A FLOWMETER PRIMER

Variable-area and thermal-mass flowmeters are widely used in heat treating applications. Selection criteria: reliability, accuracy, ruggedness, and ease of calibration and maintenance.

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For millennia, humans have been interested in the measurement of flow. As early as 5000 B.C., for example, people living in cities near the Tigris and Euphrates rivers needed the ability to measure water flow to ensure that their aqueducts were properly designed. And ancient navigators constantly worried about wind direction and velocity. Today, scientists take advantage of superchips to design elegant flowmeters requiring no physical change in the process — not even penetration of the pipe through which the medium is flowing. Measurements are based on such principles as memorizing noise patterns in any externally detectable process variable over time.

For most heat treating applications, important flowmeter selection criteria are: reliability, accuracy, ruggedness, ease of calibration, and ease of maintenance. The high accuracy and reliability of today's instruments help users run their processes more economically. The most commonly used flow measurement instruments are compared in the table.

General types of flowmeters

Flowmeters typically measure either volumetric or mass flow:

• *Volumetric flow measurement* looks at the flow of a given volume of the medium over time (for example, cubic feet per hour). This technology uses primarily mechanical flow rate indication, with electronic output normally available as an option.

• *Mass flow measurement* looks at the flow of a given mass over time (for example, pounds per hour). Industrial thermal mass flowmeters with accurate electronic output are discussed in this article.

Conversions between the two measurements can be made if you know the pressure, temperature, and specific gravity of the flowing medium.

Meter types: Flowmeters can be subdivided into several general types:

• *Variable area:* Fluid flow rate is measured as the flowing medium passes through a tapered tube. The position of a float, piston, or vane placed in the flow path changes as higher flows open a larger area to pass the fluid, providing a direct visual indication of flow rate.

• *Differential pressure:* Calculating a fluid flow rate from the pressure loss across a pipe restriction is perhaps the most commonly used flow measurement technique in industrial applications. The pressure drops through these devices are well understood, and a wide variety of configurations are available, each having specific strengths and weaknesses. Variations on the theme of differential pressure flow measurement include the use of pitot tubes.

• *Mechanical:* In these instruments, flow is measured either by passing isolated, known volumes of a fluid (gas or liquid) through a series of gears or chambers (positive-displacement type) or via a spinning turbine or rotor. Measurements using a positive-displacement flowmeter are obtained by counting the number of passed isolated volumes.

• *Electronic:* Magnetic, vortex, and ultrasonic devices are available, all of which have either no moving parts or vibrating elements and are relatively nonintrusive.

• *Thermal mass:* In contrast to volumetric flow devices, thermal mass flowmeters are essentially immune to changes in gas temperature and pressure. Because measurements can be very accurate and repeatable, these devices are used in critical flow measurement applications.

Of these types, variable-area and thermal-mass flowmeters are most often used in heat treating and processing applications.

Variable-area flowmeters

Variable-area flowmeters are simple and versatile devices that operate at a relatively constant pressure drop and measure the flow of liquids, gases, and steam. The popularity of this type of flowmeter in the heat treat shop can be explained by their direct-view design, where flow is indicated me-

