressure forces acting below and above the float. These forces combine to maintain the pressure drop across the float equal to the effects of gravity and buoyancy acting on it. For a given fluid, the immersed weight of the float is constant; therefore, at equilibrium, the pressure drop or differential pressure across the float is constant. Increasing the flow upsets this balance, increasing the upward force and raising the float to provide a wider annulus to pass the flow. The rising float and increasing annulus area allow the fluid velocity and its associated pressure and upward force to decrease until the forces on the float are in equilibrium and the float stops. When the velocity decreases, the upward velocity pressure follows suit, and the float begins dropping until the decreasing annulus allows the velocity and its resultant pressure to bring the forces back into equilibrium.

The float is fitted with grooves or vanes that cause the flowing liquid to impart rotation to the float. This gyroscopic stabilizing action maintains the float in a central coaxial position with the tube during its up-and-down motion.

Although the tapered tube is usually transparent, in some applications the float is not visible, such as for an opaque fluid or where a metallic tube is used. A metallic tube may be required in cases of large flow volume or flow under high pressure. The float position is detected by magnetic or electrical techniques to enable external metering of the flow.

As with other flowmeters, rotameter installations that can transmit pneumatic or electronic signals to connect to recorders, totalizers, controllers, and process computers are available.

Installation

Rotameters are simple to install. They are fabricated in a variety of construction materials to withstand a wide range of pressures and temperatures.

Rotameter manufacturers provide end fittings and connections of various materials and styles to meet customer requirements. Safety-shielded glass tubes are in general use throughout the industry. End fittings may be metal or plastic to meet the chemical characteristics of the fluid to be measured. Care must be taken in plastic fitting installations to avoid distortion of the threads.

Plastic tubes are also available in rotameter designs because of their lower cost and high impact strength.

Liquid measurement rotameters are usually provided with a direct reading scale and calibration data for water. If the same meter is applied to other fluids, recalibration will be necessary.

Maintenance

Maintenance of rotameters is relatively simple. Where there is potential for dirty flow, an upstream strainer is usually recommended, along with periodic cleaning. If shutdown is prohibitive, a bypass pipe may be used to allow flow to continue if the meter is to be removed for maintenance or replacement.

Advantages and Disadvantages

Advantages of variable area flowmeters are as follows:

- Low cost.
- Ease of installation.

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- Low maintenance.
- Ease of reading the measurement.
- Easy detection of faulty operation.
- Relatively long measurement range.
- Flow straighteners not required.
- Special upstream or downstream conditions not required.
- Relatively low and constant pressure drop.
- Nearly constant overall pressure loss.

Disadvantages of variable area flowmeters are as follows:

- Vertical installation required.
- Not suitable for dirty fluids.
- Not suitable for fluids with suspended solids.
- Relative fragility of device.
- Transparent metering tubes subject to pressure and temperature limits.
- Readings affected by changes in density or viscosity.

MAGNETIC FLOWMETERS

A magnetic flowmeter operates on the principle of Faraday's Law of Magnetic Induction. In a magnetic flowmeter, a magnetic field is generated around an insulated section of pipe (Figure 2-7). Water passing through the magnetic field induces a small electric current that is proportional to flow velocity. The electric current is measured and converted to a numerical indication of flow. The liquid moving through the meter must have sufficient ion content to provide a minimum electrical conductivity. Water treatment plant flows meet this conductivity requirement.

Typically, meter accuracy is +0.50 percent of actual flow when the meter performance range is limited to higher velocities and/or to modest turndowns on the order of 20:1. When operating over wide flow ranges, specifically at low flow velocities, an accuracy of +2 percent could be expected. Minimum flow velocities that can be accurately measured at these wider error limits may be on the order of 0.1 ft/s (0.03 m/s) or 0.4 ft/s (0.1 m/s), depending on the specific meter design. Maximum operating velocities may be as high as 35 ft/s (11 m/s), while maximum allowable velocities in many treatment or distribution systems would be closer to 10 ft/s (3 m/s) or 15 ft/s (5 m/s).

The head loss across a magnetic flowmeter is that caused by the length of pipe forming the body of the meter. Head loss would be increased if the pipe diameter were reduced and a smaller meter is incorporated to raise flow velocity to an acceptable level, or if the meter design incorporated internal constriction in the cross-sectional area. Sizes of magnetic flowmeters range from 0.1 in. to 10 ft (2.5 mm to 3 m) in diameter.

Area averaging makes the magnetic flowmeter less sensitive than other types of flowmeters to profile changes. The magnetic meter does not have a discharge coefficient definable by its hydraulic shape. Consequently, all magnetic meters should be wet calibrated by the manufacturer.

Some of the advantages for this type of meter include its shorter laying length and lighter weight. The solid-state electronics that generate the flow signal have a long life.

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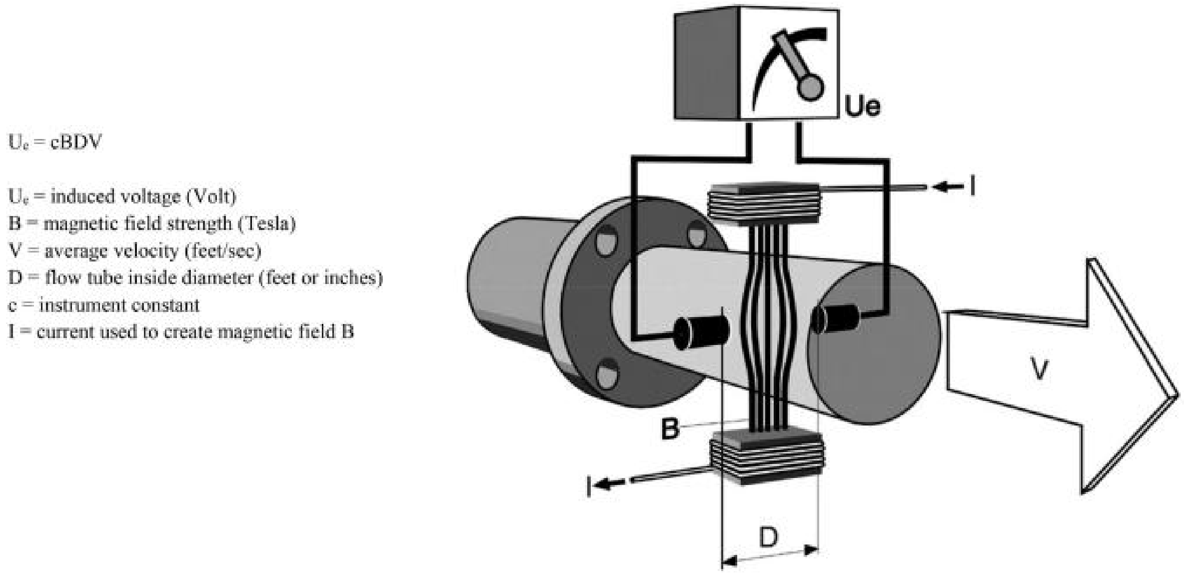

Figure 2-7 Schematic of a magnetic flowmeter

Installation

When a magnetic flowmeter is installed in a horizontal pipe section, its electrodes should be located at the ends of a horizontal diameter rather than a vertical diameter. This will ensure continued electrode immersion even when air bubbles are present. The meter must always run with full flow.

The following installation steps should be taken for the meter to function properly:

- Consider line size against minimum velocity.
- Provide suitable upstream and downstream piping length, as recommended by the meter manufacturer.
- Ensure proper grounding isolation between the meter body and the pipeline to avoid transient voltage interference.
- Provide 120 V alternating current (VAC) power input at about 100 W, if needed [models are available for 220 VAC and 24 V direct current (VDC)].
- Use electrical bonding strips to bypass the cathodic protection currents around the meter, if the meter is installed in a pipe that is part of an electro-galvanic corrosion-prevention system.
- Internal lining is critical to the application. Liners range from low-cost polyurethane to high-cost Teflon™. Consult the manufacturer for the liners most suitable to the application.

Maintenance

Some manufacturers provide special equipment for testing, troubleshooting, and recalibrating meters. Instructions and detailed diagrams are provided for disassembly and replacement of components. If a meter is considered irrepairable in the field and the instructions warn against tampering with the sealed portion of the unit, no routine maintenance is recommended. Service or installation problems should be referred to the manufacturer's service or field office. An example of a troubleshooting checklist for solid-state meters can be found at the end of this chapter.

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Electrode Cleaning

Deposits and incrustations, including calcium carbonate, on the meter's electrodes can impair accuracy, unless the deposits have the same conductivity as the fluid. Such deposits can cause variable or high resistance between the electrodes, thereby, introducing errors. Methods for cleaning the electrodes vary among the manufacturers.

The following cleaning factors may apply to magnetic flowmeter electrodes:

- Some electrodes may be removed for inspection, cleaning, and replacement without removing the meter from the line. Some magnetic flowmeters offer optional electronic electrode cleaning.
- Conical electrodes are available that extend into the flow stream where the scouring effect of the liquid velocity is more likely to inhibit coating.
- Continuous ultrasonic vibrations will prevent deposition of particulate and crystalline materials on the electrodes; however, this is not effective for grease deposits.
- Bypass piping to maintain flow may be included in the installation to allow for periodic inspection and cleaning of the meter's inner wall.

Recent advances in electronic signal conditioning have significantly reduced the effects of electrode fouling. Manufacturers now state that, except under unusual circumstances, cleaning of newer meters is not necessary for the meter to obtain a signal.

Advantages and Disadvantages

Advantages of magnetic flowmetering devices are as follows:

- They do not obstruct flow.
- There is minimum effective head loss, essentially that of the straight pipe equivalent of the meter (unless meter spool size is reduced from pipe size, causing head loss). Magnetic flowmeters are highly suitable for applications where low head loss is essential. For meter designs with internal constrictions, head loss will be increased.
- They are available over a wide range of sizes from 0.1 in. to 10 ft (2.5 mm to 3 m) in diameter.
- Because they are bidirectional, they are suitable for measuring reverse or net flows.
- Output signal is linear with flow velocity.
- Variations in fluid density, viscosity, pressure, and temperature have little effect on performance.
- Magnetic flowmeters are suitable for short runs of straight pipe upstream nonsymmetrical flow patterns, and flow disturbances, unless very severe, do not seriously affect the flow measurement.
- They can measure low flows.
- Because there are no wetted parts, magnetic flowmeters are relatively immune to freezing at the probe locations. (Although the electronics have temperature limits, they can be located remotely.)

Disadvantages of magnetic flowmetering devices are as follows:

- Metered liquid must have an electrical conductivity of 5 μS/cm or greater (this is not a problem with finished drinking water).
- For smaller pipe sizes, the meters become relatively bulky and expensive.

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- High accuracy is expensive, and each meter must be individually calibrated in a water test circuit.
- The meter is sensitive to the geometry and electric properties of the flow tube and magnetic core and is sensitive to variations in the coil supply current.

INSERTABLE FULL-PROFILE AVERAGING MAGNETIC FLOWMETERS

An insertable full-profile averaging magnetic flowmeter (Figure 2-8) has multiple magnetic fields, which are generated by electromagnetic coils placed inside a circular sensor that is inserted in the pipe section through a tap connection on the pipe wall. Water passing around each sensor encounters the magnetic field, which induces an electrical charge that is proportional to the velocity of the water passing through the magnetic field. This relationship is essentially linear. The electrical charge is sensed by multiple pairs of electrodes in contact with the water adjacent to each of the electromagnets. Each coil with its associated pair of electrodes becomes an electromagnetic velocity-sensing point along the sensor. The liquid moving through the magnetic fields must have sufficient ion content to provide a minimum electrical conductivity. Water treatment plant flows meet this conductivity requirement.

The electromagnetic velocity-sensing points are equally spaced across the sensor such that each point is in an equal area around the annulus of the pipe cross section (Figure 2-8). Because each measurement point is in the center of an equal area in the pipe, it effectively has a weighting factor equal to the area it represents. The various velocities at these points are continually averaged together and represent the area-weighted mean velocity present in the pipe. This value is converted into a numerical indication of the mean velocity and the rate of flow in the pipe cross section. This configuration allows the flowmeter to maintain excellent linearity over a wide range of Reynolds numbers and changes in the velocity profile.

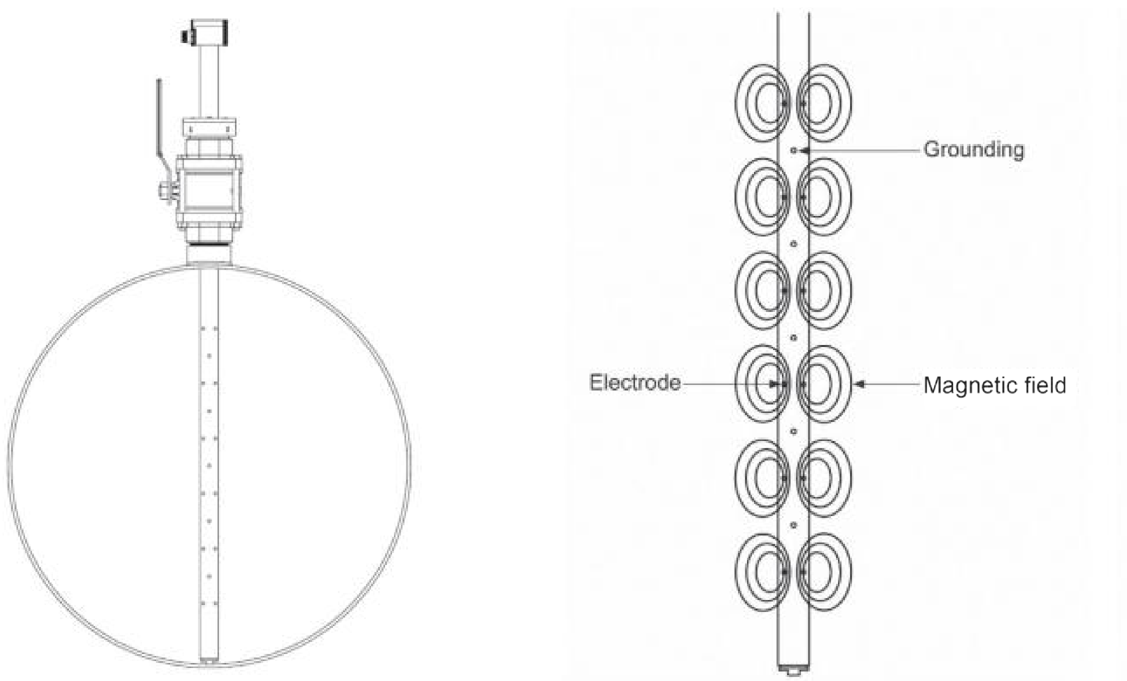

Figure 2-8 Schematic of an insertable averaging magnetic flowmeter

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The meter's accuracy is ±0.50 percent of the actual rate of flow over a velocity range of 1–35 ft/s (0.3–11 m/s). Although the magnetic flowmeter can sense very low velocity flows, its accuracy is reduced at low velocities. The range of a magnetic flowmeter is 20:1. Typical allowable velocity range in water treatment piping systems is from 0.1 ft/s (0.03 m/s) minimum to 10 ft/s (3 m/s) maximum.

