Capillary Tube Thermal Mass Flow Meters & Controllers

A User's Guide

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A USER'S GUIDE TO CAPILLARY TUBE THERMAL MASS FLOW METERS AND CONTROLLERS

John G. Olin(1)

Abstract

Capillary tube thermal mass flow meters directly measure the mass flow rate of clean gases and gas mixtures in lower flow ranges. A capillary tube thermal mass flow controller adds an integrally mounted flow control valve to the flow body of the mass flow meter and both monitors the mass flow rate and controls it to be equal to a set-point value selected by the user.

This paper describes capillary tube mass flow meters and controllers for use in general purpose industrial and laboratory applications and in the fabrication of semiconductor devices. It provides a detailed description of the major components---flow body, flow conditioner, bypass, capillary sensor tube, control valve, and electronics. Flow ranges and specifications for which this technology is best suited are presented. The paper explains the principle of operation; describes gas conversion factors that provide multi-gas capability in a single instrument; lists best practices for users, including the selection, installation, and operation of the instruments; and concludes with a discussion of preferred methods of flow calibration.

Keywords: flow meter, gas flow meter, mass flow meter, mass flow controller, thermal mass flow meter, capillary tube thermal mass flow meter, capillary tube thermal mass flow controller

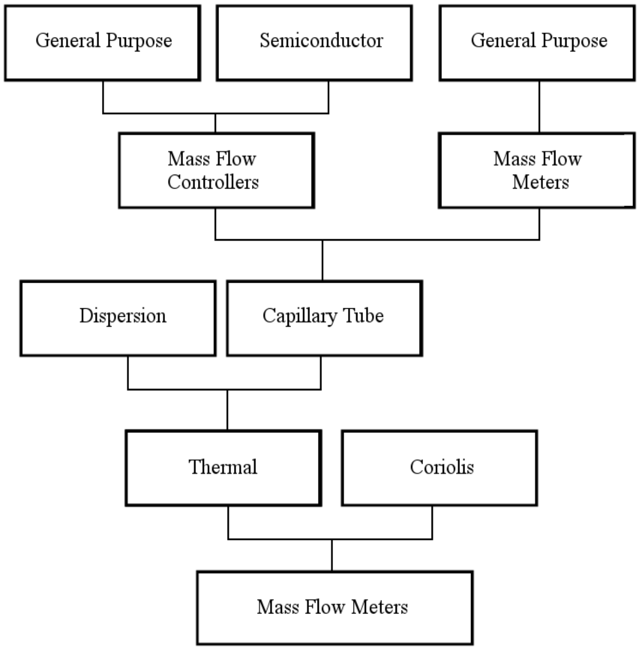

Fig. 1 Classifications of mass flow meters

1 Introduction

Capillary tube thermal mass flow meters and controllers were first commercialized in the early 1960's. The space industry was one of the first users, but before long the industry that fabricated solid state semiconductor devices recognized their usefulness. When integrated circuit semiconductor devices began their long and continuing period of exceptional growth, the market for capillary tube thermal mass flow controllers grew with it. In the 1970's and 1980's, general industry recognized the advantages of using capillary tube mass flow meters and controllers in a broad range of

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(1) Published September 24, 2013. Dr. John G. Olin is the Founder and Chairman of Sierra Instruments, Inc. He has studied thermal mass flow meters for several decades beginning with his Ph.D. dissertation at Stanford University. He holds a dozen patents and has published over 60 papers in the field.

applications, and several new companies were formed to serve this growing market. The advantages of accuracy, compactness, reliability, and cost-effectiveness continue to make capillary tube thermal instruments the choice for monitoring and controlling smaller mass flow rates of clean gases in general industry and in the fabrication of semiconductor devices.

The primary virtue, and the source of their prominence, is the fact that capillary tube thermal instruments directly measure mass flow rate, as opposed to, for example, volumetric flow rate. This is important because most industries need to measure and control the flow of the molecules, i.e., the mass, of the gas entering their process.

Fig. 1 shows the classifications of mass flow meters---a "tree" with "mass flow meters" as its root and capillary tube thermal mass flow meters and controllers as its top branches.

As shown in Fig. 1, two kinds of flow meters directly measure the mass flow rate of fluids---Coriolis mass flow meters and thermal mass flow meters. Coriolis mass flow meters directly measure the mass flow rate of most fluids, both liquids and gases, and do not require knowledge of the identity, or composition, of the fluid. Thermal mass flow meters directly measure the mass flow rate of gases, and do require knowledge of its composition. Coriolis mass flow meters have high accuracy, high pressure drop, work best with liquids, and are relatively expensive. Thermal mass flow meters have medium to high accuracy, low pressure drops, work best with gases, and are relatively inexpensive.

Both Coriolis and thermal technologies "directly measure" mass flow rate because they require no secondary measurements to deliver their mass flow rate output. Several kinds of flow meters directly measure volumetric flow rate, such as ultrasonic, vortex, turbine, positive displacement, and differential pressure producing devices. To deliver a mass flow rate output, they must become multivariable flow meters that require the secondary measurements of fluid temperature and pressure. Direct measurement of mass flow rate is preferred because it eliminates errors associated with secondary measurements and requires only one penetration of the process line.

Thermal mass flow meters are of two types---thermal dispersion mass flow meters and capillary tube thermal mass flow meters. Thermal dispersion instruments are used for general industrial gas flow applications in pipes and ducts. Capillary tube instruments are used for lower flows of clean gases in a wide range of process and laboratory applications. Both types of instruments measure mass flow rate via the heat carried away by the gas flowing over the surface of a heated element. Beyond that, their principles of operation are quite different.

In the case of the thermal dispersion, or immersible, type of mass flow meter, heat is transferred to the boundary layer of the gas flowing over a cylindrical heated sensor immersed in the main flow stream. The heat carried away by the gas provides the measurement of mass flow rate. Thermal dispersion mass flow meters have two major configurations---in-line and insertion. Their applications, description, principle of operation, and usage are discussed in references [1] to [3].

In the case of the capillary tube type of thermal mass flow meter (hereinafter, "MFM") described in this paper, the flow enters the flow body and splits into two internal flow paths. One path flows through a heated capillary sensor tube that has a small diameter and relatively long length. The second parallel path inside the flow body flows through a bypass consisting of a laminar flow element. This creates a pressure drop that forces a small fraction of the total mass flow rate through the adjacent capillary sensor tube. The ratio of the flows through the bypass and the sensor tube is a constant. The capillary sensor tube measures its internal mass flow rate by means of the heat capacity of the gas that carries heat from an upstream resistance-temperature-detector winding to a downstream winding, both on outside of the sensor tube. The difference in the electrical resistances of the two windings provides the measurement of the mass flow rate through the sensor tube, and thereby the total mass flow rate in the flow conduit.

A capillary tube thermal mass flow controller (hereinafter, "MFC") adds an integrally mounted flow control valve to the flow body of the MFM and both monitors the mass flow rate and controls it to be equal to a set-point value selected by the user either remotely or on the MFC itself.

More MFCs are manufactured than MFMs because most users want to control the mass flow rate of the gas in their process rather than just monitor it. Capillary tube thermal MFCs offer a cost-effective solution for controlling the flow of gases because they are compact, require only one penetration of the process line, and have a built-in optimized control system.

This paper applies to gas flow, and not liquid flow, because gas flow constitutes the vast majority of the applications for capillary tube thermal MFMs and MFCs. This is true because the measurement sensitivity for gases is much greater than for liquids. Nevertheless, this technology has been used to measure and control very low flow rates of liquids (less than approximately 1000 grams per hour) in specialized applications in the semiconductor, chemical, food, and pharmaceutical industries, as well as in analytical laboratories. Many of the principles of operation stated here apply to some liquids. For the remainder of this paper the fluid is a gas.

It is common practice to express the mass flow rate measured by capillary tube thermal MFMs and MFCs in units of slpm (standard liters per minute) and, for low flows, in units of sccm (standard cubic centimeters per minute). The units slpm and sccm may appear to be volumetric flow rate units, but indeed they are mass flow rate units, as described in para. 6.

2 General Purpose and Semiconductor Applications

Capillary tube thermal mass flow meters and controllers have two broad fields of application:

(1) General purpose industrial and laboratory applications

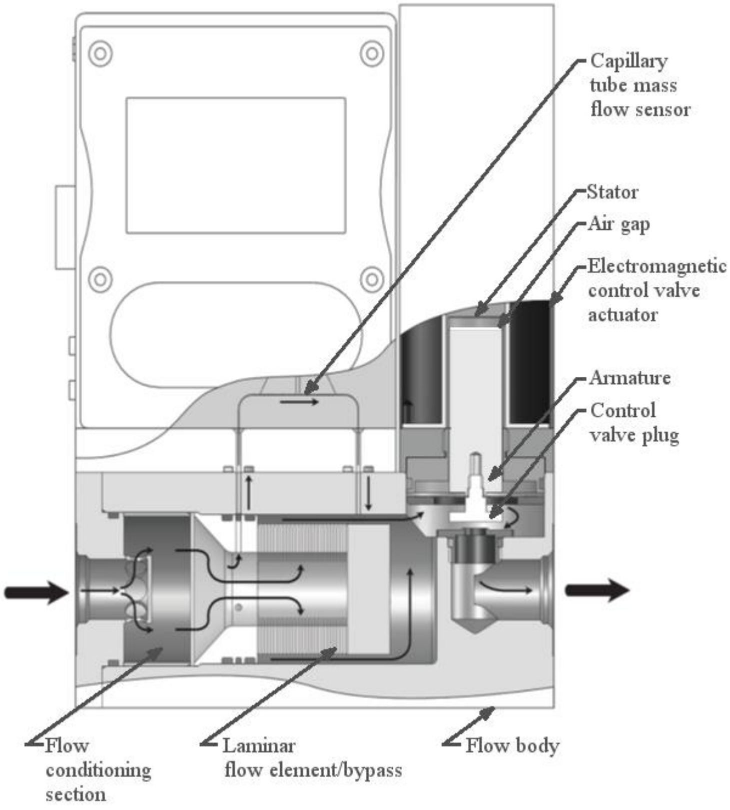


Fig. 2 Typical general purpose mass flow controller

(2) Semiconductor manufacturing and other high purity vacuum processes

Both of these applications are shown in the mass flow meter tree of Fig. 1. Semiconductor applications almost always use MFCs, and not MFMs. Semiconductor MFCs are covered in considerable detail in a series of standards published by the Semiconductor Equipment and Materials International [4]. This paper focuses on general purpose MFMs and MFCs designed to meet the needs of general industry and laboratories. Here, the terms "MFM" and "MFC" apply generically to both kinds of capillary tube thermal mass flow meters and controllers, and the term "instruments" applies collectively to both. In cases where the two major applications must be distinguished, the prefixes "general purpose" and "semiconductor" are used.

Fig. 2 shows a typical general purpose capillary tube thermal MFC that operates in the medium flow range of approximately 50 to 300 slpm.

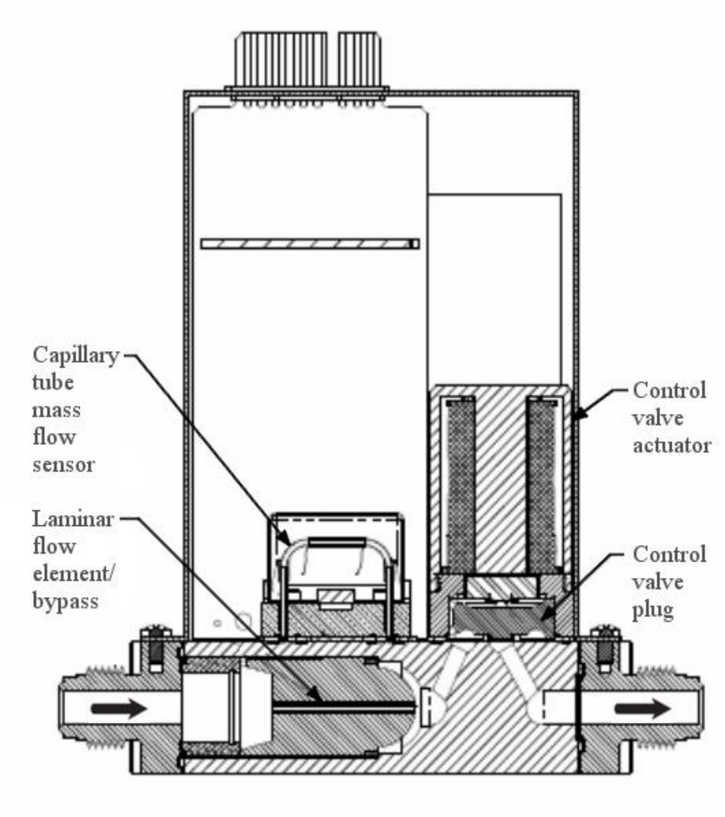


Fig. 3 Typical semiconductor mass flow controller

Fig. 3 shows a typical semiconductor capillary tube thermal MFC that operates in the range of 0 to 50 slpm.

