Feature Report

CHEMICAL ENGINEERING

ELECTRONICALLY REPRINTED FROM FEBRUARY 2014

Advanced Thermal Dispersion Mass Flowmeters

A look at the principles of operation, installation and calibration

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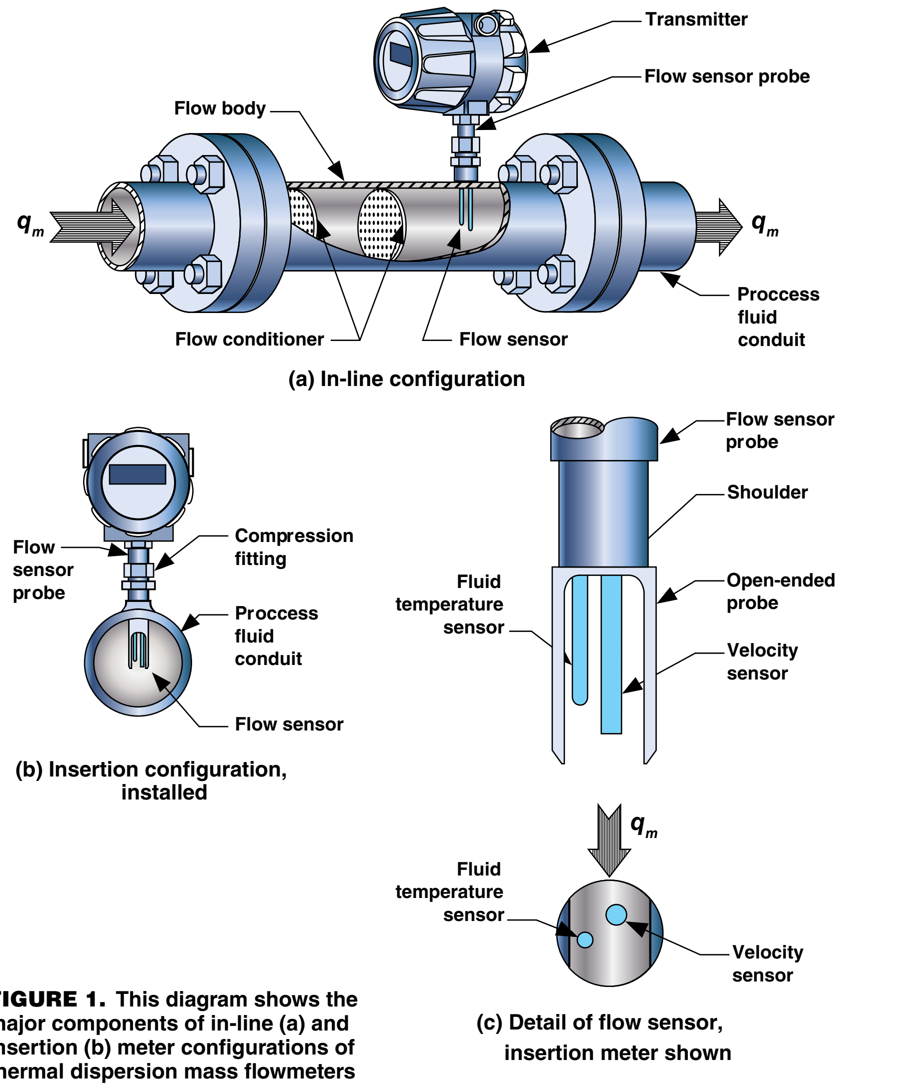

FIGURE 1. This diagram shows the major components of in-line (a) and insertion (b) meter configurations of thermal dispersion mass flowmeters

Thermal dispersion (TD) mass flowmeters measure the mass flowrate of fluids (primarily gases) flowing through a closed conduit, such as a pipe. This article describes the operation and installation of TD mass flowmeters, and gives the reader information about what applications these meters are most suited for.

Background

The first general description of TD mass flowmeters is attributed to L.V. King who, in 1914 [*1*], published his famous King's Law revealing how a heated wire immersed in a fluid flow measures the mass velocity at a point in the flow. He called his instrument a "hot-wire anemometer." The first application of this technology was hot-wire and hot-film anemometers and other light-duty TD flow sensors used in fluid mechanics research and as light-duty mass flowmeters and point velocity instruments. This class of TD mass flowmeters is described in Ref. 2.

It was not until the 1960s and 1970s when industrial-grade TD mass flowmeters emerged that could solve the wide range of general industry's more rugged needs for directly measuring the mass flowrate of air, natural gas and other gases in pipes and ducts. That is the class of instruments described here.

TD mass flowmeters measure the heat convected into the boundary layer of the gas flowing over the surface of a heated velocity sensor immersed in the flow. Since it is the molecules of the gas, which bear its mass, that carry away the heat, TD mass flowmeters directly measure mass flowrate. Capillary-tube thermal mass flowmeters constitute a second type of thermal mass flow technology, but their principle of operation and their applications are sufficiently different from TD mass flowmeters that the American Society of Mechanical Engineers (ASME) has published separate national standards for each type [*3, 4*].