The head loss across an insertable full-profile averaging magnetic flowmeter is low because of the streamlined shape of the sensor. It is not normally required to reduce pipe diameter and incorporate a smaller meter to raise the flow velocity.

Because this flowmeter is sensing and adjusting for velocity variations in multiple areas of the pipe, it is less sensitive to profile changes than other types of flowmeters.

Some advantages for this type of meter include its shorter laying length and its lighter weight. The meter can be installed through a pipe tap without interrupting the flow to users. The solid-state electronics that generate the flow signal have a long life.

Installation

An insertable full-profile averaging magnetic flowmeter may be installed in horizontal or vertical pipes at any angle if the pipe is full and there is adequate straight pipe run. The manufacturer's recommendations should be followed when installing a meter close to elbows, butterfly valves, or other flow disturbances. It is preferable to insert the flowmeter perpendicular to the plane of upstream elbows. Sensors are sized for the diameter of the pipe where they will be used. Care should be taken to ensure the sensor is sized properly for the pipe internal diameter (ID) and that adequate clearance exists for insertion and removal of the sensor. To allow insertion and removal without interrupting the flow, an isolation valve must be installed between the pipe tap and the compression seal of the flowmeter sensor. Applications containing debris such as grasses or leaves should be avoided, as these materials wrap around the sensor and necessitate frequent removal of the sensor for cleaning. Moderate amounts of sand and grit are not a problem. The meter must always run in a full-pipe condition to maintain specified accuracy.

Maintenance

Electrode or sensor cleaning is not normally required in potable water. Raw water containing concentrations of manganese, iron, or solid debris may require periodic removal of the sensor from the tap for cleaning. An example of a troubleshooting checklist for solid-state meters can be found at the end of this chapter.

Advantages and Disadvantages

Advantages of insertable full-profile averaging magnetic flowmeters are as follows:

- They can be installed and removed without interrupting the flow.
- Total installation cost is low.
- Accuracy is maintained in short runs of straight pipe because the distorted profile in the pipe is sensed and averaged over the full profile.
- Obstruction to flow is minimal.
- Effective head loss is minimal.
- They are available over a wide range of sizes from 4 in. to 10 ft. (100 mm to 3 m) in diameter.
- Bidirectional versions are available.
- Output signal is linear with flow velocity.

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- Variations in fluid density, viscosity, pressure, and temperature have little effect on performance.
- They can measure low flows.

Disadvantages of insertable full-profile averaging magnetic flowmeters are as follows:

- Meter accuracy relies on accurate knowledge of the pipe ID where the meter will be installed.
- Metered liquid must have an electrical conductivity of 10 μS/cm or greater (this is not a problem with finished drinking water).
- For smaller pipe sizes, the meters may become relatively expensive.
- The meter is not suitable for flows that contain solid debris such as rags, leaves, and grasses.

TRANSIT-TIME ULTRASONIC FLOWMETERS

A transit-time ultrasonic flowmeter compares the time differences of generated sound waves within a pipe. In a transit-time sonic (or ultrasonic) flowmeter, a pair(s) of transceivers (transmitter–receiver) is positioned across the meter body. This can be done by mounting a pair(s) of transducers either diagonally across the meter body (Figure 2-9) or on the same side of the meter using a multipath ultrasonic transmission path or a flow insert tube. The transceivers transmit and receive an ultrasonic pulse in the direction of flow, followed by a return pulse against the direction of flow. In a flowing liquid, the speed of the pulse directed downstream is increased by the speed of the stream. When directed upstream, the speed of the pulse is slowed by the stream flow. The time difference between the two pulse transmissions through the stream is a function of fluid velocity and by computation, the rate of flow. The transit-time difference and a given value of pipe diameter are converted by a microprocessor circuit in the meter to a standard output signal for volume flow. This sonic meter, used to measure the flow of clean water, is known as a *time-of-flight, transit-time,* or *through-transmission meter.* The transit-time ultrasonic meter accuracy is ±0.50 percent of rate over a 20:1 range. Accuracy must be checked in the manufacturer’s literature, because some manufacturers cite accuracy in terms of percent full scale.

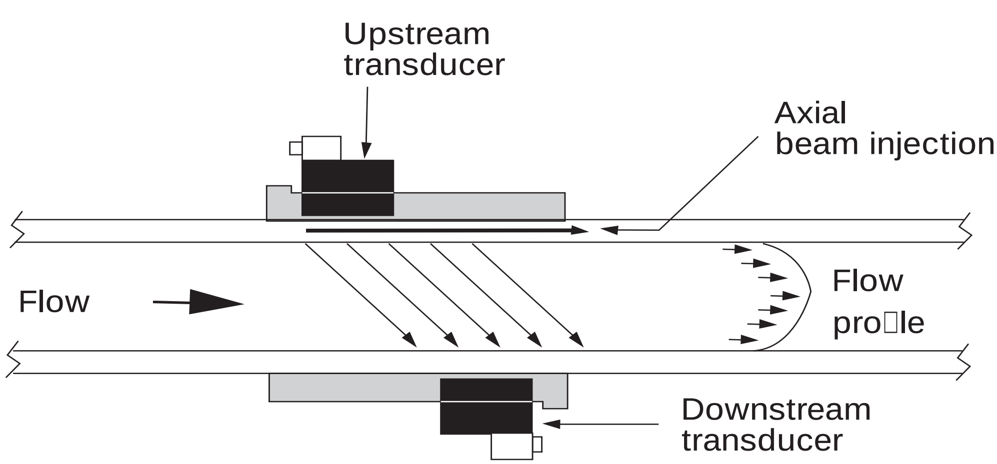

Figure 2-9 Schematic of a transit-time ultrasonic flowmeter

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Because transit-time ultrasonic flowmeters and electronic flowmeters use microprocessor circuits to generate and record flow, special digital features can be incorporated into the unit. An electronic digital display can indicate operation information or alarms. The user can select output units, ranges, totalizing, and the type of signal transmission.

The head loss of the meter is no more than that of an equivalent length of pipe. When flow rates are low, a less than line-size meter may be used, which introduces some additional head loss. Head loss is increased in meters with internal constrictions.

Depending on the internal geometry of the meter, flow conditioning may not be required. Therefore, any profile error caused by the piping configuration is carried through the meter and picked up by its velocity-sensing system. However, flow straighteners may alleviate the problem of turbulence. Some transit-time ultrasonic meters use a single-path sensor system that requires more careful layout of upstream piping. To minimize profile sensitivity, some meters have multiple-path sensing to average out the fluid profile error and thus increase accuracy.

Installation

For proper performance, provide suitable upstream and downstream piping length, as recommended by the meter manufacturer. The length of a straight run may differ with varying piping configurations and manufacturers. The meter should not be located near the point of a sudden pressure drop that might release minute quantities of gas from the liquid. Some transit-time ultrasonic meters cannot function accurately when gas bubbles are present. Isolate piping from noise and vibration that might interfere with the sound propagation of the meter.

Transit-time ultrasonic meters are available in two forms: a spool piece with integral transceivers or a transceiver assembly for clamp-on mounting outside an existing pipe.

Maintenance

Maintenance of transit-time ultrasonic flowmeters is minimal. They should have a long operational life because of unobstructed flow, solid-state circuitry, and nonmoving parts. Built-in electronic self-diagnostics generate circuit tests and display functions, and plug-in modular construction permits rapid replacement of defective parts.

Maintenance procedures are executed through the microprocessor, checking and adjusting the 4 and 20 mA output levels and the level of the transmitted and received signals. A low signal level may indicate incorrect transducer installation, obscured sonic path (bubbles and solids), sedimentation, or cabling fault. An example of a troubleshooting checklist for solid-state meters can be found at the end of this chapter.

Advantages and Disadvantages

Advantages of transit-time ultrasonic flowmeters are as follows:

- Ultrasonic meters with no obstruction to flow have no head loss. Ultrasonic meters with minimal obstruction or pipe reduction have minimal head loss.
- They are not restricted to use with conductive liquids (as are magnetic flowmeters).
- Clamp-mounted meters do not jeopardize the pipe-wall structure.
- Clamp-mounted meters do not interrupt process flow during maintenance or replacement.
- There are no mechanical moving parts.
- Linear output is over a wide range.
- The flowmeter is adaptable to a wide range of pipe diameters.

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- Flow readings are accurate down to 0.1 ft/s (0.03 m/s).
- Installation and operating costs are low.
- Bidirectional flow is allowable.

Disadvantages of transit-time ultrasonic flowmeters are as follows:

- They are sensitive to change in fluid composition.
- High solids content or entrained bubbles distort and block propagation of sound waves.
- They measure mean velocity across a diameter, which is not the same as the weighted mean velocity.
- These meters are sensitive to flow-velocity profile; accuracy can be impaired by changes in pipe-wall roughness and by changes from laminar to turbulent flow.
- Accuracy is impaired by upstream and downstream flow disturbances (e.g., elbows and valves) that affect the velocity profile.
- Positioning of the opposing transceivers is critical to ensure signal interception.
- In clamp-mounted use, the presence of sound-absorptive or scattering scale or coating on the pipe's inner walls may prevent the meter from working. (This is not true when transceivers are mounted through the wall on a spool piece.)
- They are sensitive to noise and vibration.

VORTEX FLOWMETERS

A vortex meter operates on a principle of vibrations generated in a fluid stream created by vortices around a bluff body in the flow stream. In a vortex flowmeter, a nonstreamlined or bluff body (the vortex-shedding element) obstructs and splits the flow through the pipe, forcing two streams around the barrier and creates (or sheds) vortices downstream in the flow. These vortices are caused by the swirling of the fluid into the low-pressure area behind the body (see Figure 2-10). The shedding vortices alternately rotate in opposite directions, with the spacing between them proportional to the fluid velocity. This also creates an oscillating pressure variation from side to side of the immersed vortex-shedding element.

Numerous methods are available to measure the frequency of the vortex-train or the pressure oscillations. In all cases, external electronics convert the frequency signal into a standard analog value proportional to the flow velocity or into a digital output suitable for input to a totalizer.

Accuracy of vortex flowmeters is ±0.75 percent of rate, with a repeatability of better than ±0.50 percent. Maximum flow rate is approximately 15 ft/s (5 m/s), with a range of 25:1. The flow range is a function of pipe size, depending on the Reynolds number and cavitation in the pipe.

Head loss is somewhat higher than in that of an unobstructed pipe because of the presence of the vortex element. The added loss is equivalent to about 4 psi (28 kPa) at maximum flow.

The frequency/flow characteristic in the pipe is a function only of the shape of the body. Consequently, a generic coefficient can be used for all meters having the same body profile, regardless of pipe size.

Pipe sizes used with vortex flowmeters range from ¼ to 10 in. (6–250 mm), and larger sizes can be used. The maximum size of pipe depends on the pulse frequency per unit volume. This limit exists because in larger pipes, the full-scale frequency may be too low to enable the signal-conditioning electronics to make acceptably accurate measurements.

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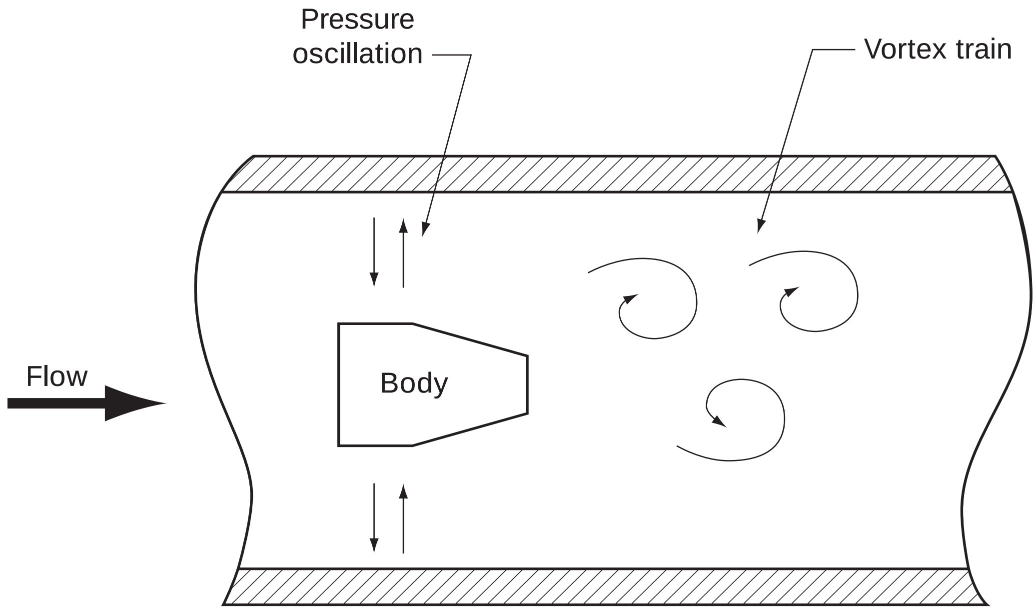

Figure 2-10 Schematic of a vortex flowmeter

The vortex meter has no moving parts, and only the spool piece and body are exposed to the fluid. It is typically constructed of stainless steel and thus has relatively low maintenance requirements.

Installation

The vortex meter requires a fully developed flow profile, which means that upstream disturbances must be minimized. An upstream straight pipe length of at least 10 diameters is desirable, and flow straighteners may be needed where severe disturbances are present. Use a length of 5 diameters of straight pipe downstream to minimize the effects of disturbances on the vortex train. Severe vibration of the pipe caused by *noisy* pumps and valves and the continued presence of bubble streams can affect meter accuracy by introducing false signals into the sensing elements. These problems must be considered before installing the meter.

Maintenance

Manufacturers provide flowcharts of troubleshooting instructions and related diagrams to isolate and remedy the problem of meter failure. An example of a troubleshooting checklist for vortex meters can be found at the end of this chapter as part of the text box "Troubleshooting Solid-State Meters."

Meter parts are usually removable and replaceable in the field, according to detailed procedures found in instruction manuals. These may include the vortex-shedding element, the sensor assembly, and output signal electronics. Often, the electronics and sensor can be replaced without interrupting pipe flow.

Because it has no moving parts, the installed fixed assembly of meter spool and vortex shedder requires virtually no maintenance. This assumes that installation is done according to the manufacturer's instructions regarding orientation, alignment, piping connections, ambient conditions, power connections, wiring, and flow range applications.

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Detailed maintenance instructions usually refer to electronic adjustments such as zero, span, noise balance, and minimum measurable velocity. However, all such adjustments, while explained in the meter manual, are set in the factory and should not be altered after proper installation.

Advantages and Disadvantages

Advantages of vortex flowmeters are as follows:

- Low head loss.
- No moving parts.
- Long-life construction.
- High turndown ratio or rangeability (the ratio of the maximum design flow rate to the minimum design flow rate).
- Simplicity in design and installation.