General purpose MFMs and MFCs have a wide range of applications, including: analytical (e.g., mass spectrometers, gas chromatographs, gas analyzers, gas mixing, and leak testing); energy (combustion fuel/air ratios and fuel cells); food and beverage (carbonization of beer and sodas, aeration, and food additives); medical and life sciences (bioreactors and mixing of artificial atmospheres); primary metals (decarbonization of steel, aluminum production, and removal of impurities); process industries (catalyst research, petrochemical pilot plants, and hydrogen cooling); surface treatment (heat treating, welding, and painting); and semiconductor fabrication (gas custody transfer, chemical vapor deposition, silicon ingot manufacturing, photovoltaics, and other vacuum processes).

In serving these applications, general purpose MFMs and MFCs monitor and control the flow of clean gases and gas mixtures, such as: air, nitrogen, oxygen, hydrogen, argon, carbon dioxide, carbon monoxide, methane, helium, nitrous oxide, some semiconductor fabrication gases and gas mixtures.

Semiconductor MFCs are used in a wide range of applications, including: chemical vapor deposition; physical vapor deposition; atomic layer deposition; metal oxide chemical deposition; rapid thermal processing; diffusion; etching; and many other high purity vacuum processes. Some of the gases used in semiconductor MFCs are corrosive and toxic.

3 Description

3.1 The Major Components of MFMs and MFCs

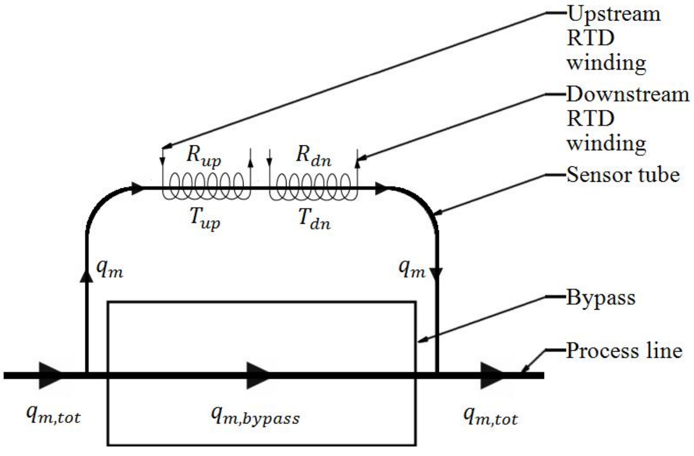
An MFM has five major components:

-- flow body
-- flow conditioning section
-- sensor tube
-- bypass
-- electronics.

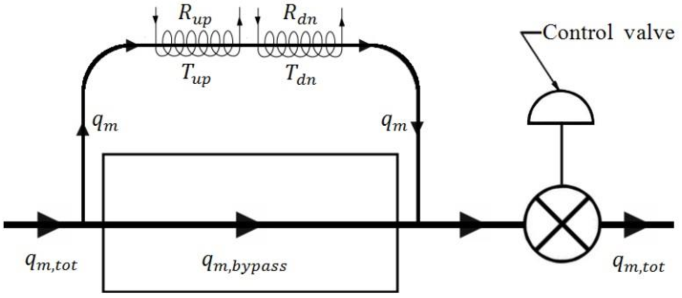
An MFC has the same components as an MFM, but also has an integral control valve mounted on the same flow body as the MFM. Figs. 2 and 3 show the major components of an MFC.

3.2 Operation

Fig. 4 (a) shows the flow paths in an MFM. In operation, the total gas mass flow rate in the process line $q_{m,tot}$ enters the flow body of the MFM and passes through the flow conditioning section where non-uniformities in the flow profile are reduced. As shown in the figure, the total mass flow then splits into two separate internal flow paths. The first flow path (the upper path in the figures) passes through the capillary sensor tube and has mass flow rate q_m. The second parallel flow path (the straight-through path in the figure) flows through the bypass, creating a pressure drop that forces a fraction of the total mass flow through the adjacent capillary sensor tube.



(a) Mass flow meter



(b) Mass flow controller

Fig. 4 (a),(b) Flow paths in mass flow meters and mass flow controllers

The bypass is a laminar flow element and has a mass flow rate $q_{m,bypass}$. Usually, q_m is much smaller than $q_{m,bypass}$. The total mass flow rate in the process line is the sum of the mass flow rates in the two paths, i.e.,

$$q_{m,tot} = q_m + q_{m,bypass} = q_m(1 + \frac{q_{m,bypass}}{q_m}) \quad (1)$$

The capillary sensor tube (hereinafter, “sensor tube”) is heated and uses thermal technology to measure the mass flow rate qm passing through it. The bypass of almost all MFMs and MFCs is a laminar flow element. In this case, the ratio $q_{m,bypass} / q_m$ is a constant, as shown in para. 5.1. As is evident from eq. (1) above, this means the measurement of q_m by the sensor tube provides the measurement of the total mass flow rate $q_{m,tot}$. The two separate mass flow paths then merge into the total mass flow that exits the MFM into the process line.

In the case of the MFC depicted in Fig. 4 (b), the gas leaving the MFM portion of the instrument then passes through the integral flow control valve where it is modulated in such a manner that its value is equal to its preselected set-point value. After the control valve, the total mass flow exits the flow body and returns to the process line.

The sensor tube measures its mass flow rate q_m by means of two identical platinum RTD windings --- an upstream winding and a downstream winding --- located symmetrically at the center of the sensor tube, as shown in Fig. 4 (a). The RTD windings both heat the sensor tube and measure their own electrical resistance. When flow in the sensor tube is zero, the temperatures and electrical resistances of the identical upstream and downstream windings are equal. When the gas begins to flow through the sensor tube, its heat capacity (which is proportional to its mass flow rate) carries heat from the upstream winding to the downstream winding. This causes the temperature of the downstream winding to become higher than the temperature of the upstream winding. As a result, the electrical resistance of the downstream winding becomes higher than the resistance of the upstream winding. The difference in these two resistances is the output signal of the instrument and is directly proportional the mass flow rate of the gas flowing through the sensor tube. Para. 5 describes how the sensor tube measures q_m.

3.3 Flow Body

General purpose MFMs and MFCs typically have only three flow body sizes covering the entire flow range of the instruments---low flow, medium flow, and high flow. The flow ranges of the three flow body sizes are shown in later in Table 1 (para. 4.2). Low flow bodies often are machined out of a single piece of stainless steel bar stock. To get an idea of their relatively compact size, MFCs have the following approximate widths and lengths (not including inlet and outlet fittings): low flow---1.0 W x 3.0 L inches (25 W x 76 L mm); medium flow---1.5

W x 4.5 L inches (38 W x 114 L mm); and high flow---3.0 W x 9.0 L inches (76 W x 229 L mm). MFMs usually have the same widths but have about two-thirds the length in the medium and high flow sizes.

The flow body has inlet and outlet flow conduit fittings and houses the flow conditioning section, the sensor tube, the bypass/laminar flow element, and, in the case of MFCs, the control valve. The electronics are mounted in their enclosure on the top of the flow body. The wetted parts of a typical flow body and its internal components are made of corrosion resistant materials. Typical wetted materials for the flow bodies of general purpose MFMs and MFCs are: 316 L stainless steel; ferromagnetic stainless steel in the valve; and “O” rings and valve seats of fluoroelastomers and other advanced elastomeric materials. Some lower cost instruments intended for light duty and lower accuracy applications have flow bodies made of plastic or aluminum.

Instruments with elastomeric seals throughout the flow body have relatively low rates of leakage in and out of the flow body. MFMs and MFCs used in vacuum processes use metal seals at all locations in the flow body to further reduce leak rates. Manufacturers should subject every instrument to a helium leak check using a mass spectrometer leak detector, or equivalent instrument. Additionally, all instruments should comply with applicable pressurized equipment standards and codes, and manufacturers should pressure test all instruments to insure compliance.

Process lines typically are tubes with outside diameters of 1/8, 1/4, 3/8, 1/2, 3/4, and 1 inches (6, 10, 12, and 20 mm). The 1/4 inch (6 mm) tubing size is most common. Some MFMs operated at very high flow rates are available in wafer and flange pipe sizes. Manufacturers offer a broad selection of process tube fittings, including: compression fittings, elastomeric “O”-ring face seal fittings, and metal gasket face seal fittings. Since the inlet and outlet fittings contribute to the pressure drop in the instruments, the size of the fittings should be as large as practicable within constraints imposed by the size of the process line.

Semiconductor MFCs often have a particulate filter, pressure regulator, and a positive shut-off valve installed upstream of the instrument and may have a positive shut-off valve and pressure regulator installed downstream. General purpose instruments also may include ancillary flow components in their installation.

Semiconductor MFCs used in the fabrication of high-end semiconductor devices have several special requirements to insure that: (1) no particulates or other contaminants enter the fabrication process; (2) no toxic process gases escape the MFC; and (3) no ambient air enters the process. Typical specifications are: wetted surfaces must have high purity and be highly polished (surface roughness in the range of about 4 to 10 microinches Ra (0.1 to 0.25 micrometers Ra); leak rates must be extremely low; and internal flow paths, as shown in Fig. 3, must have no sharp corners, cavities, or dead spaces where particles can form. Semiconductor MFCs are available in both in-line and down-port configurations. Down-port versions reduce the axial dimensions of the MFC and its ancillary flow components, thereby facilitating the compactness required by manufacturers of semiconductor equipment.

3.4 Flow Conditioning Section

The flow entering the MFM or MFC may have non-uniformities in its flow profile due to upstream disturbances caused by elbows, contractions, expansions, and the inlet fitting. This is particularly true for mass flow rates greater than about 50 slpm in the medium and high flow sizes. The flow conditioning section shown in Fig. 2 eliminates these upstream flow non-uniformities and conditions the flow so the sensor tube and bypass are able to create the necessary laminar flow in their passages. Downstream flow non-uniformities have no effect on instrument performance.

In operation, the jet issuing from the inlet fitting in Fig. 2 enters the flow conditioning section and impacts a central plate. It then flows radially outward and strikes the cylindrical inner wall of a settling chamber. This tortuous flow pattern effectively erases any non-uniform past history of the flow. A settling chamber then slows down the flow and allows viscous forces to reduce non-uniformities. The flow profile then becomes uniformized and flattened as the stream lines encounter a flow resistance as they pass through the inlet filter plate or screen that also captures any remaining particulate contaminants. After the inlet filter, the flow profile is further flattened as it passes through a flow nozzle. At this point, the uniformized flow splits into the two paths described earlier---one to the sensor tube and the other to the laminar flow element/bypass.

Low flow instruments with mass flow rates less than about 50 slpm, such as semiconductor MFCs, do not require a flow conditioning section. Because of this and the use of flow conditioners for higher flow rates, capillary tube thermal MFMs and MFCs of all sizes do not require straight lengths of upstream and downstream piping (i.e., tubing) that are required by most other kinds of flow meters.

3.5 Bypass

In some MFMs and MFCs operating at full scale mass flow rates below approximately 5 to 10 sccm (standard cubic centimeters per minute), the entire mass flow passes through the sensor tube, and no internal bypass is necessary. However, the vast majority of instruments operates at higher flow rates and has an internal bypass. As explained in para. 5.2, the flow through the capillary sensor tube is a fully developed laminar flow, and, therefore, a proper bypass also must have a fully developed laminar flow in its passages (see para. 5.1). This is why the bypass of capillary tube MFMs and MFCs is referred to as the "laminar flow element."

The designs of laminar flow elements are often considered to be proprietary by manufacturers. This has resulted in different designs for flow passages, such as: a single capillary tube or tube bundles for low flow rates; axial grooves, slots, or annular passages; and radial slots. Some MFMs with flanged or wafer process connections use axial honeycomb bypasses for very high flow rates.