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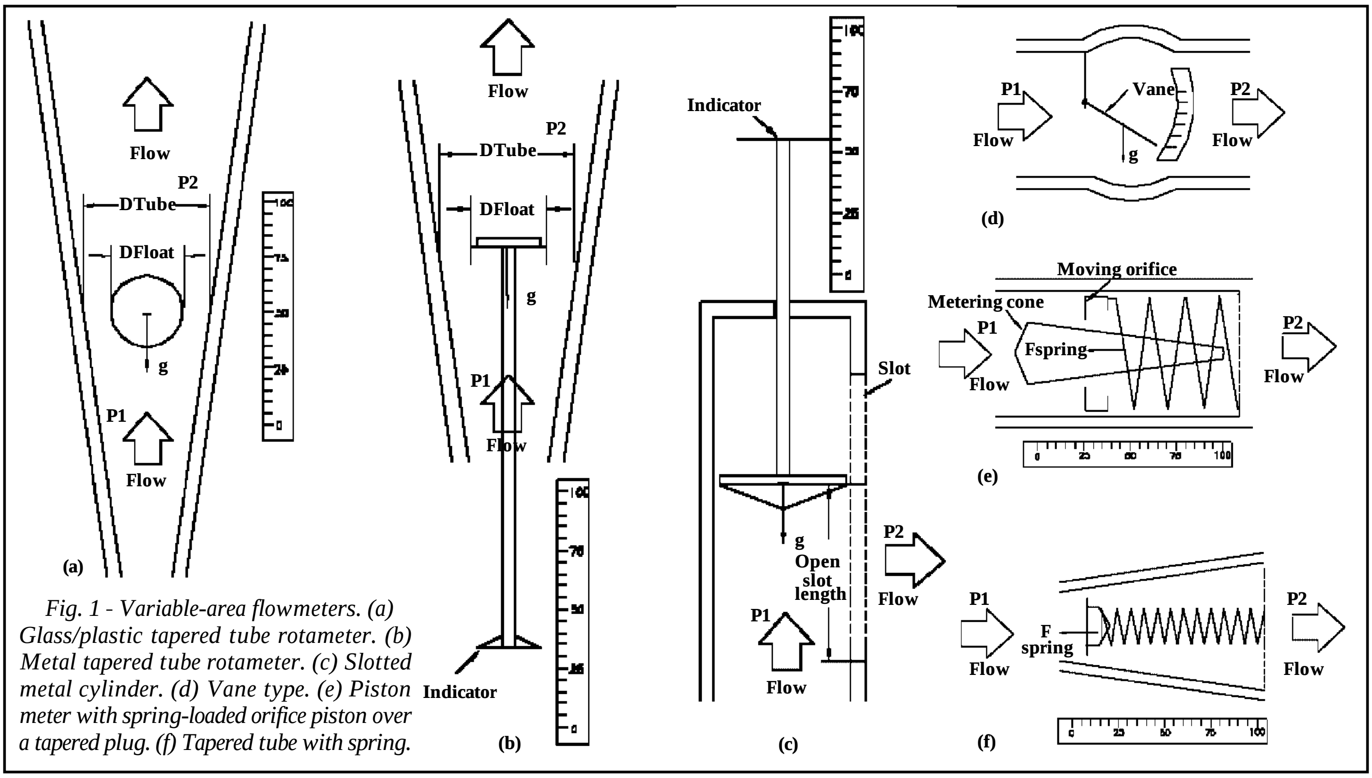

Fig. 1 - Variable-area flowmeters. (a) Glass/plastic tapered tube rotameter. (b) Metal tapered tube rotameter. (c) Slotted metal cylinder. (d) Vane type. (e) Piston meter with spring-loaded orifice piston over a tapered plug. (f) Tapered tube with spring.

chanically, which makes it easy to understand the operating principle.

Several different designs of variable-area flowmeters used in industry are shown in Fig. 1: (a) glass / plastic tapered tube rotameter, (b) metal tapered tube rotameter, (c) slotted metal cylinder, (d) vane type, (e) piston meter with spring-loaded orifice piston over a tapered plug, and (f) tapered tube with spring.

Rotameters: The glass or plastic rotameter, Fig. 1(a), is the most widely used because of its low cost, low pressure drop, relatively wide range, linear visual flow indication, and simplicity of operation. To pass through the tapered tube, the fluid flow must raise the float. The greater the flow rate, the higher the float is lifted. In liquid service, the float rises due to a combination of the liquid's buoyancy and its velocity. With gases, buoyancy is negligible, so the float responds mostly to velocity.

The float moves up and down in proportion to the fluid flow rate and the annular area between the float and the tube wall. As the float rises, the size of the annular opening increases. As this area increases, the differential pressure across the float decreases. The float reaches a stable position when the upward force exerted by the flowing fluid equals the weight of the float. Thus, every float position corresponds to a specific flow rate for a particular fluid's density and viscosity.

This is why it is necessary to size the rotameter for each application. When sized correctly, the flow rate can be determined by matching the float position to a calibrated scale on the outside of the instrument. Many rotameters come with a built-in valve for manually adjusting flow. Several shapes of floats are available for various applications.

Both glass and metal rotameters are available. Glass or plastic rotameters cost less and are more accurate than metal tapered tube rotameters, Fig. 1(b), but may not be able to provide the durability and reliability needed in a manufacturing environment. Metal rotameters are reliable, but the machined tapered tube limits the flow measurement range (turndown). Another limitation is that metal rotameters typically have brass or aluminum bodies, which may make them unsuitable for use in certain gases (ammonia, for example).