Disadvantages of vortex flowmeters are as follows:

- Sensitivity to flow profile distortion.
- Influence of pipe vibration and bubble streams.
- Not bidirectional.
- Limited range of pipe size.
- Flow below low-flow cutoff velocity cannot be measured.

CORIOLIS FLOWMETERS

Coriolis flowmeters operate on the principle of the bending force known as the *Coriolis effect*. The Coriolis effect occurs when a particle in a rotating plane moves in a direction toward or away from the center of rotation, and the particle generates an inertial force (known as the *Coriolis force*) that acts on the body.

In the Coriolis flowmeter, a rotating body is created by vibrating a tube or tubes through which the fluid or particles flow toward or away from the center of rotation. Figure 2-11 illustrates the inertial forces created by fluid particles through a straight tube as its center is rotated upward. As the tube moves upward, the fluid particles accelerate from a horizontal path of left to right to an upward path. Similar to the forces felt by a

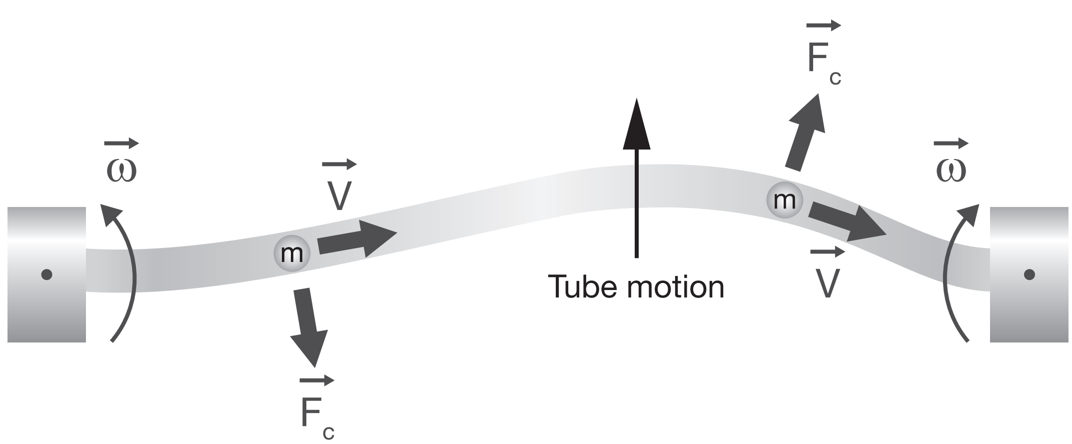

Figure 2-11 Coriolis effect

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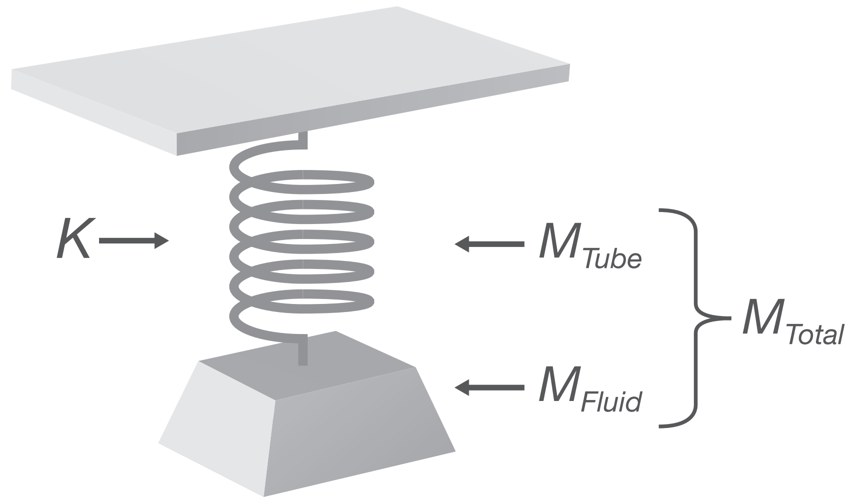

Figure 2-12 Spring mass system

person sitting in the seat of a car as it travels around a corner, the fluid particles resist the change in flow direction and exert an inertial force proportional to their weight and angular velocity downward in opposition to the upward rotation of the tube. As the fluid particles travel through the tube, they complete their upward acceleration and are then redirected downward to the flow tube's outlet. Likewise, the fluid particles resist this change in direction and impart a force upward in opposition to the downward change in direction.

Due to downward inertial force at the inlet of the tube and upward inertial force at the outlet, a torque around the midpoint of the tube is created, causing it to twist. The amount of twist depends on the magnitude of the opposing inertial forces (i.e., mass flow rate) and the stiffness of the flow tube. The twist is proportional to the mass flow rate.

Independent of mass-flow measurement, a Coriolis meter can also measure density. A Coriolis flow sensor can be considered a simple spring mass system (Figure 2-12). The flow tube(s) acts as a simple spring, where the mass of the tube (M_{tube}) and the mass of the fluid in the tube (M_{fluid}) make up the total mass of the flow tube (M_{total}), and K is the stiffness of the tube.

Resonance of a spring mass system is such that

$$\omega = \frac{1}{2\pi}\sqrt{\frac{K}{M_{\text{total}}}} \qquad \text{(Eq 2-1)}$$

As shown, the resonant frequency ω of the system varies proportionally with the square root of the system's stiffness divided by its total weight. Simplifying the relationship and identifying the different mass components in a Coriolis system, we arrive at Eq 2-2:

$$\omega \propto \sqrt{\frac{K}{M_{\text{tube}} + M_{\text{fluid}}}} \qquad \text{(Eq 2-2)}$$

Rearranging the relationship to isolate the mass of the fluid (M_{fluid}) in the tube(s), we arrive at Eq 2-3, which is the basis for the determination of fluid density.

$$M_{\text{fluid}} \propto \frac{K}{\omega^2} - M_{\text{tube}} \qquad \text{(Eq 2-3)}$$

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The relationship between the mass of fluid in the tube (M_{fluid}) and the volume of the tube (V_{tube}) is made to arrive at the fluid's density (ρ_{fluid}) by means of Eq 2-4.

$$\rho_{fluid} = \frac{M_{fluid}}{V_{tube}} \tag{Eq 2-4}$$

Since a Coriolis meter measures the mass and density of a fluid at flowing conditions ($\rho_{P\&T}$), the volume of the fluid at flowing conditions ($V_{P\&T}$) can be determined by Eq 2-5.

$$V_{P\&T} = \frac{mass}{\rho_{P\&T}} \tag{Eq 2-5}$$

The ability of a Coriolis meter to determine an accurate fluid volume at flowing conditions depends largely on the accuracy of the meter's density measurement. Accuracies vary depending on meter design and construction, but an accuracy of ±0.0005 gm/cc is typical of high-performance designs. By relating this accuracy to the density of different fluids, the feasibility of flowing-volume measurement by a Coriolis meter can be determined.

As an example, the density of water at reference conditions is 1.0 gm/cc. An error of ±0.0005 gm/cc in its density measurement would equate to a density accuracy of ±0.05 percent. Thus, using the flowing-density measurement of a Coriolis meter to arrive at a flowing-volume measurement could induce a small 0.05 percent error in the measurement of water. This is typically the case for most liquids.

The typical accuracy of Coriolis flowmeters is ±0.1 percent of rate, with a repeatability of better than ±0.05 percent over a range of 20:1 of the manufacturer's full scale. The flow range is a function of pipe size.

Head loss with a Coriolis flowmeter is higher than that of an open-pipe flowmeter because of the presence of a flow splitter and the use of tubes with a combined area that is smaller than the installed line size.

Coriolis flowmeter pipe sizes range from $\frac{1}{24}$ in. to 16 in. (25,400 mm). The Coriolis flowmeters are commonly installed in larger-diameter pipes. Larger pipes are used in the installations because the meters can accommodate higher velocities in the tubes of the meter than other types of flowmeters commonly applied in larger pipes. In piped systems, the use of flowmeters that are one size smaller in diameter is common. The smaller meter improves the rangeability and performance of the measuring system such that the Coriolis meters are often used for leak detection.

The Coriolis meter commonly has two flow tubes through which all the fluid flows, although single-tube Coriolis meters are used in specialty applications. The flow tubes are vibrated at their resonant frequency. The meter is typically constructed of stainless steel, resulting in relatively low maintenance requirements.

Installation

The Coriolis meter is not influenced by flow profile. There are no upstream or downstream straight pipe length requirements, and no flow straighteners are needed. Severe vibration of the pipe caused by *noisy* pumps and valves does not affect operation. However, as with all other flowmeter technologies, the presence of bubble streams and partially filled pipe flow can affect meter accuracy by introducing false flow signals. These problems must be considered before installing the meter.

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Maintenance

If a failure occurs, troubleshooting instructions are provided by the manufacturer to isolate and remedy the problem. Most manufacturers incorporate diagnostic systems in flowmeter electronics. In general, the electronic transmitter circuit boards and display (if available) are removable and replaceable in the field, according to detailed procedures found in the instruction manuals. The flowmeter sensor-tube assembly is typically welded closed to prevent physical or environmental damage to the internal sensor wiring and to prolong the life of the assembly. The electronics can be replaced without interrupting pipe flow.

Because it has no moving parts, the flowmeter's installed fixed sensor-tube assembly requires virtually no maintenance. This assumes that installation is done according to the manufacturer's instructions regarding orientation, alignment, piping connections, ambient conditions, power connections, wiring, and flow-range applications. An example of a troubleshooting checklist for solid-state meters can be found at the end of this chapter.

Advantages and Disadvantages

Advantages of Coriolis flowmeters are as follows:

- No moving parts.
- Insensitive to flow profile distortion.
- Long-life construction.
- High turndown ratio or rangeability (the ratio of the maximum design flow rate to the minimum design flow rate).
- Bidirectional.
- Simplicity in design and installation.
- No strainers needed.

Disadvantages of Coriolis flowmeters are as follows:

- Head loss.
- Performance affected by pipe stresses, bubble streams, and partially full pipe flow.
- Limited range of pipe size.
- High initial cost.

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Troubleshooting—Mechanical Meters

INTRODUCTION

Mechanical meter system malfunctions are usually restricted to two areas: electrical/electronic or mechanical. When a malfunction or an apparent malfunction occurs, the electrical and electronic systems should first be thoroughly checked in accordance with the manufacturer's recommended procedures prior to checkout of the meter. Only when the source of the malfunction cannot be found in the electrical or electronic systems should the meter be inspected.

SYMPTOM: Low Output or No Output

POTENTIAL SOURCE AND CORRECTIVE ACTION

NOTE: Verify that the proper K-factor value is entered if connected to an electronic readout device. If a mechanical register is used on the meter, verify that the register gear ratio is correct for the meter size and model.

1. **Primary Element**
   - ☐ Check for foreign material collected on the measuring element.
   - ☐ Check for excessive wear.
2. **Piping and Installation**
   - ☐ Check that isolation valves are fully open and bypass valve, if installed, is closed.
   - ☐ Check for entrapped gas in liquid lines and for liquid in dry lines.
   - ☐ Check that the density of fluid in impulse lines is unchanged.
   - ☐ Check for sufficient upstream and downstream piping, as recommended by manufacturer.
3. **Electronic Connections**
   - ☐ Check for adequate voltage to the transmitter.
   - ☐ Check for shorts and multiple grounds.
   - ☐ Check polarity of connections.
   - ☐ Check loop impedance.
   - ☐ NOTE: Do not use over 100 V to check the loop.

SYMPTOM: High Output

POTENTIAL SOURCE AND CORRECTIVE ACTION

NOTE: Verify that the proper K-factor value is entered if connected to an electronic readout device. If a mechanical register is used on the meter, verify that the register gear ratio is correct for the meter size and model.

1. **Primary Element**
   - ☐ Check for foreign material collected on the measuring element.
2. **Electronic Connections**
   - ☐ Check for adequate voltage to the transmitter.
   - ☐ Check for proper ground.
   - ☐ Check for shorts and multiple grounds.
   - ☐ Check polarity of connections.
   - ☐ Check loop impedance.
   - ☐ Check output scaling or signal conditioning.
   - ☐ NOTE: Do not use over 100 V to check the loop.
3. **Piping and Installation**
   - ☐ Check that pressure connection is correct.
   - ☐ Check for leaks or blockage in screen or strainer.
   - ☐ Check for entrapped gas in liquid lines.
   - ☐ Check that isolation valves are fully open and that bypass valves are tightly closed.
   - ☐ Check that the density of fluid in piping is unchanged.
   - ☐ Check for sufficient upstream and downstream piping, as recommended by manufacturer.

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Troubleshooting—Differential-Pressure Transducer

SYMPTOM: High Output

POTENTIAL SOURCE AND CORRECTIVE ACTION

1. **Primary Element**
   - ☐ Check for restrictions at primary element.
2. **Piping and Installation**
   - ☐ Check for leaks or blockage in screen or strainer.
   - ☐ Check that isolation valves are fully open.
   - ☐ Check for entrapped gas in liquid lines and for liquid in dry lines.
   - ☐ Check that the density of fluid in impulse lines is unchanged.
   - ☐ Check for sediment in transmitter process flanges.
3. **Transmitter Electronics Connections**
   - ☐ Make sure bayonet connectors are clean; check the sensor connections.
   - ☐ Check that the unit is properly grounded to the case.
4. **Transmitter Electronics Failure**
   - ☐ Determine faulty circuit board by trying spare boards.
   - ☐ Replace faulty board.
   - ☐ Check output scaling or signal conditioning.
5. **Sensing Element**
   - ☐ Check sensing element.
6. **Power Supply**
   - ☐ Check output or power supply.

SYMPTOM: Erratic Output

POTENTIAL SOURCE AND CORRECTIVE ACTION

1. **Electronic Connections**
   - ☐ Check for adequate voltage to the transmitter.
   - ☐ Check for intermittent shorts, open circuits, and multiple grounds.
   - ☐ NOTE: Do not use over 100 V to check the loop.
2. **Process Fluid Pulsation**
   - ☐ Adjust electronic damping pot (4–20 mA DC only).
3. **Piping and Installation**
   - ☐ Check for entrapped gas in liquid lines and for liquid in dry lines.
4. **Transmitter Electronics Connections**
   - ☐ Check for intermittent shorts or open circuits.
   - ☐ Make sure that bayonet connectors are clean; check the sensor connections.
   - ☐ Check that the unit is properly grounded to the case.
   - ☐ Check signal conditioning.
5. **Transmitter Electronics Failure**
   - ☐ Determine faulty board by trying spare boards.
   - ☐ Replace faulty circuit board.

SYMPTOM: Low Output or No Output

POTENTIAL SOURCE AND CORRECTIVE ACTION

1. **Primary Element**
   - ☐ Check installation and condition of element.
   - ☐ Note any changes in process fluid properties that may affect output.