Typical gases monitored by industrial TD mass flowmeters include: air, methane, natural gas, carbon dioxide, nitrogen, oxygen, argon, helium, hydrogen, propane and stack gases, as well as mixtures of these gases and mixtures of hydrocarbon gases. Common applications are: combustion air; preheated air; compressed air; fluid power; boilers;

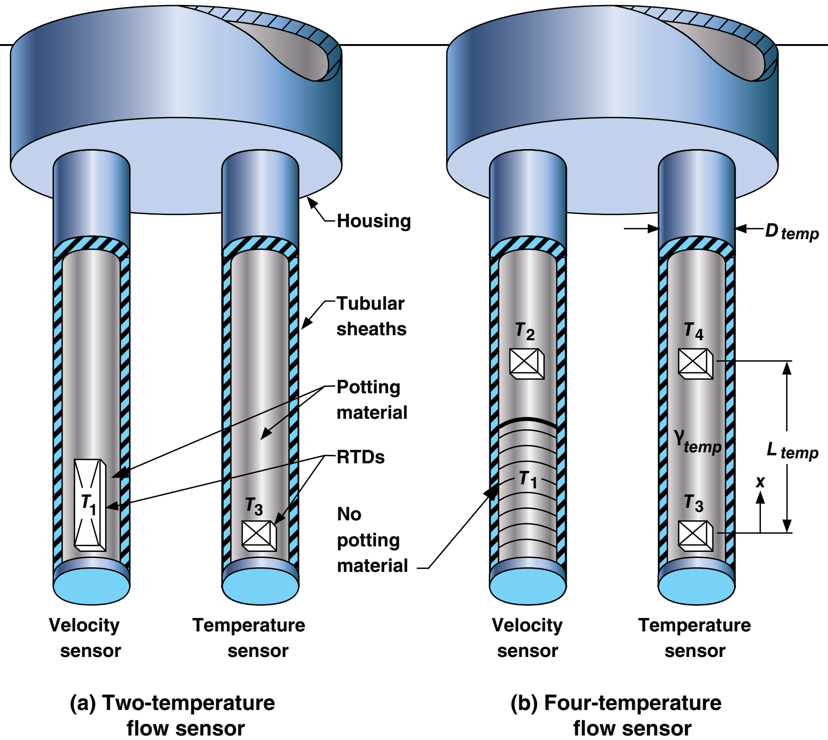

FIGURE 2. Two kinds of thermal-dispersion mass flow sensors are shown here

electric power plants; cooling, heating, and mixing; drying of materials; food and beverage industries; natural gas distribution; aeration and digester gas monitoring in wastewater-treatment plants; cogeneration with biogas; fuel gas; flare gas; semiconductor manufacturing; heating, ventilation and air conditioning; single and multipoint stack-gas monitoring; and chemical reactors.

General description

TD mass flowmeters directly measure the mass flowrate of single-phase pure gases and gas mixtures of known composition flowing through pipes or other flow conduits. As discussed in a later subsection, they also have limited application to single-phase liquids of known composition. In most of the following, we shall assume that the fluid is a gas, without the loss of applicability to liquids. Multivariable versions additionaly provide an output for gas temperature and also, but less commonly, of gas pressure.

TD mass flowmeters have two primary configurations: in-line and insertion. Figures 1a and 1b, respectively, show these two configurations and their major components. Figure 1c shows the flow sensor that is common to both configurations, although in smaller in-line meters the flow sensor may not have a shield.

In-line. In-line flowmeters are applied to pipes and ducts with pipe-size diameters typically ranging from about 10 to 100 mm (0.25 to 4.0 in.), but some manufacturers offer pipe sizes up to 300 mm (12.0 in.) dia. Process connections include flanges, pipe threads and compression fittings. The built-in flow conditioner, described later, reduces the length of upstream straight pipe required to achieve independence of upstream flow disturbances.

Insertion. Insertion flowmeters [*5*] usually are applied to larger pipes, ducts and other flow conduits having equivalent diameters typically ranging from approximately 75 mm to 5 m. Because insertion meters are more economical than in-line meters, they also have found wide use as flow switches. Compression fittings and flanges are commonly used process connections. Insertion meters measure the mass velocity at a point in the conduit's cross-sectional area, but for applications with smaller conduits, they may be flow calibrated to measure the total mass flowrate through the conduit.

Multipoint insertion meters measure the mass velocities at the centroids of equal areas in the cross-section of large pipes, ducts and stacks. The total mass flowrate through the entire conduit is the average mass velocity of the several points multiplied by the total cross-sectional area and the standard mass density of the gas [*6*].

Types of flow sensors

The flow sensor for the insertion flowmeter shown in Figure 1c has a unique design incorporating an open-ended probe with a shoulder. Traditional insertion meters have a shield with a closed end that can cause the flow over the velocity sensor to be non-uniform and turbulent. The open-ended probe shown in Figure 1c protects the sensors but does not have this problem. Additionally, the probe in traditional insertion meters has a constant diameter and no shoulder.

Whereas the largest portion of the flow around such traditional insertion probes flows circumferentially around the probe, a smaller fraction flows axially down the probe, enters the window in the shield, and passes over the velocity sensor, causing it to measure a velocity higher than the actual velocity in the flow conduit. Since the amount of this secondary flow varies with the depth of insertion into the flow stream, its magnitude during flow calibration may be different than that of the actual field application. This can impair the accuracy of velocity measurement. The probe in Figure 1c has a length of reduced diameter and a shoulder just above the flow sensor that redirects this axial downwash so that it flows circumferentially around the probe before it can pass over the velocity sensor, thereby minimizing this source of inaccuracy.