Slotted cylinder: A flowmeter used in the process industries substitutes a slotted cylinder for the tapered tube, Fig. 1(c). Compared with a metal rotameter, a greater selection of construction materials and a flow turndown of at least 25:1 (vs. 3.6:1) are provided.

The lower portion of the float is a piston that can "plug" the slot in the cylinder wall. The float rises until enough of the slot has opened to create equilibrium between the two upward-acting flow forces and the single downward-acting force. As for rotameters, when in this equilibrium position, float height is proportional to flow rate.

The basic equations for tapered tube and slotted cylinder flowmeters are similar, with their flowmeter coefficients (K factors) accounting for any differences.

Accessories: However, regardless of the design of the variable-area flowmeter, the flow measurement is taken at some equilibrium point where the fluid flow force is balanced by an opposing force exerted by a "flow element" (such as a float). Either the force of gravity or a spring is used to return the flow element to its resting position when the flow lessens. Gravity-operated flowmeters, Fig. 1(a–c) must be installed in a vertical position, while vane or spring-operated devices, Fig. 1(d–f) can be mounted in any position.

Some variable-area flowmeters can be provided with position sensors and transmitters (pneumatic, electronic, digital, or fiber optic) for connecting to remote displays or controls. Most flowmeters have only flow alarm output signals, although some provide a continuous signal that represents the flow rate.

A variable-area flowmeter or rotameter is typically provided with calibration data and a direct-reading scale for air or water (or both). To size a meter for other service, the actual flow must be converted to a standard flow. Instrument manufacturers use different standard flow units. For liquids, the standard flow is the water equivalent in gallons per minute (gal / min) at 70°F and 10 psi (21°C, 69 kPa); for gases, it's the air equivalent in standard cubic feet per minute (scfm) at 70°F (21°C) and atmospheric pressure. Tables listing standard water and / or air equivalent values are available from flowmeter manufacturers, who also may provide slide rules, nomographs, or computer software for flowmeter sizing.

Features and advantages

Common features and advantages of all *variable-area flowmeters*:

• Mechanical flow measurement with but a single moving part, ensuring measurement reliability

• Application versatility, and availability of a variety of construction materials, inlet and outlet sizes, and types

• Easy installation with generally no straight pipe requirements

• Low pressure drops

• Linear scales, allowing easy flow measurement interpretation

• Electronic output availability, preserving the benefits of mechanical flow measurement

Features and advantages of *tapered-tube rotameters*:

• Low instrument cost (when glass or plastic metering tube is used)

• Can be used for very low flow rates

Features and advantages of *slotted-cylinder flowmeters*:

• Flow measurement accuracy is determined by the precision of the slot manufacturing operation. A good flow range of 25:1 results.

• Instrument specifications can be changed by field replacement of the slotted tube and float, without having to repipe the flowmeter vessel.

• Ability to handle high flows and pressures.

• Improved immunity to the effects of pulsating flows, with no minimum back-pressure.

Limitations common to both tapered-tube and slotted-cylinder variable-area flowmeters: vertical mounting is required and they contain moving parts.

Mass flowmeters described

Thermal-mass flowmeters also are used by heat treaters. In most industrial-grade devices, gas enters the flow body and divides into two flow paths. Most of the flow goes through the laminar-flow bypass, creating a pressure drop that forces a known fraction of the flow through the instrument's sensor tube (Fig. 2).

Heat is applied to the gas flowing through the sensor tube via two externally wound resistance temperature detectors, or RTDs (T_1 and T_2). The RTDs have a dual function: to heat the gas and sense the tube temperature. When molecules of the gas pass through the upstream sensor windings (T_1), they carry away a certain amount of heat. This process is repeated at the downstream sensor windings (T_2), but less heat is transferred from these windings because the gas flow has been preheated by the upstream windings.

The temperature differential ($\Delta T = T_2 - T_1$) between the two RTDs is then measured (in a Wheatstone bridge circuit). Since the temperature difference between the two sensors is directly proportional to the mass flow of the gas, a highly accurate and repeatable flow measurement is obtained. (The coils of the power supply heater shown at the tube's center in Fig. 2 actually extend over the entire length of the tube between the two RTDs.)

Another type of mass flowmeter uses one flow channel with a temperature sensor located in the path of the flow. This technology is simpler, but often less accurate and is limited to higher flow rates.