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2. **Electronic Connections**
   - ☐ Check for adequate voltage to the transmitter.
   - ☐ Check for shorts and multiple grounds.
   - ☐ Check polarity of connections.
   - ☐ Check loop impedance.
   - ☐ NOTE: Do not use over 100 V to check the loop.
3. **Piping and Installation**
   - ☐ Check that pressure connection is correct.
   - ☐ Check for leaks or blockage.
   - ☐ Check for entrapped gas in liquid lines.
   - ☐ Check for sediment in transmitter process flange.
   - ☐ Check that isolation valves are fully open and that bypass valves are tightly closed.
   - ☐ Check that the density of fluid in impulse piping is unchanged.
4. **Transmitter Electronics Connections**
   - ☐ Check to see that calibration adjustments are in control range.
   - ☐ Check for shorts in sensor leads.
   - ☐ Make sure bayonet connectors are clean; check the sensor connections.
   - ☐ Check that the unit is properly grounded to the case.
5. **Test Diode Failure**
   - ☐ Replace test diode or jumper terminals.
6. **Transmitter Electronics Failure**
   - ☐ Determine faulty circuit board by trying spare boards.
   - ☐ Replace faulty board.
   - ☐ Check output scaling or signal conditioning.
7. **Sensing Element**
   - ☐ Check sensing element.

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Troubleshooting—Solid-State Meters

INTRODUCTION

Solid-state meters include ultrasonic, electromagnetic, Coriolis, and vortex meters. Solid-state meter malfunctions are usually restricted to two areas: electrical/electronic or physical. When a malfunction or an apparent malfunction occurs, the electrical and electronic systems should first be thoroughly checked in accordance with the manufacturer's recommended procedures prior to inspection of the solid-state meter. If the source of the malfunction cannot be found in the electrical or electronic systems, then the solid state-meter should be inspected.

SYMPTOM: High Output

POTENTIAL SOURCE AND CORRECTIVE ACTION

1. **Primary Element**
   - ☐ Check for restrictions at primary element.
2. **Piping and Installation**
   - ☐ Check that isolation valves are fully open.
   - ☐ Check for leaks or blockage in screen or strainer.
   - ☐ Check for entrapped gas in piping.
   - ☐ Check for empty pipe or partially filled pipe.
   - ☐ Check for sufficient upstream and downstream piping, as recommended by manufacturer.
3. **Transmitter Electronics Failure**
   - ☐ Determine faulty circuit board by trying spare boards (if the manufacturer allows replacement of internal components).
   - ☐ Replace faulty board.
   - ☐ Check to see that calibration adjustments are in control range.
   - ☐ Check diagnostics if available.
   - ☐ Check output scaling or signal conditioning.
   - ☐ If the meter is a clamp-on ultrasonic, confirm that the device is configured correctly for the material of piping and the proper diameter of piping.
4. **Sensing Element**
   - ☐ Check ultrasonic transducers or electromagnetic electrodes or Coriolis tubes or vortex bluff body.
5. **Power Supply**
   - ☐ Check output device.

SYMPTOM: Erratic Output

POTENTIAL SOURCE AND CORRECTIVE ACTION

1. **Power Supply**
   - ☐ Check for adequate voltage.
   - ☐ Check for intermittent shorts, open circuits, and multiple grounds.
2. **Piping and Installation**
   - ☐ Check for entrapped gas in piping.
   - ☐ Check for empty pipe or partially filled pipe.
   - ☐ Check for pulsating flow.
   - ☐ Check for homogeneous flow stream properties, which could be disrupted by devices such as chemical injectors. Avoid installing chemical injectors immediately upstream of meter.
   - ☐ Check for sufficient upstream and downstream piping, as recommended by manufacturer.
3. **Transmitter Electronics Connections**
   - ☐ Check for intermittent shorts or open circuits.

(Continued on next page)

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4. Transmitter Electronics Failure
- ☐ Determine faulty board by trying spare boards (if the manufacturer allows replacement of internal components).
- ☐ Replace faulty circuit board.
- ☐ Check diagnostics if available.
- ☐ Check signal conditioning.

SYMPTOM: Low Output

POTENTIAL SOURCE AND CORRECTIVE ACTION

1. Primary Element
- ☐ Check installation.
- ☐ Check condition of the transducers or electrodes or tubes or bluff body.
- ☐ Note any changes in process fluid properties that may affect output such as inconsistent or no conductivity of the fluid.
- ☐ Check flow direction.

2. Electronic Connections
- ☐ Check for shorts and multiple grounds.
- ☐ Check polarity of connections.
- ☐ Check loop impedance.

3. Piping and Installation
- ☐ Check for entrapped gas in pipe.
- ☐ Check for empty pipe or partially filled pipe.
- ☐ Check to see that isolation valves are fully open and bypass valve is closed.
- ☐ If the meter is a clamp-on ultrasonic, confirm that the device is configured correctly for the material of piping and the proper diameter of piping.

4. Transmitter Electronics Connections
- ☐ Check to see that calibration adjustments are in control range.
- ☐ Check for shorts in sensor leads.

5. Transmitter Electronics Failure
- ☐ Determine faulty circuit board by trying spare boards (if the manufacturer allows replacement of internal components).
- ☐ Replace faulty board.
- ☐ Check diagnostics if available.
- ☐ Check output scaling or signal conditioning.
- ☐ If the meter is a clamp-on ultrasonic, confirm that the device is configured correctly for the material of piping and the proper diameter of piping.

6. Power Supply
- ☐ Check for adequate voltage.
- ☐ Check for shorts, open circuits, and multiple grounds.

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Chapter 3

Flowmeter Selection

Flowmeter selection is important for proper flow measurement at various locations within treatment and distribution facilities. Properly installed, a flowmeter typically gives many years of reliable service, outliving most other equipment. As discussed in chapter 1, the fluid must be homogeneous with the solids or gases evenly dispersed, and the fluid should act as a single-phase fluid with no relative motion among its components. Most water-treatment fluids generally meet these conditions.

SELECTION PARAMETERS

The influence parameters and properties of flowmeters, which are important during the selection process, are discussed further.

Flowmeter Performance Properties

Properties that describe the performance of various flowmeters help in the selection process. By matching the flowmeter with the operational needs, satisfactory life-cycle performance is established within feasible financial constraints.

Accuracy. As defined by the International Organization of Legal Metrology, accuracy is "the closeness of agreement between the result of a measurement (measured flow) and the true value of the measurement (actual flow)." Accuracy is stated as a percentage representing disagreement of data within a range. However, because different manufacturers represent accuracy differently, the manufacturer should be required to explain what is meant by accuracy and how it was established using which standards. Accuracy is often confused with precision; however, it is more than precision and also includes bias.

Precision error. Precision error is random and is a function of the measuring device's technology and limitation. Therefore, this error is not correctable; nevertheless, it is statistically predictable using the bell-shaped normal distribution. The confidence range

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or level within which 95 percent of the readings are expected to fall is accepted by most standards.

Bias error. Bias error is the difference between the average measured value and the true value of the data. Whereas precision error is the scatter of the readings around the average, bias error is directional and can be added to or subtracted from the readings to obtain a closer measurement to the true value. Flowmeters can be calibrated by taking several readings at each flow point, and a bias error correction can be made using a microprocessor. A calibration curve may be drawn through bias error points and each reading corrected closer to the true value. Therefore, the calculation of accuracy is reduced to a calculation of precision because of the elimination of bias. The previously mentioned procedure is not economically feasible for every flowmeter. Therefore, flowmeters are type tested to establish a reference accuracy envelope that statistically includes bias and precision over a specific range of flow under reference conditions.

Sources of variable bias errors include

- voltage drift of a standard cell used to standardize a potentiometer,
- progressive wear of an orifice, edge, throat, and so on,
- progressive wear of a chart recorder's linkage,
- uncorrected zero shift, and
- sensors' sensitivity to temperature.

Sources of constant bias errors include

- gravity correction (or lack) of dead-weight testers,
- unknown bias in a reference measurement standard,
- using a scale to determine mass that is not corrected for buoyancy,
- a flowmeter installed too close to a disturbance that skews the velocity profile or creates a swirl, and
- incorrect measurement of an orifice, pipe bore, or throat.

Sensitivity. Sensitivity of the final flow calculation to each of the variables measured is established by mathematical relationships among the variables. From these equations, sensitivity coefficients are derived that are useful in determining what effect an instrument's directional bias has on the rate of flow. In deciding whether a more accurate device is needed, the measurement with the largest sensitivity coefficient is targeted firstfor example, the sensitivity of the measurement to fluid temperature: Is a more accurate device needed, or is compensation for the bias caused by temperature change needed?

Linearity. A flowmeter is linear if its readout is a straight line going through the origin when plotted versus rate of flow.

Repeatability. Repeatability is the flowmeter's ability to give exactly the same output when measuring exactly the same flow rate. Accuracy does not exist if readings are not repeatable. In applications where only repeatability is required, not accuracy, it is fiscally efficient to select a meter tested for repeatability only.

Rangeability. Rangeability is also known as the turndown ratio. This is the ratio of the maximum to minimum flow. Range is the flow range within which the specified accuracy is met.

Traceability. Traceability is the possibility of tracing the accuracy of a measurement standard, used for calibration, against a national standard.

Influence Quantities

Flowmeter performance is directly influenced by several quantities that must be identified before an appropriate selection can be made.

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Velocity profile. As discussed in this manual, this is the most critical influence quantity. Piping orientation, valves, equipment, pumps, swirl, and secondary flows can disturb the profile. Any of these result in radial and tangential velocity vectors that are not symmetrical. For example, some flowmeters, such as magnetic flowmeters, are not as sensitive to radial velocity components; however, single-path ultrasonic flowmeters are. Nevertheless, the discharge coefficient of a Venturi decreases with swirl and is detrimentally affected. Therefore, selecting a flowmeter should involve a complete understanding of the laying condition both upstream and downstream so that velocity profile effects can be predicted and the appropriate flowmeter selected.

Nonhomogeneous flow. This includes flow conditions in which the fluid has more than one component with nonuniform density and velocity components. The effect is that there is more than one independent flow in the conduit, each moving at a different velocity. These include two-phase flow, air or other gas in water, pulp stock, and noncolloidal solids. Pretreatment of the flow such that it is homogeneous when in the meter allows for accurate measurement. Pretreatment includes mixing to suspend solids or mixing different fluids (e.g., creating an emulsion, venting the air or gas, cooling to condense steam, warming to melt ice, etc.). Nevertheless, care must be taken to have an unskewed velocity profile that may involve flow straighteners.

Air/solids entrainment or air/solids deposit. When the amount of air or solids (dissolved air or floating solids) entrained in the fluid is large, it can become a substantial portion of the volume passing through the meter. Although it is a homogeneous fluid, the true amount of liquid is less. Also, when air or any other gas is trapped at or very near the flowmeter, it affects the velocity profile and flow area. The same applies for solid deposits. Venting of air, eliminating knees in the piping and sloping the piping up with the flow, and adjusting the fluids temperature can minimize or eliminate entrainment. Preventing solids buildup is a more involved issue concerning the type of the solid and its adhesion/cohesion or ionic properties, the proper selection of pipe, and flowmeter surface material or coatings. Continuous properly sloped piping, increased flow velocity (by increasing rate of flow or reducing pipe area), elimination of flow obstructions, adding polymers, mixing if solids removal is not feasible, and prevention of corrosion (including cathodic) and erosion can minimize the settling or solids deposit. Entrained solids are usually part of the water-treatment process, and the fluid is treated as a homogenous liquid such as sludge. However, if the solid is an impurity, it must be removed. Selection of a flowmeter that is less sensitive to air or solids buildup or passage is not a panacea because despite the accuracy of the velocity measurement, the rate of flow calculation will be biased because of change in area. Proper air/solids handling plans are important and are recommended in addition to proper flowmeter selection.

Cavitation. Cavitation is a destructive phenomenon, whether it occurs upstream of or at the flowmeter. In addition to damage to the flowmeter, cavitation causes the readings to be biased by the two-phase flow and the shock and vibrations caused by the imploding vapor. If cavitation occurs upstream of the flowmeter, eliminate the cause if possible. Treatment of cavitation is outside the scope of this manual; many other sources address the subject. If elimination of cavitation at the upstream source is impossible, adding more distance and/or a throttled valve upstream or downstream of the flowmeter would help recover the pressure enough to implode all vapor bubbles before they approach the flowmeter. This technique would cause a less expensive component to wear out and would allow for homogeneous flow measurement.

Minimizing the vibrations caused by cavitation reduces hysteresis or electronic component damage. Nevertheless, some flowmeters are less sensitive than others and can provide longer service within such constraints. If cavitation is or could be caused by the flowmeter, the flowmeter size, location, and process piping size and operating pressures must be revisited. Some flowmeters do not obstruct the flow and therefore are less likely to

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cause cavitation; however, cavitation could be caused by the pipe size, flow, and pressure at that location. The solution would be to relocate the flowmeter.

Pulsating flow. Pulsating flow presents a challenge to flow measurement. The abrupt changes in velocity that it causes have various detrimental effects on the velocity profile and inertia damping. Pulsating flow eliminates the steady-state flow condition needed to measure flow properly. In addition, pipeline resonant frequencies can negatively affect secondary measuring devices. Possible ways to reduce pulsations and improve flow measurement include volume tanks, in-line restriction, and pulsation dampeners. Pulsating flows are not typical in water treatment except in chemical-feed systems. Those systems are required by law to quantify feed rate using weighing scales. Time averaging may help provide a more stable measurement in a flow with pulsations and other transients. However, time averaging is not instantaneous and may cause problems if the flow measurement is used in a control loop without proper design considerations.

Wall roughness. Pipe or flowmeter wall roughness affects the velocity profile and may help dampen disturbances. The roughness changes with time and can cause or minimize errors. Excessive roughness change, such as tuberculation, can also change the flow area.

METER SELECTION CONSIDERATIONS

General Guidelines

Meter selection cannot be strictly rulebased and remains dependent on individual judgments based on engineering knowledge and preferences. However, choices can be made more systematically by adhering to guidelines in the following sections that help identify potential needs and problems. (Also see Table 3-1 at the end of this chapter.) The guidelines are intended to point out most—but not necessarily all—major issues. In general, reputable manufacturers provide application recommendations to improve accuracy and ensure proper performance if presented with sufficient data. Such recommendations are paramount in comparing applicability, life-cycle cost, and accuracy on an equal footing.

To select a flowmeter, the following need to be identified and manufacturers' data checked for flowmeter applicability:

- Type of fluid including
  - Solids content
  - Homogeneous or not
  - Corrosiveness
  - Air content

Any of these issues may drastically affect accuracy, maintainability, and repeatability. Some flowmeters may require additional options or special materials for proper function. These may drive costs up and/or sacrifice accuracy.