The laminar flow element bypass shown in Fig. 2 is of the radial slot design. Here, the bypass flow axially enters the inner passageway of an annular laminar flow element that has a multiplicity of small radial channels, all having a fully developed laminar flow. The flow then passes radially through the laminar flow element, makes a 90° bend, and flows out axially to the control valve through the annular passage surrounding the element.

In most MFMs and MFCs, the bore of each of the low, medium, and high flow body sizes remains constant. Manufacturers accommodate the many full scale flow rates offered for each size by selecting the properly sized laminar flow element and inserting it into the bore. Full scale total mass flow rates ranging from about 10 sccm to about 1500 slpm are accommodated in this manner.

3.6 Sensor Tube

The capillary sensor tube of MFMs and MFCs measures the mass flow rate q_m of the gas flowing through it, and thereby the total mass flow rate $q_{m,tot}$ in the process line, as explained in para. 3.2. The term "capillary tube" is defined as a long hair-like tube with a very small internal diameter. The word "capillary" is derived from the Latin word "capillus," meaning "hair."

The sensor tube is a key component in the instrument. For this reason, the details of its design are proprietary to each manufacturer. The typical sensor tube is "U"-shaped and composed of a corrosion resistant alloy. It has a total length ranging from about 0.5 to 4 inches (about 10 to 100 mm) and a relatively small internal diameter and wall thickness. The ends of the "U"-shaped sensor tube are embedded in a metal block with high thermal conductivity that acts as a thermal bus or ground, ensuring that both ends have the same temperature (i.e., T_o in Fig. 5). The sensor tube is located in an isothermal clam-shell outer case filled with a thermally insulating material or simply dead air.

Because the capillary tube has a small internal diameter, operation is limited to clean gases. Any long term drift in accuracy often is traced to particulates contaminating the inner wall of the sensor tube or the small flow passages in the laminar flow element. For this reason, it is common practice to install a particulate filter upstream of the instrument. For applications with gases that are not absolutely clean and those requiring very low pressure drops, some manufacturers offer straight sensor tubes with larger internal diameters. Sensor tubes used in very high pressure applications (e.g., 5000 psia, or 340 bar) typically have larger wall thicknesses.

The typical sensor tube shown in Fig. 4 measures its internal mass flow rate q_m by means of two windings wrapped around its outside diameter---an upstream winding and a downstream winding. The two windings are identical, adjacent to one another, and located symmetrically on either side of the center of the sensor tube’s length. Together, they cover a fraction of the total length of the sensor tube. The windings have an electrically insulating coating and are bonded to the outside surface of the sensor tube with a stable bonding compound. Since the windings (i.e., the flow sensors) are located external to the gas flow path, capillary tube thermal MFMs and MFCs have no delicate components exposed to the gas, and thus provide non-intrusive measurement of mass flow rate.

The windings are made of resistance temperature detector (“RTD”) wire. RTDs measure their temperature by means of their electrical resistance. When their temperature increases their electrical resistance increases nearly linearly. Most instruments with high accuracy specifications use high purity platinum fine wire because it has excellent stability and a high temperature coefficient of resistivity.

In operation, the electronics drive a constant electrical current through the windings. In some cases, especially in older designs, the two RTDs are the legs of a bridge circuit. The current self-heats the windings via ohmic heating and raises the temperature of the entire sensor tube. The two windings have the dual functions of both heating the sensor tube and measuring its temperature. The operation of the sensor tube is described briefly in para. 3.2 and in detail in para. 5. In addition to constant current operation, a minority of instruments have other modes of sensor drive, such as constant temperature or contoured-heat drives.

Some manufacturers offer instruments that use three RTD windings. One such winding is centrally located and self-heated. The other two are located a short distance from the upstream and downstream ends of the heated RTD, are not self-heated, and strictly measure temperature. In another configuration, the “U” shaped sensor tube is mounted transversely to the axis of the flow body for the purpose of increasing accuracy by equalizing any temperature rise at the ends of the sensor tube due to heat generated by the control valve.

3.7 Control Valve

Figs. 2 and 3 show MFCs with the most common type of control valve---the electromagnetic globe-type control valve. This kind of control valve is similar to the well-known solenoid globe valve, but instead of being an on-off valve, it is operated as a control valve by modulating the current passing through its coil. In the following, we describe the typical electromagnetic control valve having its most common orientation--- that shown in Figs. 2 and 3---where the process line is horizontal and the control valve is mounted on top of the flow body (with its axis vertical).

The electromagnetic control valve shown in the figures has the following parts: solenoid coil; ferromagnetic stator; movable cylindrical ferromagnetic armature; valve plug attached to the lower end of the armature; valve orifice; and ferromagnetic metallic enclosure around the solenoid coil.

The stator and armature are made of ferromagnetic stainless steel, and the valve plug is made of a fluorocarbon or other high-temperature, corrosion-resistant elastomeric material. The remaining wetted parts are made of a non-ferromagnetic stainless steel or other corrosion resistant alloy. The elastomeric valve plug provides shut off with relatively low leak rates through the valve. Semiconductor MFCs and other MFCs intended for high vacuum applications have all-metal valve seats and may have a small leak-by flow. The control valves of

MFCs are specifically designed to control the flow and not to provide tight shut-off. This is why most MFCs have a control range specification of 2 to 100 % of full scale. To provide tight shut-off, MFCs often have pneumatic positive shut-off valves installed in the process line at their inlet and/or outlet. Each of the three primary flow body sizes---low flow, medium flow, and high flow---have removable valve plugs and seats facilitating a wide selection of plug/seat combinations to accommodate the flow range and corrosiveness of the application. To increase their time response, the MFM and control valve sections of MFCs have minimum internal volumes.

Electromagnetic control valves are available in normally-closed and normally-open versions. When electrical power is lost, normally closed valves shut off the flow, and normally-open valves remain wide open.

When current is passed through the solenoid coil, a closed axisymmetric magnetic field is created around the coil. The magnetic field lines passing through the upper air gap between the stator and armature produce an attractive force that pulls the armature upwards (in Figs. 2, 3) towards the stator. This magnetic attractive force is opposed by springs. The magnetic attractive force is proportional to the number of ampere-turns in the solenoid coil and is modulated by the electrical current from the electronics that passes through the coil. In essence, the coil/armature combination is a linear electric motor. MFCs have means that constrain the armature/valve plug assembly to move only axially up and down along the centerline of the valve, and not radially. This configuration provides smooth operation with no friction and or scraping against the inner walls of the valve.

In operation, the electronics use the MFM portion of the MFC to measure the total mass flow rate passing through the instrument. The electronics then compare this measurement with the user-selected set-point value of the total mass flow rate. MFCs use a digital proportional-differential-integral feedback network or other valve control algorithm to modulate the current passing through the coil so that the valve plug attached at the bottom end of the armature moves up or down. Manufacturers tune their valve control system to achieve their specified time response. If the mass flow rate is less than the set-point value, the current is increased, and the valve plug is raised over the valve orifice to allow more flow to pass. If it is higher, the process is reversed. In this manner, the valve plug finds the exact height over the orifice necessary to regulate the total mass flow rate in the process line so it exactly equals its set-point value, regardless of changes in upstream process pressure, downstream process pressure, process temperature, or in the mass flow rate itself.

The combination of small internal volume, frictionless operation, and an optimized control valve algorithm in MFCs facilitates a fast time response, with negligible over-shoot or under-shoot. The MFC is able to control the mass of gas entering the user's process by following the user's set-point mass flow versus time program, such as repetitive cycles, a series of step changes, ramps, etc. Since some users require special time response characteristics for their process, such as slower response times or a programmed ramp-shaped time response, some manufacturers allow the user to specify the desired time response upon order and/or provide on-board means for changing it in the field.

Some advanced multivariable semiconductor MFCs compensate for spikes in supply pressure with an on-board pressure transducer that enables fast adjustment of the current to the valve to reduce any adverse effects of pressure spikes. These MFCs also may measure gas temperature to compensate for variations in temperature. Pressure regulators in the process line also can solve this problem.

Direct acting electromagnetic flow control valves as described above operate with full scale flow rates up to about 1000 slpm. Direct acting valves have high resolution and operate smoothly without dead time or jumping. Some manufacturers offer pilot-operated diaphragm electromagnetic control valves for higher full scale flow rates. In pilot-operated valves, a small direct acting electromagnetic control valve (the "pilot valve") modulates the process pressure to move an elastomeric diaphragm over the valve orifice. Pilot-operated valves may have higher external leak rates that preclude their use in some high vacuum applications. Motor-operated butterfly and ball-type valves have also been used for higher flow applications.

Piezoelectrically actuated control valves employ a stack of piezoelectric crystals to externally actuate the valve plug. Since they are externally actuated, they have a moving valve stem that must be sealed from the outside environment, and, therefore, they have higher external leak rates. They are limited to low flow rates due to their small valve stroke. The high voltage necessary for their actuation may be perceived as a safety hazard by some users.

3.8 Electronics

The electronics of early capillary tube thermal MFMs and MFCs were all analog. Now, the electronics of most instruments have a powerful on-board microprocessor and are nearly all-digital. This facilitates a wide range of functions. In some instruments the two RTD windings are the legs of a bridge circuit, but the electronics are digital for the remaining functions. The basic functions of the electronics are: heating and controlling the capillary sensor tube; measuring the mass flow rate of the gas in the process line; operating the control valve (in the case of MFCs); and providing internal DC power, signal conditioning, and output signals. Most instruments with require 15 to 24 VDC input power and provide the usual linear analog output signals (e.g., 0-5 VDC, 0-10 VDC, and 4-20 mA), as well RS-232 and RS-485 digital output signals. Some semiconductor MFCs are multivariable and provide output signals for mass flow rate, gas temperature, and gas pressure.

Digital industrial communications protocols---such as Modbus, Profibus DP, Foundation Fieldbus, DeviceNet, and EtherCat---are offered by some manufacturers with advanced digital electronics for two-way communication with the instrument.

Some manufacturers provide a digital communications module mounted directly on the electronics enclosure that provides: a digital readout of the mass flow rate or other variables; set-point selection for MFCs; change of gas type; zero and span adjustments; digital industrial communications protocols; and other digital functions.

The electronics of MFMs and MFCs are mounted directly on the instrument. In cases where the temperature or other conditions around the flow body may compromise performance, the electronics are located remotely. In light-duty applications, the electronics enclosure, or housing, is a made of sheet metal and offers some protection against intrusion by dust and other common ambient contaminants. For more rigorous industrial environments, some manufacturers offer thick- walled sealed electronics enclosures that meet NEMA 6 and IP67 standards and are capable of withstanding wash-down or hose-down. Enclosures and electronics must meet all applicable standards and codes for hazardous locations, electrical safety, and avoidance of electromagnetic interference.

All MFCs and MFMs require flow calibration because the small dimensions of the sensor tube and the laminar flow element are not identical from instrument to instrument. Para. 8 discusses flow calibration. The electronics provide the signal conditioning necessary to deliver a linear output over the entire flow range of the instrument based on the data obtained with the flow calibration gas. Multi-gas instruments enable the user to select an operating gas other than the flow calibration gas from a list of up to 10, or more, gas choices. The instrument automatically installs the correct flow calibration for the selected gas by applying the appropriate K-factor stored in the microprocessor's memory. K-factors are described in detail in para. 7.

4 Performance and Operating Specifications

4.1 Introduction

This section describes the performance and operating specifications of a typical general purpose capillary tube thermal MFM and MFC. The values of specifications in the following are conservative; are in the middle of the range of

Table 1 Flow ranges

Flow Body Size	Maximum Mass Flow Rate Range (slpm)
Low flow	0 to 50
Medium flow	0 to 300
High flow	0 to 1500

values offered by manufacturers; and are those for which capillary tube thermal mass flow meters and controllers are best suited and which accommodate most applications. Most specifications provided by manufacturers make no distinction between mass flow meters and mass flow controllers. Published specifications may vary from manufacturer to manufacturer. Some manufacturers offer special instruments and special flow calibration that improve their published specifications.

4.2 Flow Ranges

Table 1 shows the mass flow rate ranges of the three typical flow body sizes of general purpose MFMs and MFCs---low flow, medium flow, and high flow---that accommodate most applications. The flow ranges shown are for air at 0 °C and 1 atmosphere pressure. The lowest ranges offered by manufacturers are about 0-1 sccm to 0-4 sccm. The lowest detectable flow rate is about 0.05 to 0.1 sccm. Most MFCs with direct-acting control valves have a maximum flow range of about 0 to 1500 slpm, but some pilot-operated MFCs have higher ranges. Flanged and wafer-style MFMs may have higher flow ranges. Manufacturers offer instruments that have flow ranges that may differ from those shown.