Traditional sensors. Figure 2a shows a traditional TD flow sensor used in in-line and insertion mass flowmeters intended for industrial-grade applications. This flow sensor has a velocity sensor and a separate temperature sensor immersed in the flow stream. For that reason, TD mass flowmeters are also named "immersible" thermal mass flowmeters. The velocity sensor has a single electrically self-heated temperature sensor element located in its tip that both heats the velocity sensor and measures its own average temperature T_1. The gas temperature sensor has a single non-self-heated temperature sensor element T_3 located in its tip that measures the gas temperature T. Because it has a total of two temperature sensing elements, the flow sensor in Figure 2a is called a "two-temperature" flow sensor. The velocity sensor and the temperature sensor are mounted side-by-side. Each is enclosed in a rugged, sealed, single-ended, corrosion-resistant metallic tube, usually composed of 316 stainless steel or a nickel alloy. The introduction of this kind of rugged construction in the 1960s and 1970s is responsible for transforming thermal anemometers into industrial-grade instruments. In traditional velocity sensors of the kind shown in Figure 2a, the T_1 sensor is potted into the tip of the tubular sheath. Typically, the potting, or filler material is ceramic cement or epoxy. Heat sink grease also has been used for this purpose.

For higher accuracy and higher stability applications, the temperature sensing elements in the velocity sensor and the temperature sensor in Figures 2a and 2b are either wire-wound or thin-film platinum resistance temperature detectors (RTDs) protected by a thin insulation layer of glass or ceramic. The electrical resistance of RTDs increases as temperature increases, providing the means for transducing their electrical output into temperature. The platinum RTD sensor element in the velocity sensor is called the T_1 element and has a relatively low electrical resistance in the range of about 10 to 30 Ohms. The platinum RTD element in the temperature sensor is called the T_3 element and has a relatively high electrical resistance in the range of 300 to 1,000 Ohms. Other types of temperature sensing elements, such as thermistors, thermocouples and micro-electronic machined devices, have been used for applications with lower accuracy requirements. In the following, we shall assume that the T_1 and T3 elements are platinum RTDs.

The outside temperature external to the flow sensor may be different than the gas temperature in the flow conduit. For that reason, heat can be conducted into or out of the stems of the velocity sensor and the temperature sensor. In the field, the heat conducted in this manner through each stem may be different from its value at the time of flow calibration if the outside temperatures are different. Additionally, heat can be conducted from the hot velocity sensor to the cooler temperature sensor via their stems. Both effects are further complicated because they depend on the mass flowrate. These phenomena are collectively called "stem conduction." Stem conduction is a large fraction of the total heat supplied to the velocity sensor and is an unwanted quantity. Left uncorrected, stem conduction constitutes a major source of error in measuring mass flowrate. Flow sensors with long stems have less stem conduction than those with short, stubby stems.

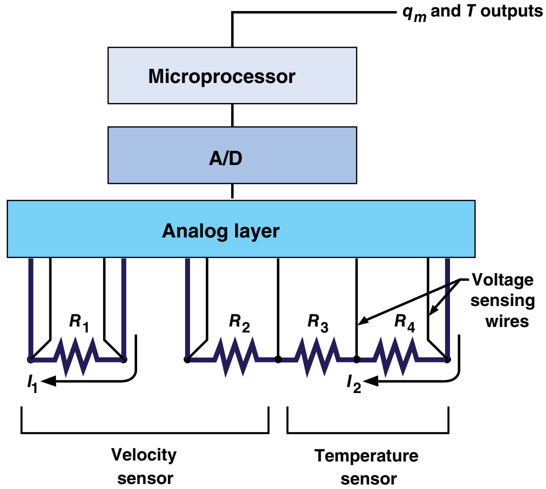

FIGURE 3. In the four-temperature microprocessor-based system, the flowmeter drives the velocity sensor so that the temperature difference $\Delta T = T_1 - T$ is maintained constant. The system automatically corrects for changes in gas selection, gas temperature and gas pressure

Four-temperature sensor. Figure 2b shows a TD flow sensor that solves the stem conduction problem by employing a total of four platinum RTD temperature-sensing elements. The velocity sensor in this "four-temperature" flow sensor has a T_1 element as before, but now has a second T_2 element in its stem that is separated from the T_1 element. The temperature sensor has a T_3 element as before, but now has a second T_4 element in its stem that is separated a distance from the T_3 element.

The T_1 element is a wire-wound platinum RTD with a resistance ranging from 10 to 30 Ohms. The T_2, T_3 and T_4 sensors are thin-film RTDs with a resistance ranging from 500 to 1,000 Ohms. In operation, the T_1 and T_2 elements together act as a heat-flux gage that measures the fraction of heat conducted down the stem of the velocity sensor. The T_3 and T_4 elements perform the same function for the temperature sensor. The addition of the T_2 and T_4 temperature sensing elements in the four-temperature flow sensor facilitates correction for stem conduction, whatever the cause.

The use of the potting material between the T_1 element in Figure 2a and the internal surface of the sheath has potential long-term stability problems because the potting material can crack or otherwise degrade due to differences in the thermal expansion coefficients of the potting material and the sheath material when exposed to gas temperatures that cycle, change frequently, or are elevated. Any change in the potting material causes a change in the "skin resistance" of the velocity sensor and thereby its stability. As discussed in the following, skin resistance, along with stem conduction, are the two major factors that can degrade measurement accuracy if not managed properly.