- Process conditions
  - Pressure and range of fluctuation
  - Fluid temperatures and range of fluctuations
  - Pressurized or gravity flow (if gravity flow, is the flow full conduit; is the conduit a round pipe, oval pipe, open channel, or other shape)
  - Pulsating or steady flow

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- Operational performance requirements
  - Type of use
    - Control (speed of response required)
    - Monitoring
    - Dosing
    - Custody transfer
  - Importance of repeatability versus accuracy or both
  - Overall accuracy needed throughout flow range
  - Effect of secondary element accuracy versus range on low-end readings
    - Feasibility of splitting range over more than one secondary element
  - Range of flow including minimum, average, and maximum flow. If not a range, identify the specific flow(s)-associated Reynolds numbers for all flows.
- Installation conditions
  - Pressurized pipe or open channel
  - Line size and meter size
  - Upstream laying lengths, flow direction changes, and obstructions
  - Downstream laying lengths
  - Need for flow conditioner
  - Presence of vibrations
  - Ambient temperatures and range of fluctuations
  - Atmospheric pressure
  - Flowmeter-induced cavitation
  - Power considerations
  - Lightning or grounding considerations
- Life-cycle costs
  - Initial cost
  - Installation cost
  - Replacement cost if longevity is not similar to or is less than needed
  - Maintenance cost versus reliability cost
  - Availability of parts and technical support (present and future)
  - Longevity
  - Energy cost to operate
  - Energy loss caused by permanent head loss from differential producers or size reduction below line size
  - Risks of trying new, promising flowmeter types

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METER SELECTION BLOCK DIAGRAM

The following block diagram (Figure 3-1) depicts the decision process that can be used in the selection of flowmeters based on various parameters such as physical constraints, accuracy, cost, maintainability, and adaptability to future changes.

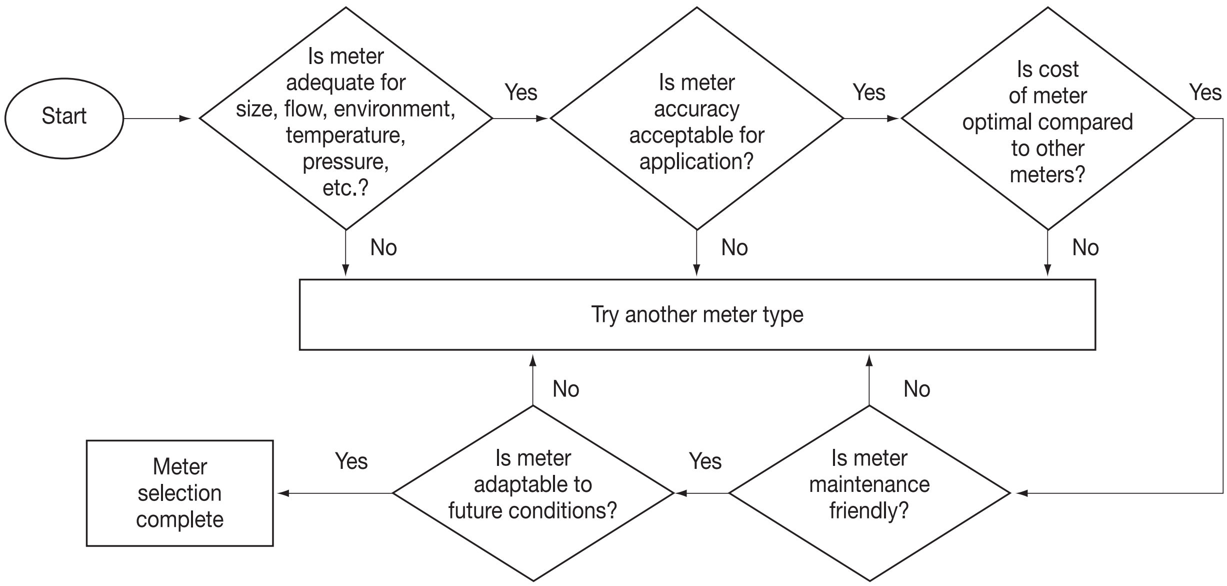

Figure 3-1 Flowmeter selection block diagram

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Table 3-1 Selected flowmeter selection data

	Orifice Plate	Modified Venturi	Flow Tube	Electromagnetic (Mag Meters)	Ultrasonic Transit-Time	Turbine	Vortex	Profile Modifying (e.g., cone meters)	Coriolis
Custody transfer	Applicable	Applicable	Applicable	Applicable	Applicable (esp. large conduits)	Applicable	Applicable	Applicable	Applicable
Process monitoring	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable
Process control/ chemical feed	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable
Max. temp., °F	See mfr	See mfr	See mfr	See mfr	See mfr	100	See mfr	See mfr	See mfr
Max. pressure, psig	Above 1,500	Above 1,500	Above 1,500	Up to 1,500	Pipe rating	Above 300	Up to 1,500	Above 1,500	Above 1,500
Size range, in.	>1	1–120	>2	0.1–120	0.25–360	0.75–20	1–10	$2 \le D \le 24$	$1/24 \le D \le 16$
Reynolds number	>10,000	>75,000	15,000	No limit	No limit		>10,000	$8,000 \le Re \le 12,000,000$	No limit
Min. flow, ft/s	See Reynolds	See Reynolds	See Reynolds	0.2	0.1	1	See Reynolds	See Reynolds	Varies
Max. flow, ft/s	Varies	Varies	Varies	30 or 60 per converter	33	20	Limited by cavitation	Varies	Varies
Pressure loss	2.5–650 × velocity head	0.1–35 × velocity head	0.1–20 × velocity head	Straight pipe	Straight pipe	1.5 × velocity head	2 × velocity head	>4 × velocity head	Varies
Accuracy, %	1–2 of full scale	0.75 of full scale	0.5–1.5 of full scale	0.5 of rate to 1 full scale	0.5–2.5 of rate	0.5–2 of rate	0.75 of rate	0.5–5 of full scale	0.05–0.2 of rate
Repeatability, %	0.25	0.25	0.25	0.25	0.25	0.2	0.5	0.25	0.05
Rangeability	10:1	Up to 10:1	10:1	30:1	20:1	40:1	25:1	10:1	20:1
Calibration of each unit	Not required	Not required	Not required	Required	Required	Required	Not required	Not required	Required
Output	Analog (square root)	Analog (square root)	Analog (square root)	Analog or digital	Analog or digital	Mechanical or frequency	Analog or frequency	Analog (square root)	Analog or frequency or digital
Secondary unit	ΔP transmitter	ΔP transmitter	ΔP transmitter	Converter	Converter	Frequency electronics	None or frequency electronics	ΔP transmitter	Converter
Upstream piping	15–60 D	10–20 D	10–20 D	10 D	>10 D	10 D	10 D	2–10 D	None
Downstream piping	5 D	2 D	5 D	3 D	5 D	5 D	5 D	0–2 D	None

D: diameter, mfr: manufacturer

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Chapter 4

Installation and Performance Issues

The reliability and accuracy of a flowmeter's output signal are highly dependent on meter installation. An improperly located and installed meter will degrade the inherent specified accuracy below an acceptable level. Responsible manufacturers provide guidance and recommendations for meter installation that should be rigorously followed. Nevertheless, the meter must be checked immediately after installation and periodically thereafter to assure the stability of reading and accuracy.

Most circumstances that affect the accuracy of flowmeters fall under the following four main categories:

- Piping configuration and flow straighteners
- Fluid condition
- Flowmeter considerations
- Electrical/electronic

PIPING CONFIGURATION AND FLOW STRAIGHTENERS

Meters discussed in this manual have limitations because of piping configurations. Upstream piping and, in some cases, downstream piping are important configuration considerations. Recent findings have determined that downstream conditions more than two pipe diameters away from the sensing point(s) have a negligible effect on most meters' performance. Upstream conditions remain critical because they affect the velocity profile of the fluid in the flow-measuring section.

Meters are calibrated with a uniform velocity profile distribution such as the one produced by a long length of upstream conditions. Therefore, a mathematical relationship

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between the influenced parameter and flow is fixed based on a certain factor or function derived from calibration test data. This mathematical relationship dictates the accuracy of the flowmeter. A skewed or distorted velocity profile causes the influenced parameter to become less stable and the calibration factor or function to become either partially or fully inapplicable, considerably increasing the flowmeter's error. Meters should not be placed near a bend, valve, or other fitting that is likely to disturb the velocity profile at the meter. Such disturbances are magnified if the bends or fittings are out of plane in such a manner as to cause a swirl or crossflow. A swirl is the rotary motion of the flow superimposed on the forward motion. Crossflow may be a part of swirl; however, it involves flow with velocity vectors nonparallel to the pipe axis. Crossflow may affect some technologies more than others. If the manufacturer's recommendations are not available, it is recommended that a minimum of 15–20 pipe diameters' distance be left upstream from valves and fittings. If a severely distorted velocity profile exists, the upstream straight pipe length may become so long that it is not cost effective, and in that case, a flow straightener becomes a viable solution. However, flow straighteners have inherent permanent head loss that should be taken into consideration when comparing the cost of straight pipe.

Flow straighteners include perforated plate (Mitsubishi), Zanker (ISO[*]), Sprenkle (ASME[†]) and several tube-bundle variations (ISO, AGA,[‡] ASME, etc.), AMCA[§], and Étoile (Figure 4-1). The Zanker, Sprenkle, and Mitsubishi straighteners are used to eliminate swirl and velocity profile distortion. The ISO, AGA, and ASME tube bundles are used to eliminate swirl and moderate profile distortion. The permanent head loss of disturbance-eliminating flow straighteners (perforated plates and tube bundles) is considerable. Other straighteners simply eliminate swirl and do not have a high head loss.

To avoid doing more harm than good, flow straighteners must be properly installed in relation to both the source of flow disturbance and the flowmeter itself. In general, straighteners should be inserted at least 3 pipe diameters downstream of the source and about 10–20 pipe diameters upstream of the flowmeter.

FLUID CONDITION

The properties of the fluid and its physical condition can affect the accuracy of the readings. These include the following:

- Presence of air or other contaminants. Excessive air and contaminants cause the fluid to act as a two-phase fluid, so that it cannot be accurately measured.
- Because density is dependent on fluid temperature, drastic changes may cause reading errors in some meters. Electronic sensors without built-in temperature compensation also may not work accurately if the fluid temperature changes drastically. Thus, some technologies may require seasonal recalibration of sensors when the ambient and water temperature change.
- Pressure fluctuations or pulsation cause unsteady flow and result in a large amount of hysteresis in the readings. If the readings fluctuate drastically, they become less valuable unless time averaging is used to smooth them. Time averaging will result in readings that are not instantaneous flow.

* International Organization for Standardization, Geneva, Switzerland.
† American Society of Mechanical Engineers, New York, N.Y.
‡ American Gas Association, Washington, D.C.
§ Air Movement and Control Association International Inc., Arlington Heights, Ill.

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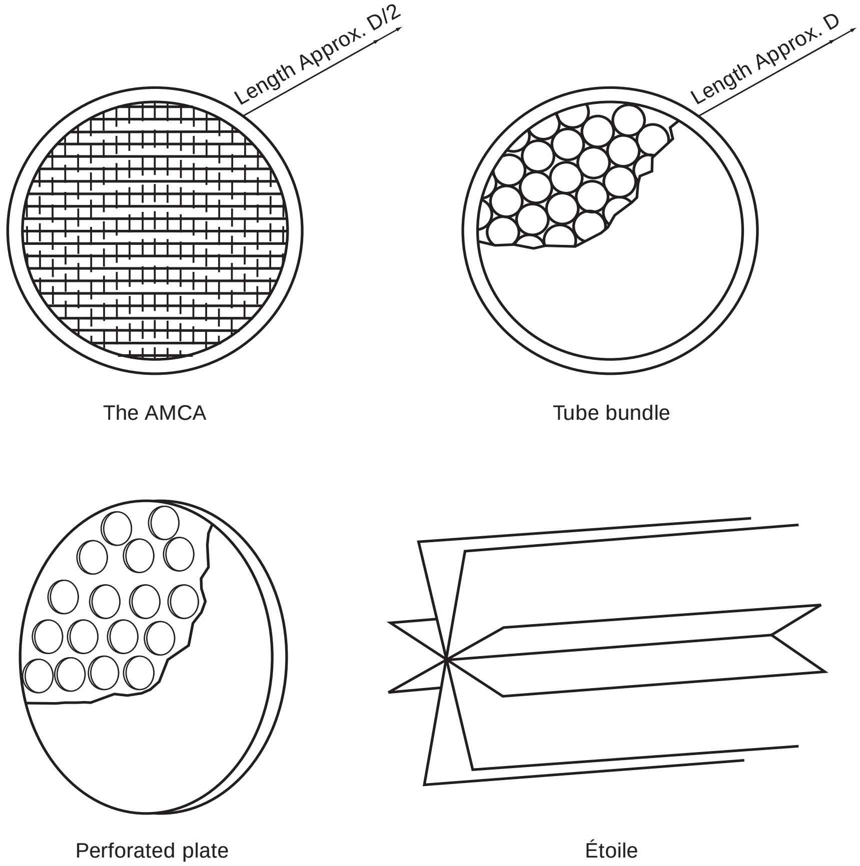

Note: AMCA: Air Movement and Control Association, D: diameter

Figure 4-1 Typical flow straighteners

FLOWMETER CONSIDERATIONS

Most flowmeters are high-quality products. Nevertheless, a few flowmeters in the market may cause errors. Because the flowmeter is part of the installation, it is relevant to discuss some of the most common issues:

- Nearby machinery, valves, or high fluid velocity can produce significant vibration. This vibration can cause some meters—particularly those with lower mechanical stiffness in individual components—to exhibit hysteresis or other fluctuations in measurement. This can be somewhat minimized by averaging the readings over a period of time or by selecting meters less affected by vibration. All piping in proximity to the meter should be properly supported to minimize vibration, as well as to address pipe weight, expansion, and other loads that the piping would otherwise transmit to the meter.
- Inadequate or inaccurate electronics can result in unstable readings caused by issues such as these:
  - Floating zero problems may cause zero instability in some sensors.
  - Changes in ambient and/or fluid temperatures may skew the readings of the sensor.

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  - Some sensors cannot handle high- and/or low-pressure surges caused by system transients.
  - Sensor accuracy is a function of range. If the range is large and covered by a single sensor, the error in reading can be larger than the stated accuracy. For example, a differential-pressure transducer with an accuracy of 0.5 percent of full scale is set for a range of 0–100 in. of water (0–25 kPa). Therefore, the accuracy is 0.5 in. (0.12 kPa), but the error of the reading when it is around 10 in. (2.5 kPa) is actually 5 percent. In some cases, splitting the range among more than one transmitter can drastically improve accuracy.
  - Inadequate calibration can be a source of errors. Some flowmeters may not have been calibrated often enough to provide sufficient confidence in the technology. Therefore, accuracy statements based on bench calibration (which is nothing more than past data) should not be accepted unless enough flowmeters, including those of similar size, have been tested.
  - Influenced parameter sensing is a major determinant of the accuracy and repeatability of the flowmeter. The influenced parameter is the measurable physical entity that is influenced by the flow. Examples are differential pressure, ultrasonic wave travel time, magnetic field, and so on. The low hysteresis of the influenced parameter and ease of measurement indicate the strength of the relationship between flow and that parameter. Even weak relationships may result in high accuracy in meters if the sensing elements and techniques are advanced enough to register changes. Also, not all sensing methods are the same, and small variations in the electronics may drastically affect accuracy. Some manufacturers use time averaging to help eliminate the hysteresis caused by the fluctuation of the influenced parameter.