The marketplace for flow meters has many different flow metering technologies, each serving a limited range of applications for which it is best suited. The maximum mass flow rate ranges shown in Table 1 are those for which capillary tube thermal mass flow technology is best suited---clean gas flows in lower flow ranges not exceeding about 1000 to 1500 slpm (about 35 to 50 standard cubic feet per minute). Higher mass flow rates may be more cost-effectively served with other kinds of technology, such as the thermal dispersion mass flow technology described in references [1], [2], and [3].

4.3 Accuracy

The American Society of Mechanical Engineers (ASME) defines the “accuracy” of flow meters as: the degree of freedom from error, or the degree of conformity of the indicated value of the instrument to the true value of the measured quantity [5].

The accuracy of most general purpose MFMs and MFCs in measuring gas mass flow rate is 1 % of full scale, including linearity, and at flow calibration conditions. Other typical accuracy statements are: (a) 0.7 % of reading plus 0.3 % of full scale; and (b) 1 % of reading (≥ 20 % of full scale) and 0.2 % of full scale (< 20 % of full scale). Low cost instruments with plastic or aluminum flow bodies typically have accuracies in the range of about 2 to 3 % of full scale.

ASME’s definition of “uncertainty of measurement” is: the range within which the true value of a measured quantity can be expected to lie with a specified probability and confidence level [5]. Because of its common use in the industry, the term “accuracy” is used in this text, instead of “uncertainty.” Most accuracy specifications include any uncertainty due to non-linearity. An accuracy specification includes errors due to: (a) uncertainty in the flow calibration standard; (b) any non-repeatability of the MFM or MFC under test; (c) disagreement between the curve-fitting function and the actual flow response curve; and (d) inability of the flow calibration facility to deliver a sufficiently constant flow rate. Para. 8 describes flow calibration in more detail. For simplicity, the usual ± sign preceding accuracy specifications has been omitted.

Manufacturers express the accuracy of their MFCs and MFMs in measuring mass flow rate in three ways:

(1) Percent of full scale:
X % of full scale

(2) Combination:
X % of reading + X % of full scale

(3) Divided range:
X % of reading (≥ Y % of full scale) and
X % of full scale (< Y % of full scale)

It may appear that one of the above expressions for accuracy is better than the others. To compare the different accuracy expressions, the user should reduce them all to % of reading at the fraction of full scale mass flow rate where the instrument most likely will operate. This is done by simply dividing the % of full scale component in the accuracy statement by this fraction and adding it to the % of reading component.

For example, consider the following three accuracy expressions: (1) 0.5% of full scale; (2) 0.5 % of reading plus 0.25 % of full scale; and (3) 0.5 % of reading (≥ 30% of full scale) and 0.2 % of full scale (< 30% of full scale). At a flow rate that is ½ (50 %) of full scale, all three of these different accuracy expressions reduce to an identical accuracy of 1 % of reading [i.e., (1) 0.5 / 0.5 = 1% of reading; (2) 0.5 + 0.25/0.5 = 1 % of reading; and (3) 0.5 % of reading]. Since most instruments are operated in the field in the upper ⅔rds of their full scale range, actual accuracies in the field are often nearly the same.

If the instrument is installed in the field and the gas temperature and gas pressure are different than that at flow calibration, then a temperature coefficient and pressure coefficient can be applied to determine the as-installed accuracy. Such coefficients are sometimes called "temperature sensitivity" and "pressure sensitivity," and collectively they are called "influence parameters." Example temperature and pressure coefficients for general purpose MFMs and MFCs are: 0.025 % of full scale per °F (0.05 % of full scale per °C) and 0.01 % of full scale per psi (0.15 % of full scale per bar), respectively.

4.4 Repeatability and Reproducibility

ASME defines flow meter "repeatability" as: the closeness of agreement among a series of results obtained with the same method on identical test material, under the same conditions (same operator, same apparatus, same laboratory, and short intervals of time) [5].

ASME defines the "reproducibility" of flow meters as: the closeness of agreement between results obtained when the conditions of measurement differ; for example, with respect to different test apparatus, operators, facilities, time intervals, etc. [5].

The repeatability of general purpose MFMs and MFCs is typically ± 0.2 % of full scale. Some manufacturers specify a repeatability of ± 0.2 % of reading. In all cases, the flow calibration standards used by manufacturers should have an accuracy that is better than their repeatability specification by a ratio of at least 2:1 and preferably 4:1, as discussed in para. 8.

Repeatability usually is associated with short term uncertainty, and reproducibility with long term uncertainty. Most manufacturers specify only repeatability. Two sources of uncertainty in repeatability are the intrinsic digital resolution of analog-to-digital converters and other digital components, as well as any intrinsic sensor noise. Manufacturers reduce this uncertainty by employing digital electronics with very high resolution and electronic components that have high stability. The primary causes of uncertainty in reproducibility are the same as those associated with repeatability plus any long term drift caused by any aging of the sensor tube and electronic components.

Some manufacturers minimize uncertainty in reproducibility due to aging by subjecting their instruments to a long term burn-in process. A longer term burn-in process will yield higher stability than a shorter term. It is recommended that manufacturers subject their MFMs and MFCs to a process such as this, or one that achieves similar results, to ensure the long term stability of their instruments.

4.5 Rangeability

The ASME definition of the "rangeability (or turndown)" of a flow meter is: the ratio of the maximum to minimum flow rates in the range over which the meter meets a specified uncertainty (accuracy) [5].

Most MFMs and MFCs have a rangeability in mass flow rate of about 20:1 to 50:1. The usable flow range of capillary tube thermal MFMs is determined at the low end by its intrinsic sensor noise and at the high end by the amount of non-linearity that is acceptable. Because control valves are designed to control the flow, and not shut it off, MFCs have an operating range of about 2 to 100 % of full scale.

4.6 Response Time

"Response time" for flow meters, as defined by ASME, is: for a step change in flow rate, response time is the time needed for the indicated flow rate to differ from the true flow rate by a prescribed amount (e.g., 10%) [5].

A typical response time specification for MFMs and MFCs is about 0.3 to 0.5 seconds to reach within ± 37 % of the final value for the largest possible step change---0 to 100% of full scale. Another typical specification is 1 to 2 seconds to reach within ± 2 % of the final value for the same step change. Some manufacturers offer, on special order, a time response that is faster, or otherwise different, than their published specification. For MFMs, the step change is in the mass flow rate reading. For MFCs, it is the set-point. In the field, most flow rate changes are less than 100% of full scale, and the instruments will respond faster. MFCs usually have a faster time response than MFMs because the operation of the control valve is tuned by the manufacturer to enhance time response.

4.7 Gas Temperature and Pressure

Most MFMs and MFCs have applications in which the gas source is a tank or process line at room temperature. For this reason, typical process gas operating temperature specifications are in the room temperature range. A typical specification is 32 to 122 °F (0 to 50 °C). Some manufacturers offer a slightly broader range of 14 to 158 °F (-10 to 70 °C). A typical ambient temperature specification is -5 to 122 °F (-20 to 50 °C).

Most instruments have a maximum gas pressure specification of 500 psig (about 35 bar). This pressure rating accommodates most applications. Applications that require very high process pressures are accommodated with instruments with higher pressure ratings, such as about 1500, 3000, and 6000 psig (100, 200, and 400 bar). Instruments are available that operate at inlet pressures (i.e., the pressure in the MFM portion of the instrument) in the moderate vacuum range, with inlet pressures less than about 0.3 psia (0.02 bar). The outlet of the instrument often is in the high vacuum range.

To provide safety, all MFMs and MFCs should be designed and pressure tested by the manufacturer to ensure compliance with all applicable pressurized equipment standards and codes (i.e., pressure vessel codes). Users should be careful to not exceed the instrument's specified pressure rating in their process.

4.8 Leak Integrity

Because the flow bodies of MFMs and MFCs have a number of seals, manufacturers should leak test all instruments. General purpose instruments with elastomeric seals have maximum leak-rate specifications ranging from about 1×10^{-9} to 5×10^{-9} atmosphere cubic centimeters per second of helium. Semiconductor MFCs and general purpose metal sealed MFMs and MFCs intended for vacuum processes have lower maximum leak rates of about 1×10^{-11} to 1×10^{-10} atmosphere cubic centimeters per second of helium. Helium is used for leak testing because it has a higher leak rate than any other molecular gas, except hydrogen which is not used for safety reasons. The unfamiliar engineering units used for the leak mass flow rates simply mean "standard cubic centimeters per second," where standard conditions are room temperature (about 20 °C) and 1 atmosphere pressure (see para. 6).

5 Principle of Operation

5.1 Laminar Flow Bypass

The total mass flow rate $q_{m,tot}$ in MFMs and MFCs is the sum of the mass flow rate q_m

measured by the sensor tube and the mass flow rate $q_{m,bypass}$ through the bypass. Eq. (1) expresses this principle as $q_{m.tot} = q_m (1 + q_{m,bypass} / q_m)$. The term $(1 + q_{m,bypass} / q_m)$ is called the "*bypass ratio*." Para. 5.2 shows that the flow in the sensor tube is purely laminar. Here, we show that the *bypass ratio* is a constant, but only if the bypass also has a purely laminar flow. This is why the bypass must be a laminar flow element and not an orifice or other differential pressure producing element.

The pressure drop ΔP_{sensor} across the entire length L of the capillary sensor tube is the following well known expression for a circular tube with a laminar fully developed velocity distribution

$$\Delta P_{sensor} = C_{tube} \left(\frac{\mu}{\rho}\right) q_m \qquad (2)$$

where:

μ = the dynamic viscosity of the gas
ρ = the mass density of the gas
C_{tube} = a constant that depends only on the geometry of the sensor tube = $128\ L / (\pi\ D^4)$
D = the internal diameter of the sensor tube

Consider a bypass consisting of a bundle of N circular capillary tubes identical in internal diameter and length to the sensor tube. Just like the sensor tube itself, this bypass has a laminar fully developed velocity distribution and is a laminar flow element bypass. The pressure drop across this laminar flow element is

$$\Delta P_{bypass} = \left(\frac{C_{tube}}{N}\right) \left(\frac{\mu}{\rho}\right) q_{m\ bypass} \qquad (3)$$

As is evident from the flow paths shown in Fig. 4, the pressure drops across the sensor tube and bypass are identical, or $\Delta P_{sensor} = \Delta P_{bypass}$. If eq. (3) is divided by eq. (2) and the quotient rearranged, the result is $q_{m,bypass} / q_m = N$, and thus the *bypass ratio* = 1+ N. In this case, eq. (1) becomes

$$q_{m.tot} = q_m(1 + N) = Constant \cdot q_m \qquad (4)$$

It is easily shown that eq. (4) is true for any bypass, regardless of the geometry of its flow passages (e.g., slots, honeycomb, etc.), if those passages have a fully developed laminar velocity distribution over their entire length. In other words, the bypass must be a laminar flow element. Eq. (4) states an important principle of operation. Because the *bypass ratio* is devoid of all gas properties and is constant, the measurement of q_m by the sensor tube directly measures the desired total mass flow rate $q_{m.tot}$ in the process line, regardless of changes in flow rate, gas temperature, and gas pressure. Manufacturers are cautioned to not force excessive flow through a laminar flow element bypass because a non-linearity proportional to the square of the flow rate may arise. Left uncorrected, this can cause measurement errors.

Now, consider a bypass that is a differential pressure producing element, such as an orifice, nozzle, or venturi. In this case, the *bypass ratio* is not constant, but instead depends on the absolute viscosity μ of the gas and the sensor tube's mass flow rate q_m. Both of these dependencies cause measurement errors. For example, a change of only 20 °C in gas temperature causes an error in $q_{m.tot}$ of over 2% of reading due to changes in viscosity. A 10 % of full scale change in flow rate causes an error in $q_{m.tot}$ of over 5% of reading. If the bypass is a differential pressure producing element, the sensor tube essentially acts as a differential pressure transducer.

Manufacturers of high accuracy MFMs and MFCs have designed their bypasses and have limited their maximum flow rates to ensure purely laminar flow in their bypasses. Products that use differential pressure producing elements for the purpose of reducing costs or extending the maximum flow range may suffer from the errors discussed above, and the primary virtue of capillary tube thermal technology---direct measurement of mass flow rate---is lost.