The construction and assembly of the T_1 element of the four-temperature flow sensor in Figure 2b eliminates the skin resistance problem by: (1) avoiding altogether the use of any potting materials between the T_1 element and the internal surface of the sheath and (2) using mating materials that have the same coefficient of thermal expansion. Filler materials are avoided

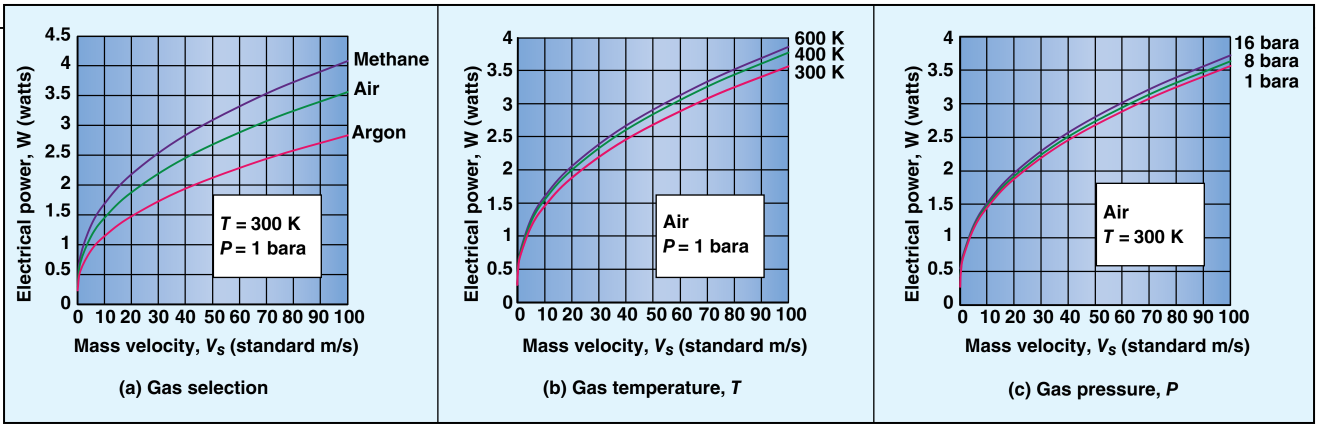

FIGURE 4. These plots show the management of changes in gas selection, gas temperature, and gas pressure with the four-temperature microprocessor-based system. ΔT = 50K. In all figures the "standard" conditions for V_S (standard m/s) are 70°F and 1 atm

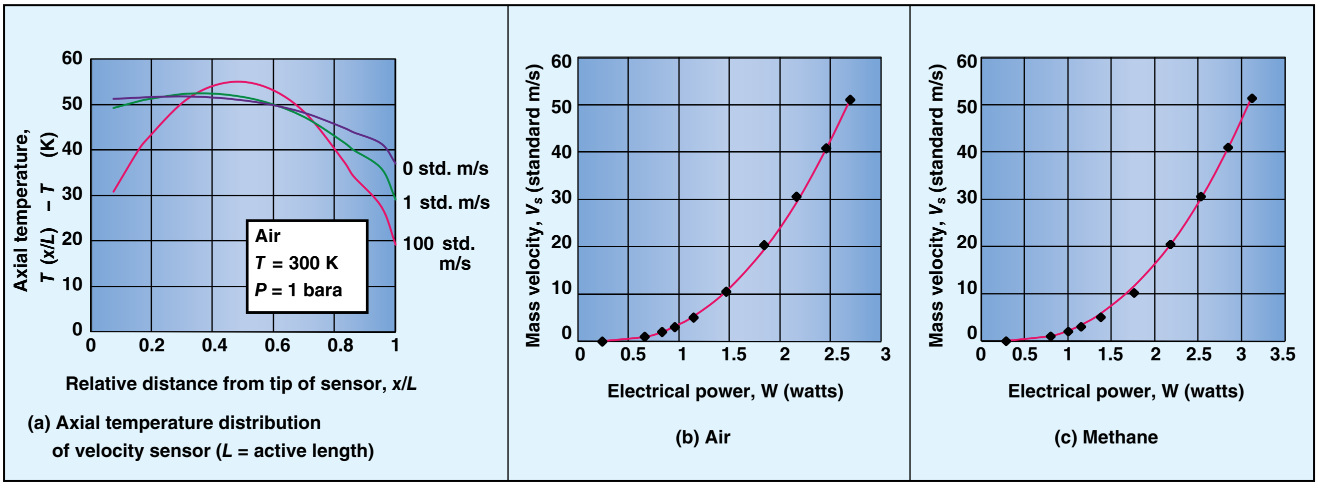

FIGURE 5. These plots compare flow calibration data and the output of the four-temperature microprocessor-based system. ΔT = 50K, and T and P are at room (ambient) conditions. "Standard" conditions for V_S (standard m/s) are 70°F and 1 atm

by means of tightly fitting, as in swaging or press fitting, the wire-wound T_1 element into the sheath. Such velocity sensors are known as "dry" sensors, as opposed to velocity sensors fabricated with potting cements or epoxies that are wet when mixed. In contrast with the velocity sensor, any degradation of potting materials in the temperature sensor changes only its time response, a relatively minor effect.

In operation, the gas temperature sensor in the TD mass flowmeter measures the gas temperature T. The sensor drive in the transmitter electronics delivers an electrical current I_1 to the velocity sensor, such that it is self-heated to an average temperature T_1 that is elevated above the gas temperature. Since it is the molecules of the gas, which bear its mass, that flow over the heated velocity sensor and carry away its heat, TD flowmeters directly measure the mass flowrate q_m of the gas or gas mixture. Heat convected from the velocity sensor in this manner depends on the properties of the gas, and therefore the composition of the gas must be known.