Accuracy, repeatability: Thermal-mass flowmeters are gas-specific devices and must be calibrated with either the actual gas or a reference gas. This "inconvenience" has led to the

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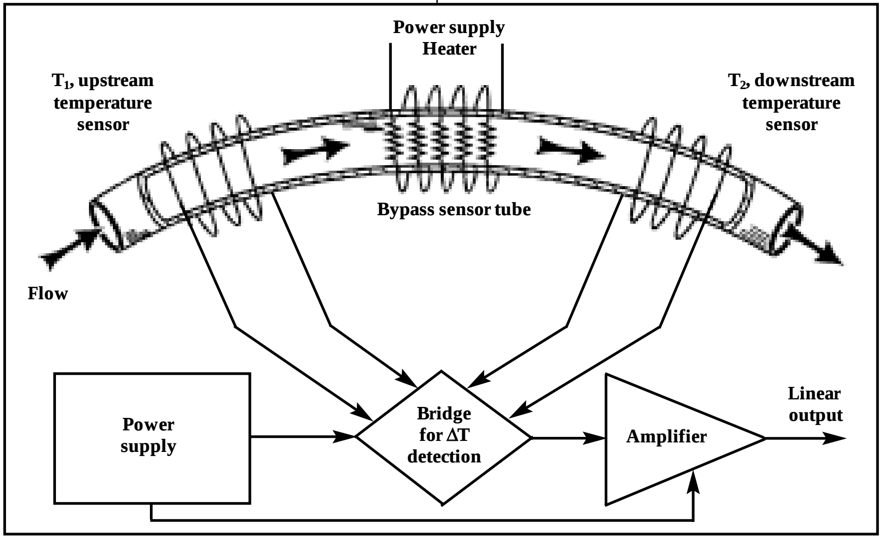

Fig. 2 - Sensor tube measurement component of a thermal-mass flowmeter. (Illustration courtesy Omega Engineering Inc., Stamford, Conn.; Web: www.omega.com.)

Commonly used flow measurement instruments

Industrial flowmeter type	Style	Manufacturer*	Disassembly without unpiping	Sensitivity to dirty fluids	Robust spare parts
Variable-area, including rotameters	Metal tube	Waukee Engineering Co. Inc.	Yes	Moderate	Delicate
	Metal cylinder tube	Meter Equipment Mfg. Inc.	Yes	Low	Moderate
	Glass or plastic tube	Fisher-Porter, Brooks Instrument, King Instrument Co., Dwyer Instruments Inc., Key Instruments	No	Sensitive	Moderate
	Vane type	Universal Flow Monitors Inc., Erdco Engineering Corp., Orange Research Inc.	No	Moderate	Moderate
	Moving orifice	Hedland, Div. Racine Federated Inc.	No	Moderate	Robust
	Piston (with spring)	Insite, by Universal Flow Monitors Inc.	No	Moderate	Delicate
Differential pressure / Orifice	Orifice	Lambda Square Inc., Flowell Corp.	No	Moderate	Robust
	Venturi	Flowell Corp., Fox Valve Development Corp.	No	Moderate	Robust
Turbine / Impeller	Rotary impeller	Roots (BNC Industrial Co. Ltd., TokicoTechno Ltd., and others)	No	Sensitive	Moderate
	Turbine	Hoffer Flow Controls Inc., Sponsler Inc., Great Plains Industries Inc.	No	Sensitive	Delicate
Thermal mass	Thermal mass	Sierra Instruments Inc., MKS Instruments, Brooks Instrument	No	Sensitive	Delicate

** Instruments also may be supplied by companies other than those listed.*

development of many "fixes," and is driving the development of smarter devices. For now, however, primary calibration with the actual gas or a gas of similar molecular characteristics is the only way to ensure accuracy.

The accuracy of mass flowmeters and mass flow controllers is determined by two factors: flow calibration and repeatability. Proper instrument calibration ensures starting point accuracy. Repeatability is the measure of continuous performance-to-specification over the lifetime of the device. Most mass flowmeters and mass flow controllers have an accuracy of ±1% of full-scale and a repeatability of ±0.25% of full-scale.

Several factors affect repeatability. To compensate, highly stable materials and electronic components, as well as precise internal voltage and current regulation, are used. Sensor and bypass design also play a major role in preventing errors caused by contamination and clogging. For example, U-type sensor tubes exhibit residual stresses from bending, which can cause long-term strains and unraveling of sensor coils. These sensors are also more likely to develop drift due to contaminant deposits.