Eq. (4) shows how the total mass flow rate is found via the measurement of the mass flow rate q_m flowing through the sensor tube. The following sections show how q_m is measured.

5.2 Characterization of the Flow in the Sensor Tube

The typical sensor tube and its internal gas flow are described by the following parameters:

(1) The ratio of the total length to the internal diameter is greater than 100:1

(2) The maximum (i.e., at the full scale mass flow rate) gas velocity is less than 5 to 10 m/s

(3) The maximum Reynolds number is less than 100

(4) The maximum Mach number is less than 0.05

(5) Maximum laminar hydrodynamic and thermal entry lengths are less than 1% of the total length of the sensor tube. The hydrodynamic entry length and thermal entry length are the distances from the entrance of the sensor tube to the points, respectively, where the velocity profile is nearly a fully developed laminar velocity distribution and where the local convective heat transfer coefficient is nearly its final value.

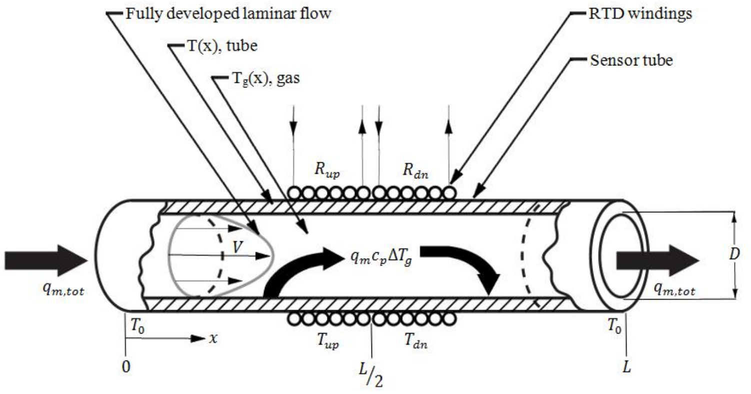
Based on these parameters, the gas flow in the sensor tube has these characteristics:

(1) The flow is purely laminar and has a fully developed velocity distribution and a constant convective heat transfer coefficient over its entire length.

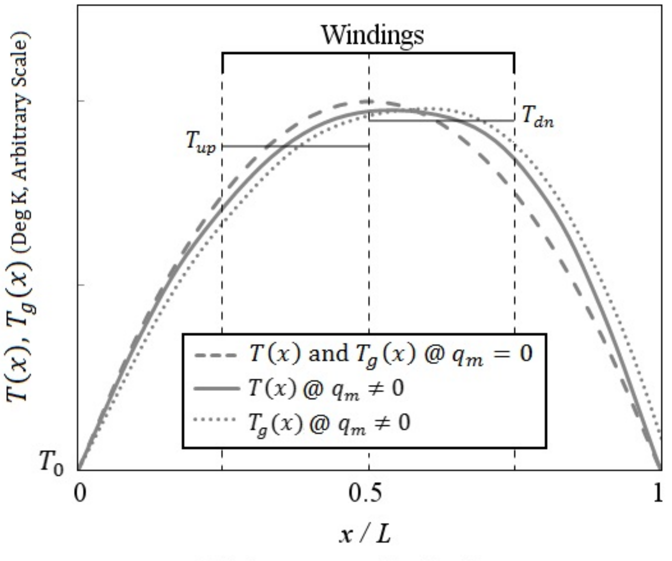
(2) The flow is incompressible.

(3) The temperature distributions of the sensor tube $T(x)$ and the gas $T_g(x)$ are a function of the axial dimension x of the sensor tube only and are independent of radial and azimuthal dimensions (in a cylindrical coordinate system).

Additionally, it is further assumed that: the flow is at steady state (i.e., independent of time); the properties of the gas and the materials of the sensor tube are constant (i.e., independent of x); the sensor tube temperature $T(x)$ is constant across the thickness of the tube's wall; and the gas temperature $T_g(x)$ is the "mean temperature" [6] over the internal cross-sectional area of the tube. These assumptions are true for the long thin-walled capillary tubes with their relatively fast response time and fully developed laminar flow.



(a) Sensor tube



(b) Temperature distributions

Fig. 5 (a),(b) Sensor tube and temperature distributions

5.3 Heat Capacity Rate, $q_m c_p$

The principle of operation of capillary tube thermal MFMs and MFCs is shown in Fig. 5. Views (a) and (b) schematically show:

(a) The sensor tube depicted for clarity as a straight tube, instead of its usual "U"-shaped configuration.

(b) The temperature distributions of the sensor tube *T(x)* and the gas flowing through it $T_g(x)$, with zero flow and non-zero flow. The average temperatures of the upstream and downstream windings, T_{up} and T_{dn}, are shown in Fig. 5(b) and demonstrate that T_{dn} is greater than T_{up} when there is flow.

Fig. 6 shows the coin-shaped differential control volume of the gas flowing inside the sensor tube. The figure shows the energy transfer streams entering and leaving the control volume. At steady state, the first law of thermodynamics (conservation of energy) states that the sum of the energy (power) transfer streams entering the control volume equals that leaving the control volume. Applying this to the control volume in Fig. 6, we arrive at the following differential energy equation for the axial temperature distribution $T_g(x)$ of the gas

$$\underbrace{-k_g A_g \frac{d^2 T_g(x)}{dx^2}}_{(1)} + \underbrace{q_m c_p \frac{dT_g(x)}{dx}}_{(2)} - \underbrace{h\pi D\left(T(x) - T_g(x)\right)}_{(3)} = \underbrace{VISC}_{(4)} \quad (5)$$

In eq. (5), the variable x is the axial dimension ($0 \leq x \leq L$) of the sensor tube and the independent variable. Eq. (5) has units of watts/m.

Terms (1) to (4) in eq. (5) are explained as follows:

Term (1) is the axial heat conduction in the control volume. k_g is the thermal conductivity of the gas (watts/m·K); D is the internal diameter of the sensor tube (m); and $A_g = \pi D^2/4$ (m^2) is the internal cross-sectional area of the sensor tube. For flows over most of the linear range, Term (1) is negligible compared to Terms (2) and (3) because the thermal conductivity of gases is small, and the second derivative $\frac{T_g(x)}{x^2}$ is significant only in the entry length of the sensor tube, which constitutes only about 1 % of the tube's total length. At very low flows, Term 1 is no longer negligible compared to Terms (2) and (3) and may be included.

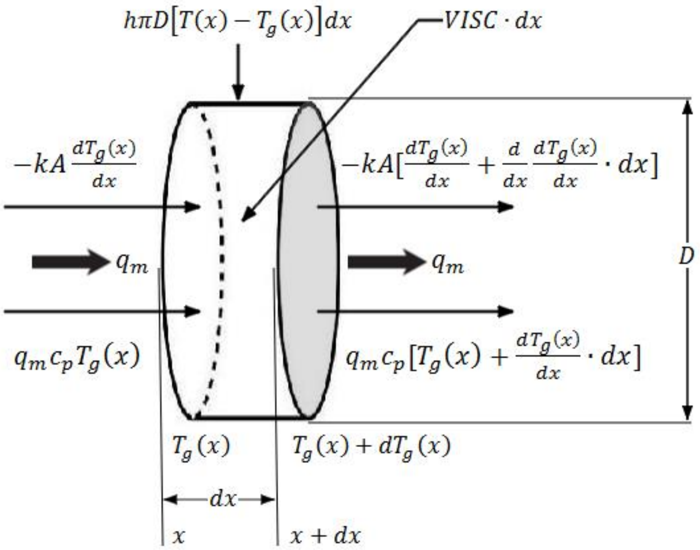


Fig. 6 Differential control volume of the gas flowing in the sensor tube

Term (2) is the energy (enthalpy) transport due to the heat capacity of the gas. "Heat capacity" is the thermodynamic property of the gas that measures its ability to store thermal energy, i.e., enthalpy. q_m is the constant mass flow rate (kg/s) through the sensor tube, and c_p is the coefficient of specific heat of the gas at constant pressure (Joules/kg·K). The product $q_m\ c_p$ (watts/K) in Term (2) is called the "heat capacity rate" and is crucial in understanding how the sensor tube measures q_m. This expression for enthalpy in Term (2) is strictly true only for ideal gases, but is also a good approximation for other incompressible fluids [3].

Term (3) is the heat transferred radially via forced convection from the sensor tube to the gas. h is the convective heat transfer coefficient (watts/m^2·K).

Term (4) is the viscous energy dissipation in the gas due to frictional effects. Term (4) is proportional to the dynamic viscosity of the gas and increases as the flow rate increases. It is negligible compared to Terms (2) and (3) because the viscosity of gases is relatively small and the mass flow rate is low.

Based on the foregoing and with some rearrangement, eq. (5) becomes

$$h\,\pi\,D\,\big(T(x) - T_g(x)\big) = q_m\,c_p\,\frac{T_g(x)}{dx} \quad (6)$$

Eq. (6) expresses a fundamental relationship in the field of heat transfer [6].

The temperature distributions $T(x)$ and $T_g(x)$ in Fig. 5(b) are related to those found in MFMs and MFCs. The hill-like shape of the temperature distribution of the sensor tube is created by the heat added by the windings in the central portion of the tube and removed by heat conduction at its two ends. At zero flow, the two temperature distributions are essentially identical and symmetrical about the center of the tube (i.e., at $x = L/2$). When there is flow in the tube (flow is to the right), the two profiles become asymmetrical and slightly shifted. Because heat transfer in the sensor tube is dominated by heat conduction at its ends, the difference between the two distributions in actual instruments is relatively small, yet has excellent sensitivity in providing the mass flow measurement. For clarity, Fig. 5(b) exaggerates this difference.

Eq. (6) shows the equality between the heat transferred via forced convection from and to the sensor tube and the gain and loss, respectively, of this heat via the heat capacity of the gas. Eq. (6) explains the temperature distributions in Fig. 5(b). The gas entering the sensor tube has the temperature T_0 of the flow body and the inlet of the sensor tube, as shown in Fig. 5(a), (b). When the gas encounters the ever increasing temperature profile of the sensor tube (i.e., $\frac{T(x)}{dx} > 0$) in the upstream half of the sensor tube, the gas temperature continually increases but is always slightly cooler than the sensor tube because each incremental distance it moves through the tube it encounters an incrementally higher tube temperature. So, in the upstream half of the sensor tube, heat is always transferred from the sensor tube to the gas via forced convection. This heat is absorbed by the gas via its heat capacity, and the gas temperature continues to increase (i.e., $\frac{T_g(x)}{x} > 0$). This process in the upstream half of the sensor tube is shown directly in eq. (6).

After reaching the center of the sensor tube, the gas encounters the decreasing temperature profile (i.e., $\frac{dT(x)}{dx} < 0$) in the downstream half of the sensor tube (due to its dominant heat conduction), but retains the heat it has absorbed in the upstream half. So, its temperature is always higher than that of the sensor tube, and heat is transferred from the gas to the sensor tube via forced convection. The heat deposited into the downstream half of the sensor tube is that which is carried in the gas via its heat capacity, and the gas temperature continues to decrease (i.e., $\frac{T_g(x)}{dx} < 0$) as the gas deposits its heat. This process is shown by eq. (6), but, since $\frac{T_g(x)}{dx}$ is negative in the downstream portion of the sensor tube, the term $(T(x) - T_g(x))$ also is negative, and therefore the direction of heat convection is from the gas to the sensor tube.

Because heat is lost by the upstream half of the sensor tube and gained by the downstream half, the average temperature of the upstream half is less than the average temperature of the downstream half. As a result, the average temperature T_{up} of the upstream winding of the sensor tube is less than the average temperature T_{dn} of the downstream winding. This is shown schematically in Fig. 5(b). The temperature difference (T_{dn} - T_{up}) is the basic output of the instrument, and, for low flow rates, is caused entirely by the heat capacity of the gas. The magnitude of this temperature difference is modulated by, and is directly proportional to, the heat capacity rate $q_m c_p$. This principle of operation is expressed as

$$q_m\,c_p = C_{temp}\,(T_{dn} - T_{up}) \quad (7)$$

In eq. (7), C_{temp} is a constant depending on the geometry and design of the sensor tube. Note that, at zero flow, $T_{dn} = T_{up}$, and q_m becomes zero, as it should. For low flow rates, eq. (7), if solved for q_m, shows that q_m depends only on c_p and no other gas property.