ELECTRICAL CONNECTIONS

Virtually all flowmeter installations generate electrical signals proportional to flow. Special attention must be given to electrical connections and secondary instruments during installation. Temperature, pressure, and electrical ratings must not be exceeded. Equipment must be protected from corrosion. If the meter is installed below grade, it and its connections must be capable of withstanding total immersion, if conditions warrant, with special attention given to electrical connections. The following precautions should be taken during meter installation:

- Provide preamplification as part of conditioning the signal sensor. This keeps a high signal-to-noise ratio, making the output signal less susceptible to noise distortion.
- Use shielded, twisted-pair wiring to transmit the signal, with the shield grounded only at the signal transmitter or lower-noise end to prevent ground loops, or per the manufacturer's recommendations.
- Maintain sufficient distance between the signal wire and power cable in accordance with the latest National Electrical Code. If wire crossing is unavoidable, allow wire and cable to cross at right angles only.
- Continuously check for proper calibration and damaged or corroded components.
- Because of the potential negative impact of electromagnetic and radio-frequency interference, be sure to follow the manufacturer's recommendations for all aspects of the electrical installation.

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Chapter 5

Communications, Information, and Signal Outputs

Water utilities often use flowmeters for more than monitoring flow rate and flow total and automating equipment operations. They also use them to assist in making business decisions (e.g., setting rates or replenishing consumables) and as part of the capital planning process (e.g., building new pumping stations or expanding treatment processes).

Utilities rely on flowmeters to produce accurate and timely data every day. Imagine the outcome if a critical facility that delivered water were to suddenly stop working. How soon would the user need to know this relevant information? Instantly, in a few minutes, or next week? Delay in information delivery can lead to less than optimum outcomes. Modern systems use flowmeters that transmit a signal to other devices and systems that allow for viewing, capturing, storing, and retrieving this flow data on demand.

In water treatment and distribution, flowmeters are used to measure flow of liquids, gases, and solids. Specific technologies vary widely and are discussed in other chapters. This chapter focuses on how to capture the flow value and what to do with it. In some cases, a simple visual observation of flow is sufficient, while in other cases, it is necessary to convert the flow value to a standard signal for integration with an advanced process control system. Various types of signals, how they are integrated into larger systems, and various design considerations specific to capturing flowmeter data are discussed.

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DEFINITIONS

CMMS — Computerized maintenance management system.

DCS — In a distributed control system, key control processors are distributed throughout the system. DCS is also used to define a higher-level control system, contrasted to a PLC-based system, where the graphical interface, the database, the local controllers, the LAN, and many of the instruments are manufactured, supported, and installed by a single entity. These types of systems are often used in the largest treatment plants, whereas PLC-based systems are used in medium-size and small facilities.

HMI — Human–machine interface is a software application that presents information to the operator about the state of a process using pictorial representations (icons) and menus. Instead of typing commands, the user executes commands and other tasks with a pointing device. HMI may also interpret the facility information and guide the interaction of the operator with the system. Also known as man–machine interface (MMI).

IEEE — Institute of Electrical and Electronic Engineers. An association responsible for many of the standards associated with signal transmission and electronic communications.

ISA — International Society of Automation. An association responsible for various standards and design practices used in automation systems.

I/O — Input/output (pronounced as eye-oh). An operation, program, or device the purpose of which is to enter data into a computer/processor or to extract data from a computer/processor.

IT — Information technology. The use of electronic computers and computer software to convert, store, protect, process, transmit, and retrieve information. IT personnel specialize in these areas, which typically do not involve the software and configuration of specialized systems like SCADA.

LAN — A local area network is a computer network limited to the immediate area, usually the same building or floor of a building. LANs are capable of transmitting data at very fast rates, much faster than the rate at which data is transmitted over the Internet. There is no limit on the number of computers that can be attached to a single LAN.

NEC — National Electric Code. A specific standard developed by the NFPA, specifically NFPA Article 70. This standard governs the electrical wiring and electrical standards associated with all water facilities.

NEMA — National Electrical Manufacturers Association. A nonprofit trade organization supported by manufacturers and suppliers of electrical apparatus in the United States. NEMA standards exist for motors' frame sizes and dimensions, horsepower ratings, service factors, temperature rises, and performance characteristics. Additionally, NEMA standards define environmental standards and ratings of control panels and equipment used in multiple industries, including the water industry.

NFPA — The National Fire Protection Association defines various standards that include the National Electric Code. These standards apply to facilities typically used by water agencies including treatment plants, pump stations, and valve vaults.

PLC — The programmable logic controller is a miniature industrial computer that contains the hardware and software used to perform control functions. A PLC

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consists of two basic sections: the central processing unit (CPU) and the input/output interface system. The CPU, which controls all PLC activity, can further be broken down into the processor and memory systems. The input/output system is physically connected to field devices (e.g., switches, sensors) and provides the interface between the CPU and the information providers (inputs) and controllable devices (outputs).

RTU — A remote telemetry unit communicates with a telemetry system. Often this is made up of a PLC, a communication device (e.g., radio, modem), and other equipment. The device operates independently of the system it is monitoring, often picking up digital and analog signals and relaying those to the SCADA system for monitoring.

SCADA — The supervisory control and data acquisition system is a scaled, distributed monitoring and control system. A SCADA system measures process variables, monitors equipment status, and controls process functions. It is designed primarily as an operational tool, and its data-acquisition function often contributes to achieving the business goals of other business systems and units in the enterprise.

TCP/IP — Transmission control protocol/Internet protocol is the main protocol of modern computer networks. Whereas the IP deals only with packets, TCP enables two hosts to establish a connection and exchange streams of data. TCP guarantees delivery of data and guarantees that packets will be delivered in the same order in which they were sent.

WIFI — WIFI was originally a brand licensed by the WIFI Alliance to describe the embedded technology of wireless local area networks (WLAN) based on the IEEE 802.11 standard. A common use of the term WIFI has broadened to describe the generic wireless interface of mobile computing devices, such as laptops in LANs.

SIGNAL METHODOLOGIES

Flowmeters are a key process measuring device and are widely used throughout the water industry. Usually they connect to the control system using industry-standard signals. The general methodologies are described below.

Analog Transmission

For many years, flowmeters have used analog signals to transmit measurement data to other devices such as indicators and controllers. These analog transmissions can be either electronic or pneumatic, with electronic transmission being more common. In general, electronic signals are used for flowmeters in environments that are not explosion proof, and pneumatic signals are used for flowmeters in specialty applications and explosion-proof environments. Environment classification is beyond the scope of this chapter; the reader can obtain additional information in the NFPA Article 70 and NEMA rating standards.

The industry standard for analog electronic transmission, defined by ANSI/ISA in standard 50.00.01-1975 (R2012), is the 4–20 mADC signal and, closely related, the 1–5 VDC signal, which is derived from the 4–20 mADC signal. The reasoning for the 4–20 mADC signal versus 0–20 mADC or similar is the live zero concept. When a flowmeter is at zero, representing zero flow, the signal reads 4.00 mADC. This allows the control system to recognize the no-flow condition. If the signal should drop below 4.00 mADC, this is generally recognized as an open circuit or equipment failure as the output signal is below

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a valid range. The maximum flow rate is represented by 20.00 mADC. Any flow rate above the maximum would also be represented by 20.00 mADC. For most flow devices, the flow rate is linear between 4 and 20 mADC points, such that at half the maximum flow rate, the signal would be 12 mADC. Where some manufacturers offer equipment with a 0–20 mADC range, incorporating this type of signalization requires additional equipment or logic to detect an out-of-range condition.

Typically, the 4–20 mADC signal is used in a series loop connecting the flowmeter to other devices such as a PLC system or a local indicator. There is a limit on how many secondary devices can be connected to the flowmeter based on their resistance value, with the standard being 600. When necessary, the signal can be boosted using a current-to-current converter (I/I) to allow for interconnection with more devices. In modern systems, however, most flowmeters are connected directly to a PLC, where the signal is digitally converted and distributed to displays and other devices.

1–5 VDC signals are primarily used in a control panel. The 1–5 VDC signal is derived by placing a precision 250-resistor in the control loop. Once the signal is converted, additional devices can be connected in parallel. The disadvantage of using the 1–5 VDC signal is distance. As the distance increases, voltage drop occurs; thus, compromising the control signal.

Besides electronic signals, the industry standard for pneumatic signalization is 3–15 psi. In the water industry, this signal type is typically found in explosion-proof environments and occasionally for valve control.

Pulse Transmission

Pulse communications are primarily used with volumetric flowmeters, where each pulse represents a unit volume. The pulse can be scaled such that the output represents a specific engineering quantity (such as one pulse per 100 gallons) or can be unscaled directly from the measuring element (such as one pulse per 0.2375 gallons). The signal is a discrete close/open cycle of a relay contact, transistor, or solid-state output. The flowmeter connects to a counter or PLC input, and as each pulse occurs, the counter is increased by one unit.

Some manufacturers also use pulse communications to communicate with the electronic system for translation to a standard signal to be used by other devices and systems. These pulse communications vary in either the length of the pulse or the space between pulses. Depending on the total on or off time associated with the pulse length, the connected electronics can determine a specific flow rate.

Other pulse flowmeters generate a specific number of pulses over a unit of time, thus, allowing for the translation into a flow rate (e.g., gallons per minute). This type of output is generally found on meters at smaller pump stations or in areas where there is limited to no-analog instrumentation. As a cost-savings measure, the pulse output is connected directly to a discrete I/O of a PLC system.

Discrete Transmission

Some flowmeters include a discrete signal for communicating a digital change of state (e.g., flow/no flow). These signal types can be used to convey an alarm or abnormal condition to the control system or other devices.

Digital Communications

The most significant advances in the conveyance of information have taken place in the form of digital communication. While not widespread in the water industry, the use of digital communication and the ability to connect multiple devices such as flowmeters into a single network offer an advantage over traditional methods previously described. With

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digital data, a user can access more than one data element. For example, using digital communication, a user can retrieve the flow measurement value, flow totals for different time periods, and data on flowmeter health and calibration. These additional data points can be integrated into other systems such as CMMS to simplify operations.

Digital communications can use different architectures and standards, and flowmeters that directly support digital communication typically have dedicated communication ports to match up with the applicable standard. Beyond the physical connectivity, digital communication leverage different communication protocols. Some are manufacturer dependent; others are open architecture to support interconnectivity to many other third-party systems and devices. The more common protocols include the following:

- Modbus—A *de facto* industry-standard communication protocol used by many manufacturers to promote communication to instruments, equipment, PLCs, and DCS systems. Modbus is primarily a low-speed serial network.
- HART—Highway addressable remote transducer (HART) protocol is widely used by many manufacturers to transmit digital data across the analog wiring between smart devices. In the water industry, HART is primarily used to gather additional data beyond a measurement signal and to facilitate digital calibration of various devices.
- Fieldbus—A digital network intended for process control that interconnects field devices, such as flowmeters, to a process control system. This network operates over standard analog wiring and provides a multitude of data from the various devices back to a centralized controller.
- Ethernet—This is a widely used local area network standard technology. The most common protocol over Ethernet is TCP/IP. Ethernet includes various IEEE standard variants including wired and wireless systems. In the water industry, Ethernet is primarily used to communicate between intelligent systems and equipment, and many flowmeter manufacturers are now embedding this technology in their products.
- Profibus—Originating in Germany, this protocol is supported by many manufacturers as a fieldbus technology. There are several variants of this protocol (DA, FP, FMS), each with similar capabilities to allow for the transfer of digital data from field-level devices to a control system.
- UCA—Utilities Communications Architecture (UCA™) is a protocol primarily used in the electrical power industry. The concept is to superimpose digital data over power lines, thus eliminating the need for a separate communications medium. Applications include accessing signal information from remotely located pump stations; however, this protocol is not widespread in the water industry.

DESIGN AND SYSTEM INTEGRATION

Organizations measure flow with the intent of using the flow value to make decisions. At the fundamental level, flow values are used to monitor and control equipment. Rarely is the monitoring done exclusively by a person; instead, the flowmeter signal is connected to a system.

The thought process of what and how to connect devices into a system is called *design*. In the design process, the engineer determines requirements, develops plans and specifications, solicits the help of an internal department or external contractor to procure materials, and then implements the work. Once the work proceeds past design, the engineer may assist with startup and commissioning to validate the new system.

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With rare exceptions, contractors do not perform design. Their role is to procure, fabricate, and physically install equipment, and then perform the necessary PLC and SCADA configurations to complete the installation. For most installations, the contractor hires a specialty contractor, known as a *systems integrator*, to perform the work associated with connecting instruments like flowmeters into a PLC system and then completing the necessary software integration to make a complete and operable system.

For automation projects, including the installation of new flowmeters, design is typically performed by a registered professional engineer, while installation is typically performed by a systems integrator. The selection of each specialist is subjective based on criteria beyond the scope of this chapter.

Monitoring

Flow signals are generally measured and displayed locally, at or near the measuring device, and then transmitted to a control system. The control system interface is typically a PLC located in a control panel. Once the signal reaches the PLC, it is converted to a digital signal for use within PLC logic and for transmission to the SCADA. At the SCADA level, the flow signal is scaled to engineering units and displayed on an HMI graphic, either as a numerical value or as part of a graphic animation. Sometimes the signal is also sent to a historian to time and date stamp the value for historical trending and similar purposes.

Control

Often, flow is measured with the intention of initiating automated action based on the actual flow value. For example, the treatment plant influent flow may be used to pace chemical metering pumps. In this example, a flow signal is transmitted to a control system, typically a PLC system. The signal is digitally converted and used within the PLC logic. The PLC system is connected to SCADA, and from the HMI, an operator enters a flow ratio setpoint, alarm setpoints associated with flow (i.e., low flow, high flow), and similar parameters. These signals are transmitted to the PLC, which then controls equipment based on the actual flow and the various setpoints.

Distribution System

Most pump stations have several flowmeters to measure both influent and effluent station flow. This signal is typically sent to a local PLC or RTU for monitoring and control purposes. Additionally, the flow signal is traditionally transmitted to a centralized location, such as a treatment plant, to allow for remote monitoring and supervisory control of the station using the SCADA system.

Design Considerations

When installing flow-measurement devices, several items, depending on the application, should be considered as part of the design process. These include:

- Differential head devices (liquid-flow measurement). Mount the secondary differential pressure transmitter at or below the centerline of the measuring device so entrained air or gases will vent back into the process line.
- Differential head devices (gas-flow measurement). Mount the secondary differential pressure transmitter at or above the centerline so any condensate will drain back into the process line.
- Open-channel flow devices. Mount the secondary transmitter device in a way that allows easy servicing and calibration.