Consideration should also be given to the bypass element. Accuracy can be degraded by changes in temperature if the bypass is an orifice (or venturi), as opposed to a pure laminar-flow element. With an orifice bypass, the pressure drop is proportional to the square of the bypass flow. In this case, the ratio of bypass flow to sensed flow is not a constant, but instead is a complex nonlinear function having temperature-dependent terms such as gas viscosity. Both the nonlinearity and temperature dependence of the orifice bypass can seriously degrade the accuracy of a mass flow controller.

Vacuum process: A heat processing application of thermal mass flowmeters and mass flow controllers is maintaining a specified gas flow rate into a vacuum chamber when the process requires a partial pressure of additive gas. Typically, a throttle valve or an orifice-limiting device is used to control the output of a vacuum pump. This is an extremely pressure-sensitive method and can result in inefficient gas delivery and poor product quality. Mass flow controllers automatically compensate for changes in system pressure caused by vacuum pump fluctuations, and deliver a precisely controlled gas flow rate to the chamber.

Flowmeter selection basics

The first step in selecting a flow sensor is to determine if the required flow rate information should be continuous or totalized, and whether these data are needed locally or remotely. If remotely, should the transmission be analog, digital, or shared? And, if shared, what is the required minimum data-update frequency? Once these questions have been answered, the properties and flow characteristics of the process fluid (gas or liquid), and the properties and con-

Special installation requirements	Mechanical flow reading	Mechanical flow reading/ scale type	Electronic flow reading	Typical full-scale accuracy, % of reading	Typical turndown	Pressure drop
Vertical mounting	Yes	Easy / linear	Available	3.5	3:1	Low
Vertical mounting	Yes	Easy / linear	Available	1–2	25:1	Low
Vertical mounting	Yes	Easy / linear	No	1–2	10:1	Low
No special requirements	Yes	Easy / linear	No	2–5	5:1	High / average
Straight pipe upstream and downstream required	Additional instrumentation required	Complex / square root	Available	2–3	3:1–10:1	Low / average
No special requirements	Yes	Easy / linear	No	1–5	5:1	Low / average
Straight pipe upstream and downstream required	Additional instrumentation required	Hard / square root	Available	0.5–2	3:1–10:1	High
Straight pipe upstream and downstream required	Additional instrumentation required	Hard / square root	Available	0.5–2	3:1–10:1	Average
No special requirements	Additional instrumentation required	Moderate / linear, total flow counter	Available	0.5–2	10:1–20:1	Average
Straight pipe upstream and downstream required	Additional instrumentation required	Moderate / linear	Yes	0.5–3	10:1–20:1	Average
Straight pipe upstream and downstream required	No	Not applicable	Yes	1–2	10:1–100:1	Average / high

figuration of the piping that will accommodate the flowmeter should be evaluated.

Next, determine the required flowmeter range by identifying the minimum and maximum flows (mass or volumetric) that will be measured. After that, the required flow measurement accuracy needs to be determined. Accuracy typically is specified in percentage of actual reading, percentage of calibrated span, or percentage of full-scale units. Accuracy requirements should be separately stated at minimum, normal, and maximum flow. Unless you know these requirements, meter performance may not be acceptable over its full range.

Flowmeter sizing: When purchasing a new flowmeter to measure gas flows in heat treating applications, it's important to remember the distinction between the instrument's operating range and design range.

Some variable-area flowmeters offer full-scale operation, while others offer a very limited range: "not below 25% and not above 90% of scale capacity," for example. In other words, if the flowmeter is rated for 0 to 2000 cubic feet per hour (cfh), you can only obtain accurate readings when the flow is between 500 and 1800 cfh.

If flow measurement has to cover a wide flow range, then select a flowmeter that has a high turndown. An alternative but costly approach is to install several different-size flowmeters with automatic or manual switching based on flow range.

A good rule of thumb for sizing a flowmeter is to purchase one "in the middle third"; that is, size it so that the actual flow will be no less than 33% and no higher than 67% of the scale you select. This gives you the ability during actual operation to compensate for unexpected changes in flow requirements that may occur. Over the life of a heat treating furnace, process requirements and operating conditions often change, sometimes dramatically, and you want your gas measurement to remain accurate.