In yet another thermal flow sensor construction for in-line meters, the flow sensor is embedded in wall of the flow body and is not immersed in the flow. This flow sensor consists of a heater element with adjacent upstream and downstream temperature sensing elements. The difference in the two temperatures increases as flow increases, providing the output. This construction is used primarily for low-flow liquid applications.

Transmitter

The transmitter shown in Figure 1 is the electronic system that provides the flow sensor drive and many other functions for the flowmeter. It accepts the inputs from the two or four temperature sensing elements as well as the heating current I_1 input and transforms these independent variables into linear outputs of the primary dependent variable, mass flowrate q_m, and, in the case of multivariable versions, the gas temperature T. Transmitters can be housed in an enclosure that conforms with relevant U.S. and international codes, such as hazardous area codes or area classifications. Digital transmitters with digital displays in engineering units facilitate additional functions, including flowmeter diagnostics, validation, calibration adjustment and reconfiguration. Later, this article describes an advanced system consisting of a microprocessor-based digital transmitter and a four-temperature flow sensor that provides gas selection and automatic correction for changes in gas temperature, gas pressure and outside temperature.

Many transport properties of the gas that are involved in convective heat transfer, such as thermal conductivity, viscosity and Prandtl number, depend on temperature. Likewise, the thermal conductivity

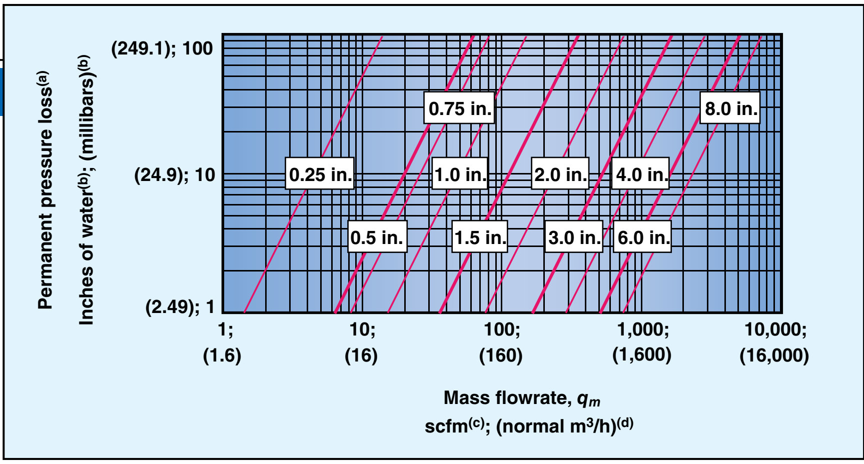

FIGURE 6. This graph shows the permanent pressure loss for in-line flowmeters with a built-in flow conditioner consisting of two upsteam separated perforated plates. Notes: (a) for air and nitrogen at 21.1°C and 1 atm; (b) 1 in. of water = 0.0361 psi; (c) at standard conditions of 21.1°C and 1 atm; and (d) at standard (normal) conditions of 0°C and 1 atm

of some of the materials in the flow sensor depends on temperature. For this reason, TD mass flowmeters must correct for changes in gas temperature. In traditional flowmeters, this is done by means of an analog Wheatstone bridge at the front end of the flow sensor drive. The velocity sensor and the temperature sensor are located at opposite legs of the bridge. This provides compensation for changes in fluid temperature by adjusting the overheat of the velocity sensor. The bridge voltage is a high-level output signal on the order of several volts that provides a high signal-to-noise ratio. The Wheatstone bridge and its temperature-compensation capabilities are thoroughly described in the literature [*2*, *6–9*]. Modern flowmeters with a microprocessor-based flow sensor drive digitally correct for changes in temperature without requiring a Wheatstone bridge.

The flow sensor drive in TD mass flowmeters has two modes of operation: the constant-temperature-differential mode and the constant-current mode. In the constant-temperature-differential mode of operation, the flow sensor drive maintains at a constant value the difference $\Delta T = T_1 - T$ between the heated velocity sensor T_1 and the gas temperature T. The output signal is the electrical power W supplied to the heated velocity sensor that is required to keep ΔT constant.

In the constant-current mode of operation, the flow sensor drive maintains at a constant value the current I_1 supplied to the heated velocity sensor. In this case, the output signal is ΔT. Measuring mass flowrate with constant current operation is slower than constant temperature differential operation because the temperature of the entire mass of the velocity sensor must change when velocity changes and also because the masses of the velocity and temperature sensors may be imbalanced. In the following, we assume constant temperature differential operation and that therefore ΔT is a constant, usually in the range of 20 to 100K.

Liquid flow applications

The vast majority of applications are gas flow applications because they benefit from the exceptional low-flow sensitivity and wide rangeabililty of measurement. Thermal dispersion technology is not well suited for liquid flow applications because at the zero-flow condition, a majority of the heat budget is carried away by the liquid via conduction, instead of the desired convection. This is caused by the high thermal conductivity of liquids relative to gases. The result is reduced measurement sensitivity for liquid flows.

Additionally, for liquid flows, the temperature differential $\Delta T = T_1 - T$ must not exceed an upper critical limit, or else at higher flowrates the liquid may flash to the vapor phase and subsequent cavitation may occur, creating unwanted erratic readings. For water flows, this upper critical limit in ΔT is approximately 10 to 20°C. The constant-differential-temperature mode of operation is preferred for liquid flows because ΔT is controlled, whereas in the constant-current mode ΔT varies and may exceed the upper critical limit. Application of thermal dispersion technology to liquid flows has been limited to cases, such as ultra-low flow applications, where it offers advantages over other technologies.