In 1930, P.M.S. Blackett (who later won the Nobel Prize for other work) and his colleagues at Cambridge University published what is believed to be the first paper describing the physics of a heated capillary tube with a gas flowing through it [7]. Blackett first suggested, for very low mass flow rates, that the difference in the average downstream and upstream temperatures of the tube is linearly proportional to the heat capacity rate $q_m c_p$, thereby giving us the basis for eq. (7).

The arrow in Fig. 5(a) labeled with the symbol $q_m c_p \Delta T_g$ schematically represents the heat (in units of watts) transported by the gas from the upstream half of the sensor tube to the downstream half by means of its heat capacity. ΔT_g (K) is a fictitious temperature differential representing the increase and then decrease in gas temperature as it flows through the sensor tube.

5.4 Instrument Output

The typical sensor tube described in para. 3.6 has two symmetrical and identical platinum RTD windings on its outside diameter, one on each side of the center of the sensor tube [i.e., at $x = L/2$ in Fig. 5 (a)]. Although the two windings cover a fraction of the total length of the sensor tube, the principles stated in the previous section still apply.

The windings provide the heat to the sensor tube that creates temperature profiles similar to those shown in Fig. 5(b). They also measure their own temperature. The digital electronics measure the electrical resistance R_{up} and R_{dn} (ohms) of the upstream and downstream RTD windings, respectively. For temperatures in the normal operating range of MFMs and MFCs (about 0 to 100 °C), the average winding temperatures T_{up} and T_{dn} can be found from the electrical resistances using the following two relationships

$$R_{up} = R_r\,[1 + \alpha\,(T_{up} - T_r)]$$
$$R_{dn} = R_r\,[1 + \alpha\,(T_{dn} - T_r)] \qquad (8)$$

In eqs. (8), R_r is the electrical resistance (ohms) of both windings at reference temperature T_r (K), and α is the temperature coefficient of resistivity (K^{-1}). The resistances of the two windings are adjusted to be equal at zero flow.

The difference in the two resistances is $R_{dn} - R_{up} = \alpha\, R_r\, (T_{dn} - T_{up})$. Combining this with eq. (7), we arrive at the two final expressions for the output of capillary tube thermal MFMs and MFCs operating in the so-called “linear range” where q_m is small (see following para. 5.5)

$$q_m\, c_p = C_{cap}\,(R_{dn} - R_{up}) \qquad (9)$$

$$q_m = C_{mass}\,(R_{dn} - R_{up}) \qquad (10)$$

Eq. (10) shows how capillary tube thermal MFMs and MFCs measure the mass flow rate qm in the sensor tube. In these equations, $C_{cap} = C_{temp} / (\alpha \cdot R_r)$, and $C_{mass} = C_{temp} / (\alpha \cdot R_r \cdot c_p)$. The meter factor C_{cap} depends only on the geometry and electrical properties of the winding of the sensor tube, and not the gas.

Eq. (11), which follows, is the relationship that describes how MFMs and MFCs measure the final result ---the total mass flow rate $q_{m,tot}$.

$$q_{m,tot} = C_{tot}\,(R_{dn} - R_{up}) \qquad (11)$$

In eq. (11), $C_{tot} = (\textit{bypass ratio}) \cdot C_{mass} = (\textit{bypass ratio}) \cdot [C_{temp} / (\alpha \cdot R_r \cdot c_p)]$. The constant C_{tot} depends on: the geometry and design of the sensor tube; the geometry of the laminar flow element; and the coefficient of specific heat c_p of the gas, and no other gas property. Because $q_{m,tot}$ does depend on the gas property c_p, the identity of the gas must be known.

Table 2 c_p [kilojoules/(kg·K)] for selected gases used in general purpose applications [8]

Gases	Pressure (bar)	Temperature (K)		
		260	300	340
Helium (He-4)	1	5.193	5.193	5.193
	10	5.193	5.192	5.192
Argon (Ar)	1	0.5220	0.5215	0.5212
	10	0.5376	0.5324	0.5292
Nitrogen (N_2)	1	1.042	1.041	1.042
	10	1.062	1.056	1.053
Air	1	1.006	1.007	1.009
	10	1.026	1.021	1.019
Hydrogen (H_2)	1	15.20	14.85	14.66
	10	15.24	14.87	14.68
Methane (C_2H_4)	1	2.159	2.236	2.340
	10	2.238	2.289	2.379
Carbon Dioxide (CO_2)	1	0.8142	0.8525	0.8900
	10	0.9450	0.9209	0.9320

Due to their small size, the dimensions and construction of sensor tubes and laminar flow elements are not absolutely reproducible from sensor to sensor. Consequently, the constant C_{tot} is different for each instrument and must be determined via flow calibration for the specific gas of the application. If the gas of the application is the same as the flow calibration gas, the value of c_p need not be known. But, if the instrument is to be used for more than one gas---as in the case of multi-gas instruments---the identity of the gas (i.e., its composition) and its c_p must be known.

Table 2 shows c_p for seven gases commonly used in general purpose industrial and laboratory applications over a range of gas temperature and pressure that is broader than most applications [8]. As shown in the table, the temperature and pressure dependency of c_p is weak for most gases listed. Only methane and carbon dioxide exhibit some dependency. cp for carbon dioxide varies about 4% from 300 to 340 K at 1 bar, whereas its dynamic viscosity and thermal conductivity vary by 13% and 20%, respectively, over the same range.

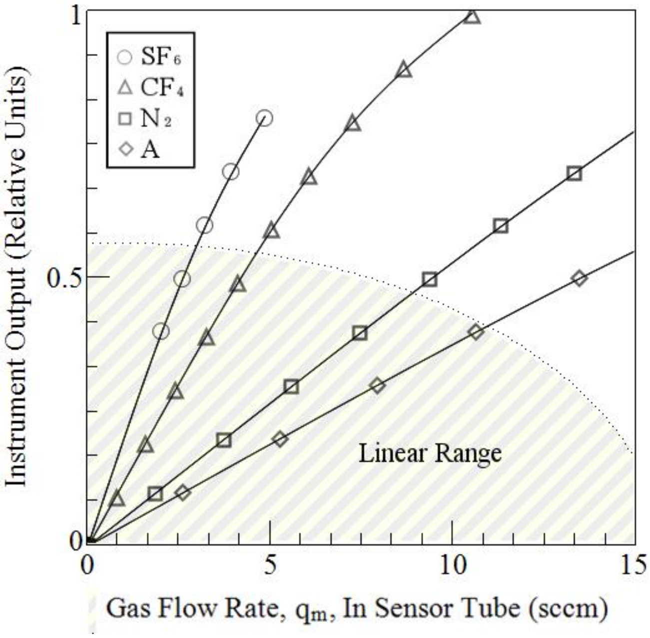


Fig. 7 Instrument outputs versus the mass flow rate, q_m, through the sensor tube for four different gases

Additionally, the effect of gas temperature and pressure usually is small because most instruments are operated in the field at nearly the same conditions for which the instrument was flow calibrated, i.e., room temperature and with an upstream pressure regulator set at its flow calibration value (typically 2 to 4 bar).

c_p is a fortuitous gas property because: it is the only gas property needed for MFMs and MFCs operating at lower flow rates; it is known with a high degree of accuracy; it has a weak dependency on gas temperature and pressure relative to other gas properties; and, in most applications, can be treated as a constant.

5.5 Linear Range

Fig. 7 shows experimentally determined instrument outputs of capillary tube thermal MFMs and MFCs for four different gases as a function of the mass flow rate q_m in the sensor tube. The gases in the figure are selected to show the extent of variations from gas to gas.

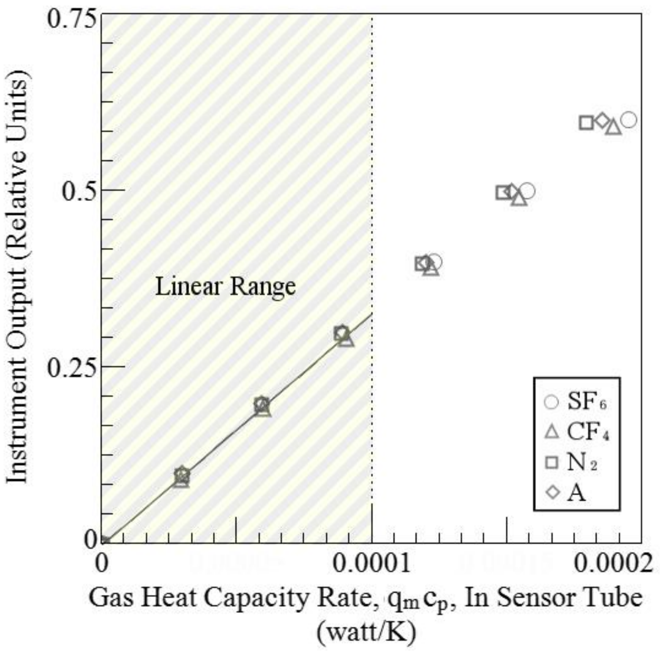


Fig. 8 Instrument outputs versus heat capacity rate, $q_m c_p$, for the same four gases in Fig. 7

The instrument output curves in Fig. 7 are nearly linear at low values of q_m. In practice, MFMs and MFCs are operated in this “linear range.” The linear range occurs at low values of q_m where the intrinsic linearity is better than about 1 %. Multi-point flow calibration is used by manufacturers to eliminate this intrinsic non-linearity and achieve nearly perfect linearity.

Fig. 8 shows the experimentally determined instrument output for the same four gases shown in Fig. 7 when plotted as a function of the heat capacity rate $q_m c_p$. As shown in the figure, at low values of $q_m c_p$ (i.e., at low values of q_m), the data for all four gases merges essentially into a single straight line in accordance with Blackett [7]. Fig. 8 demonstrates the primary principle of operation of capillary tube thermal MFMs and MFCs.

6 Standard Volumetric Flow Rate

6.1 Description

The most common mass flow rate units used in the industry served by capillary tube thermal MFMs and MFCs are the following two “standard volumetric flow rates”---slpm (standard liters per minute) and sccm (standard cubic centimeters per minute). Although the units “slpm” and “sccm” may appear to be purely volumetric flow rates, they are indeed mass flow rates, as shown later in the text. The following conversion factors may be useful: 1 slpm = 1000 sccm = 0.001 standard cubic meters per minute = 0.035315 standard cubic feet per minute = 2.1189 standard cubic feet per hour.

The law of conservation of mass (the continuity equation) applied to the flow in the capillary sensor tube is

$$q_m = \rho\, q_v = \rho_s\, q_{v,s} \qquad (12)$$

In eq. (12), ρ and q_v are the mass density and volumetric flow rate of the gas, respectively, at static temperature T_g and static pressure P. ρ_s and $q_{v,s}$ are the same quantities but are evaluated at “standard conditions” of “standard static temperature” T_s and “standard static pressure” P_s. In this text, $q_{v,s}$ is called the “standard volumetric flow rate.” In some segments of the industry, $q_{v,s}$ is also called the “volumetric flow rate referenced to standard conditions.” In primary metric units, q_m has units of kg/s; ρ_s has units of kg/(standard m^3); and $q_{v,s}$ has units of standard m^3/s.

Three sets of standard conditions are in common use:

(1) T_s = 0 °C = 273.15 K;
P_s = 1 atmosphere = 14.6959 psia = 101325 Pa = 1.01325 bar

(2) T_s = 20 °C = 293.15 K;
P_s = 1 atmosphere = 14.6959 psia = 101325 Pa = 1.01325 bar

(3) T_s = 70 °F = 21.11 °C = 294.26 K;
P_s = 1 atmosphere = 14.6959 psia = 101325 Pa = 1.01325 bar

The standard conditions in Set (1) above are often called “normal conditions” and are used in Europe and by the semiconductor industry [9].

For most gases, the mass density ρ_S (kg/m^3) at standard conditions obeys the following real gas law equation of state

$$\rho_S = P_S\, M \,/\, (Z\, R\, T_S) \qquad (13)$$

In the above, M is the molecular weight of the gas (kg / kg-mole); Z is its compressibility (dimensionless); and R = the universal gas constant = 8.31451×10^3 [(m^3 · Pa) / (kg-mole · K)]. In eq. (13), both T_S and P_S must be in absolute units (e.g., K and Pa, respectively). For perfect gases, $Z = 1$, and eq. (13) becomes the familiar ideal gas law. For some non-ideal gases (such as carbon dioxide or sulfur hexafluoride), Z is a function of gas temperature and pressure. For gas temperatures and pressures not far from room conditions, the value of Z is nearly unity for most gases.