For a variable-area rotameter, if knowing the proper flow rate is required, be aware that a change in temperature, pressure, or specific gravity of the gas from that for which the meter was calibrated will cause a serious error in the indicated scale reading. It is quite common in a heat treat shop to find flowmeters operating at pressures and temperatures different from those for which they were calibrated.

Mass flowmeters: For a thermal-mass flowmeter, it is important to understand its principle of operation and calibration requirements. As is true for most instrumentation, application conditions must be completely and accurately known to avoid costly mistakes that can delay a start-up or even damage the device. Information required to properly specify a mass flowmeter includes gas type, estimated flow rate, pressure range, temperature range, and the allowable pressure drop for the system.

Once flow parameters have been

defined, the proper flow body size can be determined by following these steps:

1. Consult manufacturer product specifications for the acceptable flow range of each flow body.

2. Convert the estimated flow rate to the corresponding units listed in the product specifications.

3. If the gas to be measured is not the manufacturer's specified standard gas (typically nitrogen), convert the flow rate to the equivalent nitrogen flow rate. This is done with a correlation factor, K, defined as the ratio of the actual gas flow rate to the equivalent nitrogen flow rate. To obtain the equivalent nitrogen flow rate, divide the actual gas flow rate by the K factor.

4. Select the flow body size that will accommodate the estimated flow rate.

5. Ensure that the differential pressure falls within the acceptable range for the selected flow body size and flow rate.

(*Note:* As mentioned previously, primary calibration with the actual gas or a gas of similar molecular characteristics is the only way to confirm proper accuracy.)

Flow variations with correspondingly large pressure drops require a limitation on turndown to maintain accuracy. Thus sizing, turndown, and accuracy must be considered when selecting a thermal-mass flowmeter.

Remember, too, that mass flowmeters are not sensitive to inlet pressure and temperature; in other words, they "auto compensate" for changes in these variables.

All flowmeters, regardless of type, should be checked periodically for calibration and accuracy, before flow measurement errors start affecting your process. Thermal-mass flowmeters use electronic measurement, therefore sensor failure modes are not always known — a failed sensor may give readings that are either too high or too low. Users can visually inspect most variable-area flowmeters by following the manufacturer's instructions.

Future flowmeter trends

The heat treat shop of tomorrow will see even more intelligent or "smart" instrumentation capable of using well-defined digital protocols to communicate with remote supervisory systems. Expect to see diagnostics performed via the Internet or satellite. Plant location won't be a factor. In a future scenario, a manufacturer in one country could monitor and perhaps change process parameters of equipment running in another factory halfway around the world. And given proper authorization, that same manufacturer could sit at his desk and remotely monitor an installation for status checks. Suppliers of heat treated parts exploiting this feature could save service trips and avoid lengthy delays in production. **HTP**

Resources

• *Encyclopedia of Fluid Mechanics: Solids and Gas-Solids Flows,* N.P. Cheremisinoff (Ed.): Gulf Professional Publishing, Elsevier Science / Harcourt, Burlington, Mass., 1986, ISBN 0872015149, 1506 pages.

• "Frequently Asked Questions About Flowmeters," by Daniel H. Herring: *Heat Treating Progress*, Vol. 2, No. 7, October 2002, p. 23–25.

• *Modern Compressible Flow: With Historical Perspective,* by John D. Anderson: McGraw-Hill Companies, New York, 1990, ISBN 0070016739, 650 pages.

• National Institute of Standards and Technology (www.nist.gov), Gaithersburg, Md.

• *Principles of Gas-Solid Flows*, by Liang-Shih Fan and Chao Zhu: Cambridge University Press, New York, 1998, ISBN 0521581486, 575 pages.

• Useful websites: http: / / apps.fss.gsa.gov (Federal Supply Service, U.S. General Services Administration); www.flowmeterdirectory.com; www.manufacturing.net (Reed Business Information, Div. Reed Elsevier Inc.); www.omega.com (Omega Engineering Inc.); www.sensorsmag.com (*Sensors,* Advanstar Communications Inc.); www.yokogawa.com (Yokogawa Electric Corp.).

• "Variable-Area Flowmeters," by C.R. DeFasselle: *Measurement & Control,* 1994.

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Very useful, **Circle 270**
Of general interest, **Circle 271**
Not useful, **Circle 272**