Advanced system

Figure 3 shows a simplified block diagram of the microprocessor-based thermal dispersion mass flowmeter with the four-temperature flow sensor shown in Figure 2b. It has a dry velocity sensor and is operated in the constant temperature differential mode. As before, we call this configuration the four-temperature microprocessor-based system. The voltage sensing wires in Figure 3 make the measurement of the RTD resistances independent of the length of the flow sensor cable, facilitating remote location of the transmitter. The heating current I_1 depends on the electrical resistance R_1 and the electrical power input W required to maintain constant ΔT. W ranges from about 0.2 to 5 W depending on the overheat ΔT, the mass flowrate, and the size of the velocity sensor. The temperature sensing current I_2 is held constant and is less than 1 mA to avoid self-heating the T_2 sensor. The analog layer shown in Figure 4 includes precision resistors for measuring the currents I_1 and I_2 but has no bridge circuit.

The four-temperature microprocessor-based system shown in Figure 3 digitally linearizes the q_m output and, optionally, the T and P outputs and provides analog outputs for these variables. The system has algorithms based on the principle of operation that manage changes in gas selection, gas temperature and gas pressure.

Figures 4 a–c show how the four-temperature microprocessor-based system manages changes in gas selection, gas temperature, and gas pressure for air, methane, and argon. These figures are plotted in the conventional manner with the mass velocity, V_s, shown as the

TABLE 1. TYPICAL SPECIFICATIONS FOR THERMAL DISPERSION MASS FLOWMETERS		
Specification	**Two-temperature system**	**Four-temperature system**
Gases	Most clean gases, including air, methane, Ar, CO_2, He, N_2, O_2, C_3H_8, and mixtures of these components	Most clean gases, including air, methane, Ar, CO_2, He, N_2, O_2, C_3H_8, and mixtures of these components
In-line flow body sizes[a]	0.25, 0.5, 1.0, 1.5, 2.0, 4.0 in.; DN6 to DN100	0.25, 0.5, 1.0, 1.5, 2.0, 4.0 in.; DN6 to DN100
In-line meter mass flowrate range for air	0.0001 to 1.5 kg/s; 0.1 to 2,600 scfm[b]	0 to 1.5 kg/s; 0 to 2,600 scfm[b]
Insertion meter mass-velocity range for air	1.4 to 140 normal m/s; 300 to 30,000 standard ft/min[c]	0 to 140 normal m/s; 0 to 30,000 standard ft/min[c]
Temperature range[d]	–40 to 200°C; –40 to 392°F	–40 to 200°C; –40 to 392°F
Pressure range	0.01 to 16 bara	0.01 to 16 bara
Accuracy[e]	1% of reading plus 0.5% of full scale (FS)	1% of reading from 10 to 100% of FS; 1% of reading plus 0.5% FS from 0 to 10% FS
Rangeability	100 : 1	100 : 1
Repeatability	0.2 % of full scale	0.15 % of full scale
Time response[f]	3 s (constant power operation); 1.2 s (constant ΔT operation)	2 s
Stability	1 year; typical drift 1 to 2% per year	10 years; typical drift 0.1% per year

Notes to Table 1: (a) Some manufacturers offer sizes up to 12.0 in. (DN300); (b) Based on the point mass-velocity range for insertion flowmeters cited below; (c) "Normal" conditions are 0°C and 1 atm, and "standard" conditions are 70°F and 1 atm; (d) High-temperature models are available up to approximately 450°C = 842°F; (e) FS = full scale; and (f) Time response is the time required to reach 63% of the final value (that is, the 1 sigma value).

independent variable and the electrical power, W, shown as the dependent variable, whereas in the system they have reversed roles. The three figures reflect the strong direct dependence the electrical power has on the thermal conductivity of the gases. Thus, Figure 4a results from the fact that $k_{methane} > k_{air} > k_{argon}$, and Figures 4b and 4c result from the fact that thermal conductivity increases as gas temperature and pressure increase, respectively. The fact that thermal conductivity, and therefore W, increases with gas pressure as shown in Figure 4c is a phenomenon that has heretofore been ignored, but for higher accuracy applications should be included.

Figures 4 a–c also reveal the non-linear, logarithmic nature of the output. A log versus log plot of these figures will reveal a nearly straight line over approximately 1 to 150 standard m/s. This logarithmic property is responsible for the exceptional rangeability and low-velocity sensitivity of TD mass flowmeters. A rangeability as high as 100:1 is common. Even higher rangeabilities are achieved with multi-range flow calibration. Detectable minimum-point mass velocities as low as approximately 0.1 standard m/s (20 standard ft/min) are reported by some manufacturers. In the early days of analog electronics, it was difficult to linearize the output of TD mass flowmeters. But now, with microprocessor-based electronics, it is not a problem, and the non-linear, logarithmic nature of the output bears only advantages.

Figures 5 a–c show further results of the four-temperature microprocessor-based system. Figure 5a reveals how the temperature distribution $T_1(x)$ of the heated section of the velocity sensor undergoes major changes as V_s increases from 0 to 100 standard m/s. Figures 5a and 5b show, for air and methane, the excellent comparison between results calculated via the four-temperature microprocessor-based system and actual flow calibration data. Comparisons for other gases are likewise as good. Algorithims exist that make the output of the system match flow calibration data even better.