Eqs. (12) and (13) provide us with a simple proof that the standard volumetric flow rate $q_{v,s}$ is a mass flow rate. Since T_S and P_S are constants in eq. (13), ρ_S must also be a constant. Because $q_{v,S}$ in eq. (12) equals the mass flow rate q_m when it is multiplied by the constant ρ_S, it must itself be a measure of mass flow rate.

The standard (or “normal”) conditions in Set 1 above (i.e., 273.15 K and 101325 Pa) are convenient for any process involving chemical reactions, such as those in the semiconductor industry [9]. This is the case because at those standard conditions, one gram mole of any ideal gas occupies a volume of exactly 22,413.6 cubic centimeters. It follows that a flow rate of 22,413.6 sccm of any perfect gas is one gram mole per minute.

6.2 Conversion of Volumetric Flow Rates

Conversion from one set of standard conditions to another is often required. Additionally, flow calibrators that measure volumetric flow at non-standard conditions must convert that measurement to the desired standard conditions. From eq. (12), for the two sets of flow conditions “1” and “2”, it can be shown that $\rho_1\, q_{v,1} = \rho_2\, q_{v,2}$. Based on this relationship and eq. (13) (with the s subscripts removed), it follows that

$$q_{v,2} = (P_1 / P_2)\, (T_2 / T_1)\, q_{v,1} \qquad (14)$$

For example, if the flow calibration of an MFM or MFC yields a volumetric flow rate of 100 lpm at a temperature of 30 °C and a pressure of 5 psig and we wish to convert this to the standard flow conditions in Set (1) above, eq. (14) yields this result

$$q_{v,s} = \left[\frac{(5+14.6959)}{14.6959}\right] \text{x} \left[\frac{273.15}{(30+273.15)}\right] \text{x}\, 100 = 120.76 \text{ slpm} \qquad (15)$$

7 Conversion from One Gas to Another

Capillary tube thermal MFMs and MFCs have the advantage of enabling flow calibration with a reference, or surrogate, gas and converting it to any other gas. This facilitates: (1) using less expensive and safer gases for flow calibration; (2) calibrating rare gases; and (3) providing the multi-gas feature of advanced digital MFMs and MFCs. Manufacturers offering multi-gas operation provide a list the different gases supported by their instruments.

This advantage is based on eq. (9), which shows that if two gases, Gas 1 and Gas 2, have the same instrument output in the linear range, then $q_{m,1}\, c_{p,1} = q_{m,2}\, c_{p,2}$. This equation, combined with eq. (12), results in

$$\rho_{S,1}\, q_{v,S,1}\, c_{p,1} = \rho_{S,2}\, q_{v,S,2}\, c_{p,2} \qquad (16)$$

Based on this relationship, it can be shown that

$$q_{v,S,2} = K_{1,2}\, q_{v,S,1} \qquad (17)$$

where

$K_{1,2} = (\rho_{S,1}\, c_{p,1}) \,/\, (\rho_{S,2}\, c_{p,2})$ = the “gas conversion factor,” or simply “K-factor,” that converts the flow calibration of Gas 1 to Gas 2.

Eq. (17) is true only for low flow rates in the range where the instrument outputs for both Gas 1 and Gas 2 are in the linear range described in para. 5.5.

Gas conversion factors $K_{i,j}$ [as shown in eq. (17)] have been used since the first commercialization of capillary tube thermal MFMs and MFCs to convert the flow calibration for a reference gas to any other gas. Most manufacturers provide a long list (often with well over a 100 entries) of gas conversion factors relative to a single primary reference gas, usually air or nitrogen. By using test data, some manufacturers have slightly modified the values of the gas conversion factors expressed in eq. (17) for the purpose of increasing accuracy and extending the flow range beyond the linear range. This is why gas correction factors can differ by small amounts from manufacturer to manufacturer and, for a given manufacturer, from instrument model to model.

In some cases, it may be advantageous to flow calibrate with a secondary reference gas that is different than the primary reference gas. If the primary reference gas is Gas 1, the secondary reference gas is Gas 2, and the gas to which the secondary conversion is to be applied is Gas 3, then the application of eq. (17) to Gases 2 and 3 yields $q_{v,s,2} = K_{1,2}\, q_{v,s,1}$ and $q_{v,s,3} = K_{1,3}\, q_{v,s,1}$. Rearrangement of these equations results in the following relationship for converting the flow calibration of Gas 2 to any other gas (Gas 3 in this case).

$$q_{v,s,3} = (K_{1,3} / K_{1,2})\, q_{v,s,2} \qquad (18)$$

For example, if the primary reference gas is air (Gas 1); the secondary reference gas is argon (Gas 2: $K_{1,2}$ = 1.40, approximately); the gas to which the secondary conversion is to be applied is hydrogen (Gas 3: $K_{1,3}$ = 0.975, approximately); and the argon flow calibration data point is $q_{v,s,2}$ = 300 slpm, then eq. (18) yields

$$q_{v,s,3} = \left(\frac{0.975}{1.40}\right) q_{v,s,2} = 0.696 \cdot 300 = 209 \text{ slpm} \qquad (19)$$

8 Flow Calibration

8.1 Introduction

All MFMs and MFCs must be flow calibrated by the manufacturer because the small dimensions of the sensor tube and laminar flow bypass and the assembly of the windings are not absolutely reproducible from instrument to instrument. This section describes flow calibration where the fluid is a gas, not a liquid.

The term “flow calibration” used in this standard has the following definitions:

(1) The process of comparing the indicated mass flow rate output of the MFC or MFM to a traceable flow calibration standard and

(2) The process of adjusting the instrument’s mass flow rate output to bring it to a desired value, within a specified tolerance, for a particular value of the mass flow rate input.

8.2 Gas Flow Calibration Facility

The typical gas flow calibration facility is an open-loop system with the following major components:

(1) Gas source---usually a pressurized tank of the calibration gas

(2) Upstream flow regulator---usually another capillary tube thermal MFC or a stand-alone flow control valve

(3) Upstream pressure regulator

(3) Device under test (i.e., the MFM or MFC)

(4) Downstream pressure regulator (optional)

(5) Flow calibration standard --- the component that provides the mass flow rate input to which the output of the device under test is compared

(6) Discharge subsystem---a vent to the outside environment or, if required, a scrubber, collection tank, or equivalent subsystem that protects human health and the environment

8.3 Data Points and Curve Fitting

If possible, MFCs and MFMs are flow calibrated with the actual gas of the user's application. Alternatively, for operating gases that are expensive or are flammable, corrosive, toxic, or otherwise harmful, the instrument is flow calibrated with a reference, or surrogate, gas that is safe and benign (such as air or nitrogen). The proper K-factor, as described in para. 7, is then applied to convert the instrument output to that of the desired operating gas.

Low-cost, low-accuracy instruments may use a minimum two-point flow calibration that measures the zero and full-scale mass flow rates. Instruments with higher accuracy specifications require multi-point calibration because the mass flow rate output signal is nearly linear, but not exactly so. Four or five calibration points often are sufficient to provide specified accuracy, but as many as ten flow calibration points are sometimes used, especially in applications requiring flow rates above the linear range.

Instruments with higher accuracy reduce the uncertainty of the measurement by fitting a curve through the data points using a least-squares approach or another curve-fitting technique. The parameters of the curve-fitting function are stored in the instrument's memory and used to calculate the instrument output.

8.4 Flow Calibration Standards

The flow calibration standard, or master, is the flow measuring device that generates the flow calibration data points. It is recommended that the manufacturer's flow calibration standard have an accuracy that is 4 times more accurate than the MFM or MFC under test and has less random noise. If this is the case, the standard has errors that are statistically negligible compared to the device under test, and least squares curve fitting is valid. At a minimum, the manufacturer's flow calibration standard must be 2 times more accurate than the device under test. Some MFMs and MFCs are flow calibrated using another capillary tube thermal MFM or MFC as the standard. This is acceptable if the thermal standard has a special flow calibration and recalibration protocol that ensures the proper accuracy factor.

8.5 Primary and Secondary Standards

Primary flow calibration standards are those that measure flow rate by directly using one or more of the three primary measurements: mass, length (or volume), and time. In the SI system, the primary measurement units are kilograms, meters, and seconds. Secondary flow calibration standards are those that make secondary measurements to measure flow rate, such as absolute pressure, differential pressure, etc. Instruments that make secondary measurements must be traceable to a flow calibration performed by an accredited flow standards laboratory. Traceability documentation should be made available to users. Primary flow calibration standards are recommended over secondary standards.

8.6 Primary Standards---Piston Provers and Bell Provers

Piston provers and bell provers are the two primary gas flow calibration standards used by manufacturers of high accuracy MFMs and MFCs. Both standards measure flow rate by making two primary measurements---volume and time, i.e., volume displaced over time. Weighing methods are also primary gas flow standards, but they are seldom used because it is difficult to collect a large enough mass of gas at the low flow rates of capillary tube thermal MFMs and MFCs to be accurately measureable against the background mass of the collection tank.

In **piston provers**, the flow calibration gas enters the bottom of a vertical tube (usually a precision bore glass tube) below a sealed low-friction piston. The tube has a constant and precisely known internal diameter ranging from a fraction of a centimeter to about 6 centimeters. The piston moves vertically upward as the gas fills the portion of the cylinder below the piston. The vertical position of the piston is measured with ultrasonic or other highly accurate position transducers. The volume displaced divided by the time taken for the displacement to occur measures the volumetric flow rate q_V flowing through the instrument. The temperature and pressure of the flow calibration gas are measured with laboratory-grade transducers, and the mass density ρ of the gas is determined. The mass flow rate is found from eq. (12) as $q_m = \rho\ q_V$.

Piston provers have an accuracy (uncertainty) of about 0.2 % of reading. This meets the 4:1 accuracy rule for almost all instruments. Their turndown is about 15:1, and their stability exceeds 10 years. Flow rates ranging from about 1 sccm to 50 slpm are accommodated by using tubes with different bore diameters.

Bell provers are used for higher flow rates from about 50 to 5000 slpm. They operate on the same principle as piston provers but have larger internal diameters as high as 1 meter and are externally sealed in an oil bath. The volume of calibration gas is measured by the rise of the entire bell itself.

8.7 Secondary Standards

The three most common secondary flow calibration standards are: pressure rate of rise devices, laminar flow elements, and critical flow nozzles. Laboratory grade capillary tube thermal mass flow meters have been proposed for measuring very low flow rates. All secondary measurements must be made with highly accurate laboratory grade instruments.

Pressure rate of rise devices are located downstream of the device under test and collect the flowing calibration gas in a tank with an accurately known internal volume. This process is also called the “volumetric method.” As the gas accumulates, the rise in the tank’s pressure is measured with a pressure transducer. The temperature of the gas and the time interval of the fill are also measured. The mass flow rate is the mass of gas accumulated during the time interval divided by the time interval, which is proportional to the rate of rise of the pressure dP/dt. The temperature of the gas should be constant during the fill [10]. This flow calibration technique is used in the semiconductor industry and has the advantage of collecting the flow calibration gas for subsequent use or scrubbing.

Laminar flow elements measure the differential pressure across a flow component that has a fully developed laminar flow, not unlike the laminar flow element bypasses used in MFMs and MFCs described in para. 3.5. The absolute pressure and temperature also are measured to obtain the mass density of the gas. The differential pressure across the laminar flow element must be kept sufficiently small to maintain its laminar flow characteristic, which can challenge the sensitivity of the differential pressure transducer. If the pressure drop is increased to counteract this, the measurement may become non-linear. The volumetric flow rate measurement made by the laminar flow element depends on the viscosity of the gas and therefore is temperature dependent.

Critical flow devices employ critical flow through a flow nozzle or orifice [11]. Critical, or choked, flow means the Mach number in the throat of the flow nozzle is unity, and the flow is sonic there. When this occurs at a fixed temperature, the mass flow rate through the nozzle is directly proportional to the absolute pressure upstream of the nozzle. To attain choked flow for air and nitrogen, the ratio of the upstream to downstream pressure must be at least 2:1. For this reason, critical flow nozzles can never achieve a zero flow. A bank of critical flow nozzles is used in the calibration facility to cover all the flow ranges. Critical flow nozzles are suitable for higher flow rates, and, if kept clean, have good stability.