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- Devices with remote-mounted electronics. Mount the electronics at a level that is easily viewable by an operator and outside of any classified area if possible. If mounted outdoors, consider adding a sunshield to allow viewing in bright daylight.
- Upstream and downstream distances. Most flowmeters require an unobstructed flow path to and from the flowmeter to improve accuracy and repeatability. These distances vary by device and are generally provided by the manufacturer.
- Accessibility. When locating the flowmeter and its ancillary devices, consider maintenance activities such as reading displays, calibration, and removal/replacement. Include additional valves to provide isolation and bypass so the process can continue in the absence of the flowmeter. Additionally, consider the time of day and potential weather conditions by addressing lighting, access to power, and overhangs to limit the effect of wet weather on service personnel.
- Ground loops. A ground loop occurs when more than one ground connection path exists between two devices or instruments. Ground loops affect the instrumentation signals, leading to instability and inaccurate signalization. The two most common ground-loop situations encountered when connecting a flowmeter to a PLC system are redundant connections of the shield wire and ground connection between the device body and signal output. For the first, the solution is to simply remove the shield connection at one end. The second requires removing the connection between the device body and signal output or installing a signal isolator on the signal output.
- Maximum loop resistance. While less common today, total loop load occasionally occurs on loops with several physically connected devices. Most instruments are designed to support a maximum loop load resistance of 600–750 , which translates to two or three devices. The way to address this situation is to install a signal booster, such as a current-to-current isolator.

Signal Conditioning

Depending on the flowmeter technology deployed, measurement conditioning of the raw flow measurement value may be necessary. Most flowmeters have a built-in converter to translate the measurement value to a useable value such as gallons per minute. Differential-pressure-based measurement is an example of a nonlinear measurement that requires conversion by a secondary instrument (in this case, square root extraction). Another example is open-channel flow using a weir or a flume, which requires a secondary instrument to convert the nonlinear level measurement to a flow value. The key is to recognize the need to determine the specifics of measurement conditioning as part of the design, understanding that not all flowmeters generate a signal linear to actual flow.

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Chapter 6

Field Testing

Large rate-type flowmeters are vital components in water treatment and delivery processes. They are used to control chemical-feed rates, for billing purposes in custody transfers, for process control, and to account for the total volume of water being introduced into a distribution system or treatment process. Unfortunately, these meters are prone to failure due to age, corrosion, mineral buildup, and misuse. Overbilling, overfeeding chemicals, loss of process control, and skewed distribution estimates are just some of the problems that occur when these meters become inaccurate. Periodic flowmeter calibration is necessary to ensure proper flow measurement and process control.

IN SITU TESTING METHODS

Because of their size and function, it is not usually possible to remove these flowmeters and send them to a testing facility for calibration. Also, the piping and proximity of obstructions like valves, check valves, elbows, and strainers can have a tremendous impact on a meter's accuracy. If possible, it is best to test these meters on site in their *natural setting*. There are several methods for doing this, all based on a comparison between the meter flow and the testing method flow—performing a reservoir drawdown test, using a Pitot rod to independently establish the flow rate, or attaching a portable ultrasonic flowmeter (e.g., a transit-time flowmeter or a Doppler device) near the meter. Table 6-1 summarizes in situ testing methods.

Reservoir Drawdown Testing

Water volumes in reservoirs such as tanks, standpipes, towers, and underground basins can be used to determine the accuracy of an influent or effluent meter, which either feeds or withdraws from said reservoir. The volume of water inside a storage structure can easily be determined based on its geometry. By recording the change in volume over a fixed period of time, the average flow rate or change in storage volume, can be computed and

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Table 6-1 Summary of in situ flowmeter testing methods

Field Testing Methodology	Accuracy Range of Test	Variables That Affect Test Accuracy
Reservoir drawdown testing	±3%	• Measurement device accuracy. The method used to measure the level in the reservoir and the corresponding precision and accuracy of the measurement device • Time length of the test. Longer tests yield more consistent and accurate test results. • Isolation-valve leakage can dramatically affect test accuracy; 24-hour tank isolation verification can reduce or eliminate this variable.
Pitot testing	±2%	• Measurement device accuracy. Accuracy and precision of the differential sensor or manometer. • The precision of the measured pipe diameter. • Test methodology. Rod biasing, order of operations, and measurement validation. • Time length of test. Longer tests yield more consistent and accurate test results. • Velocity profile and pipe factor. This is critical to accurate Pitot testing and is measured as part of the testing methodology. • Length of unobstructed upstream straight pipe.
Ultrasonic transit time	±5%	• Measurement device accuracy. The accuracy, precision, and placement of the velocity sensors. • The precision of the measured pipe diameter. This is often difficult to obtain without breaching the pipe wall. Thickness gauges can be used along with circumference measurements to calculate the inside diameter. • Test methodology. Sensor validation and biasing, order of operations, proper sensor orientation, and measurement validation. • Time length of test. Longer tests yield more consistent and accurate test results. • Velocity profile and pipe factor. Often this information is unavailable unless the test site is ideally situated. • Length of unobstructed upstream straight pipe. This variable is critical in ultrasonic testing. The sensors must be installed following good flowmetering practices including upstream and downstream distances from obstruction.

compared to the average metered flow rate (or total metered volume) recorded over the same time period.

Reservoir isolation. Prior to conducting a drawdown test, it is necessary to first perform a reservoir isolation test, which consists of the following steps:

1. The reservoir is filled to its maximum level.
2. It is then isolated—i.e., all the valves that either feed the reservoir or withdraw water from it are closed.
3. The water level in the reservoir is monitored for an extended period (24–48 hours) to ensure that the level remains constant.
   a. If the level rises, it indicates that the influent valve(s) is leaking and allowing water to enter the storage structure.

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b. If the level falls, it indicates that the effluent valve(s) and/or the storage structure itself is leaking or allowing water to escape.

c. Ideally, the level in the tank should remain constant, indicating full isolation of the reservoir, which is necessary if an accurate drawdown test is to be performed.

d. Losses due to evaporation are usually negligible except when the reservoir is open to the atmosphere or in climates where the humidity is very low.

Once it has been determined that the reservoir can be isolated over an extended period with little to no change in level, a drawdown test can be performed.

Influent meter testing. Any meter that measures the volume of water fed to a storage structure can be tested, provided that the reservoir's discharge piping is properly isolated. With the reservoir empty or at its lowest level, plant personnel will begin to fill the structure. Once the flow rate has stabilized, the test can begin. The reservoir level and meter reading are recorded at both the start and end of the test period, which concludes when the reservoir reaches its maximum level. The difference in the storage levels is used to compute the total volume of water that entered the storage structure (Figure 6-1). This volume is compared to the volume recorded by the meter to determine the meter's accuracy.

Effluent meter testing. Any meter that measures the volume of water discharged from a storage structure can be tested, provided that reservoirs influent piping is properly isolated. With the reservoir completely full, or at its highest level, plant personnel will begin to discharge water through the effluent meter. Once the flow rate has stabilized, the test can begin. The reservoir level and meter reading are recorded at both the start and end of the test period, which concludes when the reservoir reaches its minimum level. The difference in the storage levels is used to compute the total volume of water that was discharged from the storage structure (Figure 6-1). This volume is compared to the volume recorded by the meter to determine the meter's accuracy.

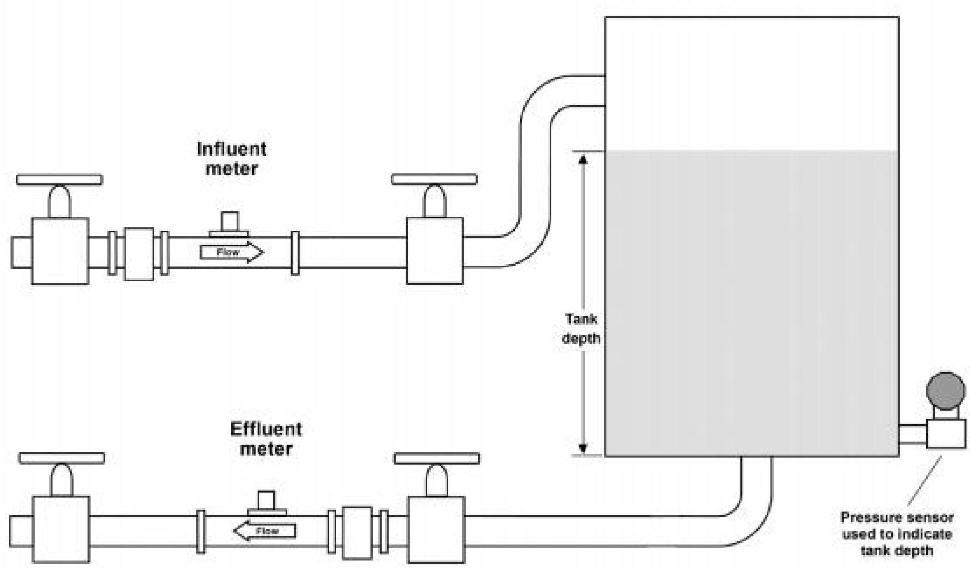

Figure 6-1 Influent/effluent meter comparison

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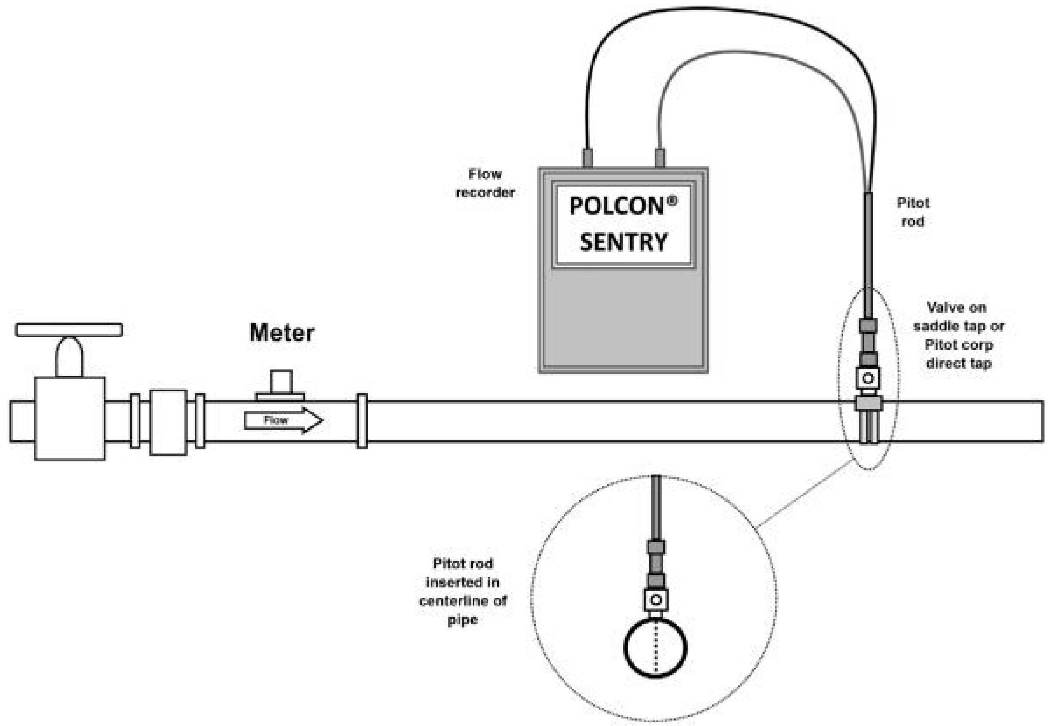

Figure 6-2 Pitot test meter

Pitot Testing

Pitot testing is an in-line testing method in which the flowmeter is operated under normal conditions while the flow rate is monitored and recorded by an inserted Pitot rod. The flow recorder acts as a test meter (Figure 6-2). The performance of both the test meter (Pitot meter) and the flowmeter are compared at various flow rates, spanning the range of the meter. From this comparison, the flowmeter's accuracy is calculated at each flow rate, and its performance is documented.

A Pitot test meter consists of an insertable rod, pressure-sensing lines, and a differential pressure sensor. Water flowing past a Pitot rod generates a differential pressure across the orifices of the rod that is proportional to the flow velocity. The measured flow velocity, along with the measured or known cross-sectional pipe area, is then used to calculate the volumetric flow rate through the pipe. This measured flow rate is then compared to the metered flow rate to determine the accuracy of the meter.

One important aspect of Pitot testing is the measurement of the pipe factor at the test site. This is accomplished by measuring the velocities at multiple points throughout the pipes' cross-sectional areas in what is known as a *traverse*. The pipe factor is used to adjust the measured velocity in the center of the pipe to accurately represent the average velocity across the pipes' cross section at the test site (Figure 6-3).

To conduct a Pitot test, there are certain hydraulic requirements. Ideally, the selected test site would have 20 pipe diameters upstream and 10 pipe diameters downstream of any obstruction, which includes elbows, butterfly valves, strainers, meters, pumps, and flow straighteners (Figure 6-2). Realistically, 10 diameters upstream and 5 downstream is acceptable. Often, it is not possible to obtain an ideal test site, in which case the best possible location is chosen.

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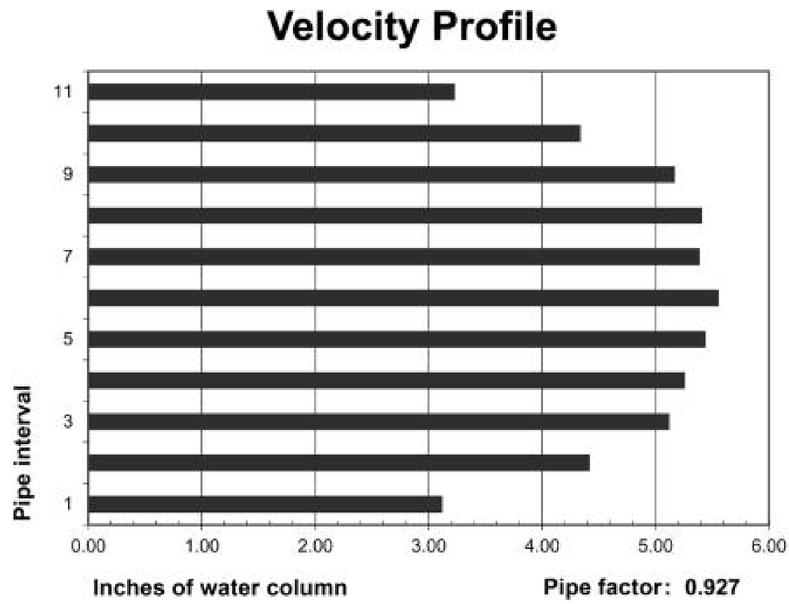

Figure 6-3 Traverse graph

Testing with an Ultrasonic Flowmeter

One commonly used approach to validate the proper operation of flowmeters that are not easily removed for testing in a laboratory environment leverages a clamp-on ultrasonic-style flowmeter. These units are available for rent or purchase from a variety of sources and each has specific requirements relative to the setup for testing. The user is advised to consult the manufacturer on installation and operational requirements before starting the validation process.