Specifications

Table 1 shows specifications for currently available TD mass flowmeters. Specifications for the column labeled "Two-temperature system" refer to the flow sensor shown in Figure 2a and may vary from manufacturer to manufacturer. Specifications for the column labeled "Four-temperature system" refer to the microprocessor-based system with the four-temperature flow sensor having the dry velocity sensor shown in Figure 2b. Accuracy specifications in Table 1 may apply to gas temperatures and gas pressures that lie within bands around their respective values at flow calibration. Table 1 is also useful in selecting and sizing the proper TD mass flowmeter for the application.

Installation

In all cases, specifications and instructions provided by the manufacturer should be followed in sizing and installing in-line and insertion TD mass flowmeters. Ref. 3 is an excellent source for details regarding sizing, installation, safety and flow calibration.

Figure 6 is helpful in the flowmeter selection process for in-line TD mass flowmeters. The permanent pressure loss shown in Figure 6 applies to an in-line meter with a built-in flow conditioner consisting of two upstream separated perforated plates. In sizing TD mass flowmeters, as with all flowmeters used for gas flow applications, the Mach number of the gas flow should be kept under approximately 0.3 to avoid compressibility effects. At an absolute gas pressure of 1 bara (approximately 1 atmosphere), the permanent pressure loss is about 0.1 bar (approximately 2 psi) at all full-scale mass flowrates. This is one or two orders of magnitude less than that required by Coriolis mass flowmeters for gas flow applications. Almost all of the permanent pressure loss shown in Figure 6 is due to the built-in flow conditioner.

Insertion flowmeters have very low permanent pressure loss, especially for larger line sizes. In-line flowmeters without a built-in flow conditioner and no shield on the flow sensor likewise have low pressure drops. These two configurations are why TD mass flowmeters are considered to be in the class of flowmeters with low pressure drops.

As with most kinds of flowmeters, the performance of TD mass flowmeters can be degraded if the flowmeter is installed where flow conditions are different than those for which it was flow-calibrated. Improper installation is the single biggest cause of measurement inaccuracy for any kind of flowmeter. Components in the piping system upstream and, to a far lesser extent, downstream of the flowmeter can create non-uniformities in the flow profile, swirls and turbulence. All of these phenomena degrade performance. Such flow-disturbing components include single and multiple elbows, expansions, contractions, tees, valves and pumps. Fortunately, viscous forces in a sufficiently long length of straight pipe upstream and downstream of the flowmeter reduce swirl and drive the flow toward a fully developed velocity profile.

Table 2 shows the straight pipe length requirements for both in-line and insertion TD mass flowmeters and, for purposes of comparison, an orifice-plate flowmeter with a 0.7 beta ratio (ratio of the orifice diameter to the pipe internal diameter). The in-line flowmeter in Table 2 has a built-in flow conditioner consisting of two upstream separated perforated plates. Figure 7 shows the upstream straight-pipe requirements downstream of a single elbow for three kinds of flowmeters. This shows the marked contrast between the one pipe diameter length required for the TD mass flowmeter with the built-in flow conditioner versus the ten and twenty-eight diameter lengths required for typical vortex and orifice-plate flowmeters, respectively. Since piping systems in the industrial process-control field seldom have suitably long straight piping runs preceding the desired location for flowmeter installation, Table 2 and Figure 7 reveal the

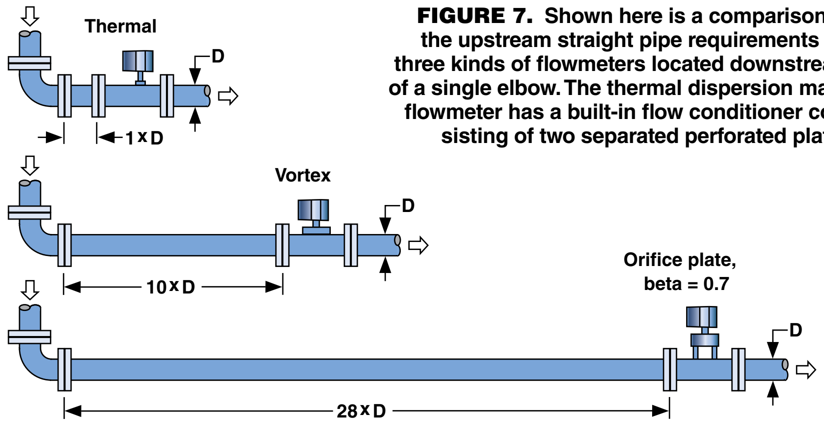

FIGURE 7. Shown here is a comparison of the upstream straight pipe requirements for three kinds of flowmeters located downstream of a single elbow. The thermal dispersion mass flowmeter has a built-in flow conditioner consisting of two separated perforated plates