9 Best Practices

9.1 Gases to Avoid

Capillary tube thermal MFMs and MFCs are designed to accommodate clean pure gases and gas mixtures and some liquids. They should not be used with the following: (a) chemically unstable gases that decompose or evaporate under moderate heating (up to about 100 °C); (b) condensing vapors that liquefy or solidify in the cooler portions of the instrument; (c) corrosive gases that attack the walls of the sensor tube (e.g., ozone); (d) single-phase gas mixtures with proportions that vary over time; (e) turbulent flows; (f) non-Newtonian gases; (g) multi-phase flows; and (h) liquids that release bubbles inside the sensor tube (e.g., hydrogen peroxide).

9.2 Best Practices for Users

Best practices by users for the selection, safety, installation, and operation of their capillary tube thermal MFMs and MFCs are as follows:

(1) The user should select an MFC instead of an MFM if the intent of the application is to control the mass flow rate of the gas and not just measure it.

(2) The user should select only those MFMs and MFCs wherein the manufacturer's specifications meet the conditions of the application, such as maximum and minimum flow rate, pressure, and temperature. Some manufacturers have software programs that recommend the instrument model best suited for the user's application.

(3) To minimize pressure drop and flow non-uniformities, the user should select the instrument with the largest inlet fittings compatible with the size of the process line. In the case of corrosive gases, the instrument selected should have materials of construction that provide protection against corrosion.

(4) If possible, it is recommended that the user size the instrument so it operates in the upper ⅔rds of its full scale mass flow rate range.

(5) The user shall install the instrument only in those locations that comply with applicable codes and standards for hazardous locations, electrical safety, and electromagnetic interference.

(6) The user shall install the instrument only in process lines that meet the manufacture's pressure and temperature ratings. A margin of safety should be provided if spikes and surges exist in the process. Proper pressure relief valves and burst plates should be installed in high pressure applications.

(7) To avoid obstructions in the sensor tube and the narrow flow channels in the laminar flow element, the user should install the instrument in process lines that have clean gases. Upstream particulate filters are recommended for all applications.

(8) To avoid thermal siphoning (or, the so-called, "chimney effect"), the user should install the instrument in the process line with the axis of the flow body oriented horizontally, not vertically. At zero flow, if the axis is vertical, the gas heated by the sensor tube rises upward through the sensor tube and creates a closed flow loop in the flow body that causes the instrument to read a flow rate when there is none. This effect is significant only in the very lowest portion of the full scale range. If system constraints require vertical mounting, then the instrument should be rezeroed in the field. Vertical mounting requirements should be communicated to the manufacturer upon order so the instrument can be adjusted to meet these special requirements.

(9) To avoid stress on the springs in the control valve, particularly in medium and high flow MFCs, the user should install the instrument in the process line with the axis of the flow body oriented horizontally as required in item (8) above and, additionally, with the control valve located on top of the flow body as shown in Fig. 2, not on the bottom or the side. If system constraints require a different instrument orientation, the user should communicate this requirement to the manufacturer upon order so that adjustments can be made.

(10) After turning on the instrument, users should allow the instrument to warm up for the time period specified by the manufacturer. A warm-up time of about 10 to 30 minutes typically is required for the instrument to reach full accuracy.

(11) Users should zero their MFMs and MFCs prior to first use and periodically thereafter on a schedule based on the manufacturer's recommendations or their own experience. The zero flow output signal should be averaged over a sufficient time interval. Preferably, zeroing should be performed with the actual gas to be measured at the same pressure and temperature of the application, or close thereto. If there is a change of gas, the instrument should be flushed with the new gas before being zeroed.

Obviously, for proper zeroing, the flow rate must be zero. This is best accomplished, in the case of MFCs, by commanding the control valve to be shut, and, in the case of both MFMs and MFCs, by closing shut-off valves installed just upstream and downstream of the instrument. In the absence of these valves, the process line must have other means to ensure that the flow is zero.

9.3 Best Practices for Manufacturers

Best practices by manufacturers for the design, manufacture, and testing of their MFMs and MFCs are as follows:

(1) Manufacturers shall design and manufacture their instruments to have a burst pressure sufficiently above their specified pressure rating of the instrument. The instrument shall meet applicable pressure vessel codes, and these codes should be cited in the specifications of the instrument.

(2) Manufacturers shall pressure test every instrument at a pressure sufficiently above its pressure rating to ensure safety when in use. However, the test pressure should be sufficiently less than the yield pressure so that the integrity of the instrument is not compromised during the pressure test.

(3) Manufacturers' instruments shall comply with the hazardous-area and electrical-safety codes and other standards and codes cited in the specifications of the instruments.

(4) Manufacturers shall provide to users only those instruments that have a leak integrity specification that ensures safe use with the gas of the application. Manufactures shall leak test their instruments. Leak testing equipment should have sufficient sensitivity to insure compliance with the leak integrity specification of the instrument.

(5) Manufacturers should burn-in their instruments using a protocol that ensures compliance with their long term drift and accuracy specifications.

(6) Manufacturers shall flow calibrate every instrument. The flow calibration standard used should have an accuracy that is at least factor of 2, and preferably a factor of 4, better than the accuracy specification of the instrument under test.

9.4 Flow Recalibration

Users are responsible for flow recalibrating their instruments on a periodic basis. With use and the passage of time, MFMs and MFCs may drift beyond their accuracy specification if they are not periodically recalibrated. Some manufacturers recommend a scheduled flow recalibration on an annual basis. It is recommended that users return their instruments for recalibration to the manufacturer. Manufacturers are familiar with their products, and established manufacturers have laboratories with accurate flow calibration facilities and standards (see para. 8).

10 Conclusion

Capillary tube thermal mass flow meters and controllers directly measure the mass flow rate of gases. In their linear range, they depend only on the coefficient of specific heat c_p at constant pressure, and no other gas property. Because c_p must be known, the identity of the gas or gas mixture must be known. c_p is a fortuitous gas property because it has a weak dependence on gas temperature and pressure compared to other gas properties, and, in most applications, can be treated as a constant.

Capillary tube thermal MFMs and MFCs measure and control the mass flow rate of clean gases in lower flow ranges. The overall flow range for which they are best suited is about 0.1 sccm to 1500 slpm, typically accommodated with only three flow body sizes—low flow, medium flow, and high flow. MFMs and MFCs accommodate almost any gas, including those that are corrosive, toxic, and flammable. The measurement of mass flow rate is nonintrusive because the RTD sensor windings are on the outside of the sensor tube, and no delicate components are exposed to the flow. K-factors facilitate flow calibrating with a reference gas and enabling the instrument to measure and control the mass flow rate of another gas. Advanced instruments offer this multi-gas feature, as well as digital communications protocols common in the industries they serve. Capillary tube thermal instruments have high accuracy when operated in the upper two-thirds of their full scale flow range. They have fast time response and low leak rates. They operate at vacuums and at high process pressures. They are compact and are installed with one penetration of the process line. Face seal process connections facilitate easy installation and removal, and no straight lengths of upstream and downstream tubing are needed.

In applications requiring flow control, flow meters based on other technologies typically incorporate stand-alone control valves that are specified separately and located separately in the process line. Capillary tube thermal MFCs integrate mass flow rate measurement and control into one flow body. This provides a compact, cost-effective package with only one penetration of the process line and a built-in optimized control system. The electromagnetically actuated control valve is non-intrusive because the magnetic lines of force pass through the wall of the valve. This means it requires no seal for a valve stem or a diaphragm. Because it has no seals and is frictionless, it has a long life and low external leak rates.

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Nomenclature

A = cross-sectional area of inside of sensor tube (m^2)
bypass ratio = ratio of total mass flow rate in the process line to the mass flow rate measured by the sensor tube (--)
c_p = coefficient of specific heat of the gas at constant pressure [Joules/(kg·K)]
D = internal diameter of sensor tube (m)
h = convective heat transfer coefficient [watts/(m^2·K)]
$K_{i,j}$ = gas conversion factor (or K-factor) that converts the flow calibration of gas i to gas j (--)
k_g = thermal conductivity of the gas [watts/(m·K)]
L = overall length of sensor tube (m)
M = molecular weight (molar mass) of the gas [kg/(kg-mole)]
MFM = capillary tube thermal mass flow meter
MFC = capillary tube thermal mass flow controller
P = absolute static pressure of the gas (Pa, bar)
P_s = absolute static pressure of the gas at standard conditions (Pa, bar)
q_m = mass flow rate of the gas through the sensor tube (kg/s)
$q_{m,bypass}$ = mass flow rate of the gas through the bypass (kg/s)
$q_{m,tot}$ = mass flow rate of the gas through the process line (kg/s)
q_v = volumetric flow rate of the gas (m^3/s)
$q_{v,s}$ = standard volumetric flow rate of the gas (sccm, slpm)
R = universal gas constant [m^3·Pa/(kg·mole·K)]
R_{dn} = electrical resistance of the downstream winding of the sensor tube (ohms)
R_{up} = electrical resistance of the upstream winding of the sensor tube (ohms)
R_r = electrical resistance of a winding at the reference temperature T_r (ohms)
T_{dn} = average temperature of the downstream winding of the sensor tube (K, °C)
T_{up} = average temperature of the upstream winding of the sensor tube (K, °C)
T_g = absolute static temperature of the gas (K)
T_r = reference temperature for the temperature coefficient of resistivity of a winding, usually 0 °C (K, °C)
T_s = absolute static temperature of the gas at standard conditions (K)

$T(x)$ = axial temperature distribution of the sensor tube; a dependent variable (K, °C)
$T_g(x)$ = axial temperature distribution of the gas flowing in the sensor tube; a dependent variable (K, °C)
T_o = temperature at the inlet and exit of the sensor tube (K, °C)
x = axial dimension of the sensor tube and its internal gas flow; the independent \ variable (m)
Z = compressibility of the gas (--)

Greek Symbols

α = temperature coefficient of resistivity (K^{-1})
μ = dynamic viscosity of the gas [kg/(m·s)]
ρ = mass density of the gas (kg/m^3)
ρ_s = mass density of the gas referenced to standard conditions of T_s and P_s (kg/m^3)

Subscripts

g = gas
m = mass flow rate
s = a quantity referenced to standard conditions of T_s and P_s
v = volumetric flow rate

References

[1] ASME MFC-21.2-2010, "Measurement of Gas Flow by Means of Thermal Dispersion Mass Flowmeters," American Society of Mechanical Engineers, 3 Park Avenue, New York, NY 10016.

[2] J.G. Olin, "Thermal Anemometry," Chapter 29.2 in J.G. Webster (ed.), *The Measurement, Instrumentation, and Sensors Handbook*, CRC Press (1999).

[3] J.G. Olin, "Industrial Thermal Mass Flow Meters—Part 1: Principles of Operation," *Measurements and Control*, Issue 193, February 1999: 83-90.

[4] SEMI E12-0303, SEMI E29-93, SEMI E52, SEMI E56-1104, SEMI E69-0298, and SEMI E77-1104, Several standards related to capillary tube thermal mass flow meters and mass flow controllers, Semiconductor Equipment and Materials International, 3081 Zanker Road, San Jose, CA 95134.

[5] ASME MFC-1M-2003(R2008), "Glossary of Terms Used in The Measurement of Fluid Flow in Pipes," American Society of Mechanical Engineers, 3 Park Avenue, New York, NY 10016.

[6] T.L. Bergman, A.S. Lavine, F.P. Incropera, and D.P. DeWitt, *Fundamentals of Heat and Mass Transfer, 7th Edition*, John Wiley and Sons (2011): 518-530.

[7] P.M.S. Blackett, P.S.H. Henry, and E.K. Rideal, "A Flow Method for Comparing the Specific Heats of Gases," *Proc. Roy. Soc. London*, A 126 (1930): 319-354.

[8] D.R. Lide (ed.), *CRC Handbook of Chemistry and Physics, 90th Edition*, 2009-2010, CRC Press, Boca Raton, FL (2009): 6-15 to 6-37.

[9] SEMI E12-0303, "Standard for Standard Pressure, Pressure, Density, and Flow Units Used in Mass Flow Meters and Mass Flow Controllers," Semiconductor Equipment and Materials International, 3081 Zanker Road, San Jose, CA 95134.

[10] T.O. Maginnis, "Pressure Rate of Rise Measurement: When is the Fill Isothermal," Measurement Science Conference, Anaheim, CA, 2009.

[11] ASME/ANSI MFC-7M-1987, "Measurement of Gas Flow by Means of Critical Flow Venturi Nozzles," American Society of Mechanical Engineers, 3 Park Avenue, New York, NY 10016.

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