Clamp-on flowmeters typically leverage either transit-time or Doppler technology. Both are considered ultrasonic meters, and each is used for different applications. Transit-time technology is typically deployed on clean-water applications where the fluid stream is homogeneous and has minimal solids content or air bubbles. Doppler technology is typically deployed in fluid streams containing solids, air bubbles, or a nonhomogeneous fluid.

Transit-time transducers. Transit time transducers typically operate in the 1–2 MHz frequencies. Higher-frequency designs are normally used in smaller pipes, and lower frequencies are used for large pipes up to several meters in diameter. Transit-time flowmeters typically use two transducers, one that transmits an ultrasonic pulse and the other that receives it. The technology measures the time it takes for an ultrasonic signal to be transmitted from one to the other.

There are two types of installation for this type of device: reflective and direct. In reflective mode, the first sensor generates an ultrasonic signal that reflects off the opposite pipe wall and is received by the second sensor. In direct mode, the first sensor generates an ultrasonic signal that is received by the second sensor mounted on the opposite side of the pipe. In both cases, the process is reversed and repeated, and the upstream and downstream time measurements are compared. With no flow, the transit time should be equal in both directions. With flow, sound travels faster in the direction of flow and more slowly against the flow. This difference in time is used to calculate average fluid velocity, which can be translated into a volumetric flow rate such as gallons per minute. Figure 6-4 provides details on transit-time flowmeters.

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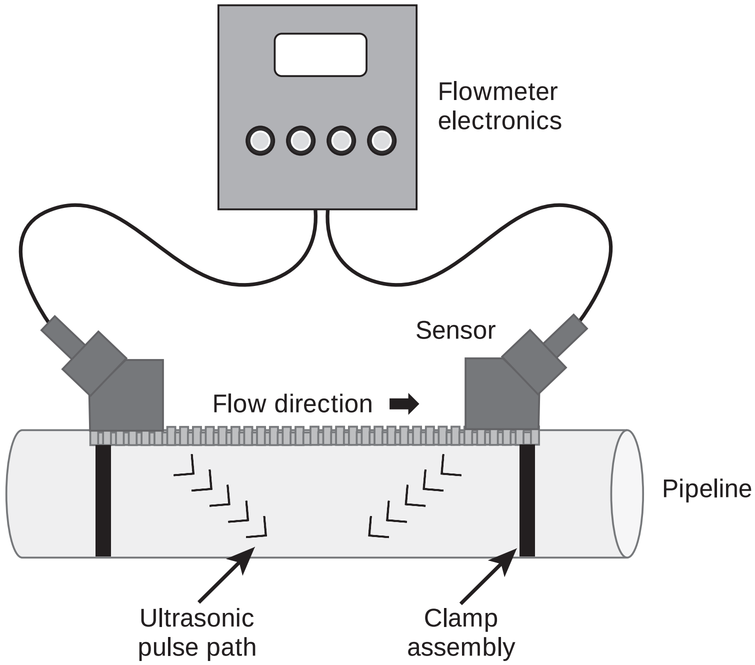

Figure 6-4 Transit-time flowmeter

Doppler transducers. Doppler transducers usually operate within the 640 kHz to 1 MHz frequencies. Doppler flowmeters typically use a single transducer to transmit and receive the ultrasonic sound pulse. The Doppler effect is based on frequency change and is best described using the passing-train analogy. In this scenario, a train approaches and is sounding its whistle. As the train nears, then passes, the listener perceives a distinct change in tone. The reason for the tone change (the Doppler effect) is that the listener is not moving, whereas the train that is transmitting the sound is in motion. Doppler flowmeter technology uses this same principal; sound waves return to a sensor at an altered frequency if reflectors in the liquid are in motion. This frequency shift is in direct proportion to the velocity of the liquid. Accordingly, Doppler technology works best with a fluid that contains solid material or bubbles to reflect the sound wave. Figure 6-5 provides details on Doppler flowmeters.

Performing the test. In general, to conduct testing, the user will need the following:

- Access to a horizontal section of the pipe containing the flowmeter requiring validation. The location of the clamp-on meter must follow good flowmeter installation practice including upstream and downstream distances from obstructions and sensor orientation on the pipe.
- The thickness and type of all pipe layers including exterior coating, primary pipe material, and any interior lining. These measurements are critical to allow for accurate flow measurement.
- Details on the fluid including viscosity and/or density (varies by manufacturer and technology).
- Power source to power the test equipment.
- Data logger to capture flow results over time. If the meter requiring validation is not connected to a data logger such as SCADA, the testing data logger should have two channels to allow for synchronization of the two measured flow values.

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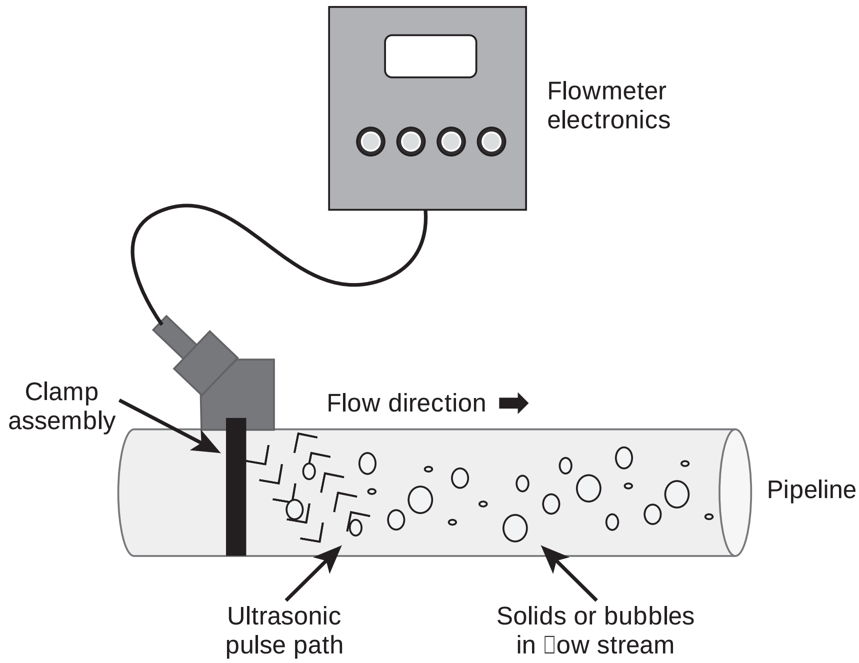

Figure 6-5 Doppler flowmeter

- Installation materials specific to the device, such as sandpaper to remove paint layers, clamping devices to hold sensors in place, and a coupling compound for good connectivity of the sensor(s) to the pipe.

Installation should follow the manufacturer's instructions. Once installed and appropriately calibrated, the system should operate for a period of time to allow sufficient capture of data.

DIAGNOSTICS AND VERIFICATION

Diagnostic Measurements

Electronic meter designs may offer diagnostics that automatically or manually identify conditions that may affect meter performance. Diagnostic methods may require the use of an external tool or may be integrated into a meter's design.

The following list provides examples of parameters or analysis measures that a manufacturer may provide for diagnostic measurement via a local display or a digital interface (e.g., RS-232, RS-485):

- Erasable programmable read-only memory checksum
- Configuration change flag
- Status and measurement quality indicators
- Alarm and failure indicators
- Frequency output test
- Digital status output test
- Analog output test
- Power supply test

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Table 6-2 Diagnostic parameters for various flowmeter types

Voltage-Based Technologies	Time-Based Technologies
Electromagnetic flowmeter parameters	Coriolis flowmeter parameters
Coil current	Drive gain or power indication
Coil voltage	Pickoff or signal amplitude
Coil signal time	Temperature output(s)
Reference voltage	Live zero flow indication
External reference	Flowing density or flow tube resonant frequency
Linearity of measuring circuit	Flow tube health indication
Offset of measuring circuit	Flow tube balance or symmetry
Orifice flowmeter parameters	Ultrasonic flowmeter parameters
Upstream pressure	Raw velocities (profile factor and ratios)
Downstream pressure (differential)	Path symmetry
Recovered pressure	Speed of sound (path/chord and average)
Temperature sensor	Gain control levels and limits
	Signal-to-noise ratio
	Vortex flowmeter parameters
	Capacitance sensor
	Temperature sensor
	Reference frequency

Note: Consult the manufacturer for the diagnostic parameters that may be available.

Each type of flowmeter may have unique parameters based on the fundamental measurement principle that may also be tested (see Table 6-2).

To further optimize the use of diagnostics, the operator may baseline a meter's diagnostic indicators manually and/or through an automated process inherent to the meter's design during either meter calibration, initial installation, or both. Deviations from baseline diagnostics are useful in establishing acceptance criteria. During the calibration, meter diagnostics may be monitored for alarm or an out-of-tolerance condition. If an advanced diagnostic test for flow tube health exists, it may be performed after calibration is complete and results are reported. Actual diagnostic capabilities vary by design; the flow calibration facility may consult with the manufacturer to determine an appropriate set of diagnostics for the design.

A meter log file generated at calibration can establish the meter baseline data. Meter log data and/or the results of an automated flow tube health diagnostic may be included to provide a baseline of the metering module performance at calibration. This baseline data can be used to verify the meter's performance upon startup, during operation, and after component changes. The baseline data can also be useful in conducting health checks of the metering module. It is recommended that the manufacturers identify the parameters that define the baseline performance for their products.

Installation Baseline

The operator may baseline the meter, either manually or through an automated process inherent to the meter's design, during the meter's initial installation. Some parameters described previously can be used to baseline a meter's performance. Some manufacturers offer diagnostics that infer change in a meter's flow performance or flow factor. These baseline relationships are useful in establishing acceptance criteria for the various relationships and the need for a flow performance test and adjustment (if necessary).

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Maintenance

Users should follow the manufacturer's recommendations for maintenance. Monitoring diagnostics, performing periodic meter verification procedures, and possibly using long-term monitoring of performance indicators can identify trends and alert the user to abnormal conditions.

Maintenance procedures, like cleaning, should be condition-based (i.e., based on meter diagnostics, process conditions, and/or meter usage). The monitoring of performance indicators can identify the need for cleaning. For example, by monitoring the measured flow density and comparing it to the calculated/real density, it is possible to infer coating of the flow tubes. Performance indicators available to the user are design specific; the meter manufacturer should be consulted about available performance indicators and their interpretation.

Field Meter Verification

The field verification of a metering system consists of monitoring and evaluating metering conditions, diagnostic indicators output by the transmitter, and/or ancillary devices of the metering system designed to identify possible change in the system's performance and the cause. The evaluation of these indicators guides the operator in determining the need to execute a flow performance test (in situ or laboratory), adjust maintenance intervals, and implement design improvements, if necessary, to the metering system.

The operator should follow design-specific meter verification procedures recommended by the manufacturer. At a minimum, the following general meter verification procedures should be performed.

The meter transmitter verification should include the following procedures:

- Verify that the sensor calibration and correction factors in the configuration of the transmitter are unchanged from most recent calibration.
- Verify that all transmitter diagnostic indicators are in the normal state.

For sensor verification, sensor diagnostics may be available that continuously, on-command, or procedurally verify the performance of the sensor and/or infer change in measurement performance.

Users should consult the meter manufacturer for the availability of these types of diagnostics.

RECALIBRATION/PROVING

Some regulatory agencies and/or contracts specify a recalibration/proving interval. In some cases, meter diagnostics may be used to assess the condition of the meter and determine if recalibration/proving is necessary. A flow performance test does not mandate adjustment. The meter under test should not be adjusted or recalibrated if its performance is within the uncertainty of the reference and meter specifications.

Calibration reports generated for all meters should include before-and-after adjustment accuracy data to allow assessment of any error encountered.

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Index

Note: *f*. indicates figure; *t*. indicates table

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M25, *Flexible-Membrane Covers and Linings for Potable-Water Reservoirs*, #30025
M27, *External Corrosion Control for Infrastructure Sustainability*, #30027
M28, *Rehabilitation of Water Mains*, #30028
M29, *Water Utility Capital Financing*, #30029
M30, *Precoat Filtration*, #30030
M31, *Distribution System Requirements for Fire Protection*, #30031
M32, *Computer Modeling of Water Distribution Systems*, #30032
M33, *Flowmeters in Water Supply*, #30033
M36, *Water Audits and Loss Control Programs*, #30036
M37, *Operational Control of Coagulation and Filtration Processes*, #30037
M38, *Electrodialysis and Electrodialysis Reversal*, #30038
M41, *Ductile-Iron Pipe and Fittings*, #30041
M42, *Steel Water-Storage Tanks*, #30042
M44, *Distribution Valves: Selection, Installation, Field Testing, and Maintenance*, #30044
M45, *Fiberglass Pipe Design*, #30045
M46, *Reverse Osmosis and Nanofiltration*, #30046
M47, *Capital Project Delivery*, #30047
M48, *Waterborne Pathogens*, #30048
M49, *Butterfly Valves: Torque, Head Loss, and Cavitation Analysis*, #30049
M50, *Water Resources Planning*, #30050
M51, *Air Valves: Air-Release, Air/Vacuum and Combination*, #30051
M52, *Water Conservation Programs—A Planning Manual*, #30052
M53, *Microfiltration and Ultrafiltration Membranes for Drinking Water*, #30053
M54, *Developing Rates for Small Systems*, #30054
M55, *PE Pipe—Design and Installation*, #30055
M56, *Nitrification Prevention and Control in Drinking Water*, #30056
M57, *Algae: Source to Treatment*, #30057
M58, *Internal Corrosion Control in Water Distribution Systems*, #30058
M60, *Drought Preparedness and Response*, #30060
M61, *Desalination of Seawater*, #30061
M63, *Aquifer Storage and Recovery*, #30063
M62, *Membrane Applications for Water Reuse*, #30062
M65, *On-Site Generation of Hypochlorite*, #30065
M66, *Cylinder and Vane Actuators and Controls—Design and Installation*, #30066
M68, *Water Quality in Distribution Systems*, #30068

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This manual provides information about the most common large flowmeters used in water treatment and in custody-transfer applications, including the Venturi, modified Venturi, orifice plate, electromagnetic (mag), turbine and propeller, transit-time ultrasonic, vortex, averaging Pitot, and averaging insertable electromagnetic (mag). The discussion of these meters covers basic theory, installation, maintenance, and advantages and disadvantages. General concepts applicable to flowmeters are also discussed, including flow characteristics, installation, and performance.

The third edition of this manual contains significant updates that aim to provide more specific information on flowmeters. Additional information has been added on data signals, electronic communication information signal outputs, field testing, and more.

M33

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30033 5/18

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