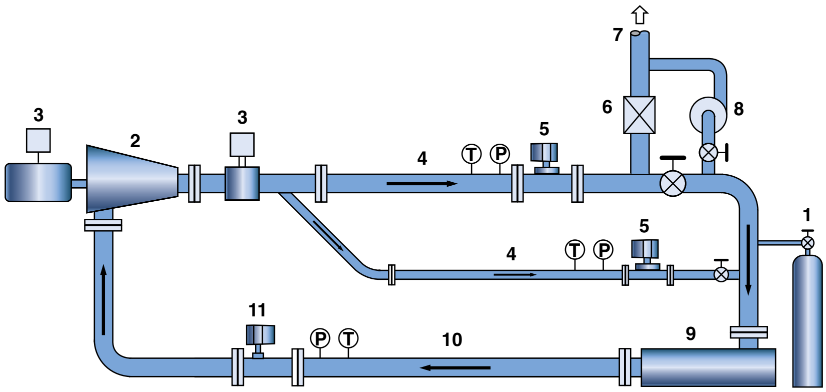

FIGURE 8. A setup for a pressurized closed-loop gas-flow calibration system is presented here. The numbered components are as follows: 1 is the gas charging source; 2 is the flow source; 3 is the flow control element; 4 is a flow-conditioning section for a flow calibration standard (two shown); 5 is an in-line flow calibration standard (two shown); 6 is the pressure relief element; 7 is the vent to the outside environment or to a scrubber or other gas purifying device; 8 is the vacuum pump for evacuating the gas charge; 9 is the heating section; 10 is the flow-conditioning section for the flowmeter under test; and 11 is the flowmeter under test

installation advantage in-line TD mass flowmeters with the built-in flow conditioner have over alternative flowmeters. In essence, in-line flowmeters with the built-in flow conditioner trade the advantage of greater accuracy for a small amount of pressure drop.

Normally, the transmitter is mounted directly on the flow body or probe. In cases where the ambient temperature at the pipe line exceeds the specified limit for the transmitter (usually, approximately 60°C), then the transmitter must be located remotely. Additionally, in some cases the application requires that the transmitter be located remotely for easier access. Since the wires leading to the sensors are part of each sensor's electrical circuit, remote location can cause measurement errors if the cable length is altered in the field from that for which it was flow calibrated. The four-temperature microprocessor-based system avoids this problem by incorporating high-impedance voltage sensing wires in the flowmeter's cable (see Figure 3) that essentially make remote transmitter location independent of cable length.

Some applications require that the flow in the process line not be interrupted. This case is solved by employing an insertion flowmeter installed in the pipe with hot-tap hardware. The hot-tap method and assembly provides an isolation

TABLE 2. STRAIGHT PIPE LENGTH REQUIREMENTS FOR THERMAL-DISPERSION MASS FLOWMETERS IN MULTIPLES OF PIPE DIAMETER[a]

Flow disturbance	Thermal dispersion mass flowmeters				Orifice plate, $\beta = 0.7$[c]	
	In-line[b]		Insertion			
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
Single elbow	1	0	15	5	28	7
4:1 Reduction	3	0	15	5	14	7
4:1 Expansion	3	0	30	10	30	7
Control valve[d] or *P* regulator	3	0	40	5	32	7
Two elbows in the same plane	3	0	20	5	36	7
Two elbows in different planes[e]	5	0	40	10	62	7

Notes to Table 1: (a) Requirements for the length of intervening straight pipe in multiples of pipe diameter at 1 bara pressure; consult manufacturer for pressure effects; specifications may vary from manufacturer to manufacturer; (b) For an in-line meter with a built-in flow conditioner consisting of two upstream separated perforated plates; (c) For comparison purposes only; based on ISO standard 5167 [*10*]; (d) If the control valve is always wide open, base the length requirement on the valve's inlet or outlet fitting size; (e) For three elbows, the required length is doubled.

valve facilitating installation, insertion, retraction and removal of the insertion flowmeter from an active process pipe line without interruption of the flow or the leakage of process gas. The retraction mechanism provides operator safety for pressurized process lines.

Flow calibration

Because the critical dimensions of the flow sensor of TD mass flowmeters are so small, manufacturing technology is generally incapable of maintaining sufficiently small tolerances to ensure a high degree of reproducibility from flow sensor to flow sensor. Additionally, the internal diameters of the pipes used in in-line flow bodies have substantial variations. For these reasons, every general-purpose TD mass flowmeter is flow calibrated by the manufacturer, just like most other kinds of flowmeters. Exceptions may include flow switches and low-accuracy flowmeters.

The gas-flow calibration facilities of manufacturers, flow calibration laboratories and users should be capable of: (1) generating a stable, steady-state, reproducible gas mass flowrate; (2) accommodating the entire mass flowrate range specified; (3) having a flow calibration standard that has an accuracy at least three times better than the flowmeter under test; and (4) reproducing the gas composition, temperature and pressure to be encountered in the actual application. Gas-flow calibration facilities are of two types: open loop and closed loop.

Closed-loop facilities are recommended because they allow flow calibration at elevated pressures and temperatures, and with gases other than air. The preferred pressurized closed-loop system for high-accuracy applications has the following major components (Figure 8), listed in flow sequence: (1) a gas charging source, such as a compressed gas tank; (2) a flow source, such as a high-pressure axial or centrifugal in-line pump; (3) a flow controller, such as a precision flow control valve or variable speed motor drive; (4) flow-conditioning section(s) upstream of the flow calibration standard(s); (5) the in-line flow calibration standard (more than one may be needed to cover the mass flowrate range); (6) a heating section, such as an in-line electric heater; (7) a flow-conditioning section upstream of the flowmeter under test; and (8) the flowmeter under test. Additionally, the facility should have: accurate gas temperature and pressure instrumentation at both the flow calibration standard and the flowmeter under test; pressure relief and venting components; a vacuum pump for evacuating the system prior to charging; and, optionally, a cooling section downstream of the flowmeter under test. High-accuracy in-line flow calibration standards include custody-transfer grade multi-path ultrasonic flowmeters; turbine flowmeters; flow nozzles; and positive-displacement flowmeters. ■

Edited by Gerald Ondrey

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