Process Gas Mass Flow Controllers An Overview

J.G. Olin
Sierra Instruments, Inc.
Carmel Valley, California

A mass flow controller (MFC) is used to control the flow of gases in a wide range of microelectronic processes. A well-designed MFC maintains a constant flow within 1 percent of the full-scale flow, has a repeatability of 0.2 percent of full scale, and has a response time of 1 second to reach within 2 percent of the desired (command) flow; all of this is in response to any changes in command flow, upstream pressure, downstream pressure, gas temperature, or any other variations imposed on the instrument. For enhanced accuracy, simplicity, and cost-effectiveness the MFC should *directly* monitor gas mass (molecular) flow without the separate measurement of temperature and pressure.

A mass flow controller consists of a mass flow monitor (MFM) and a servo-control valve. In operation, to be described in more detail later, an output signal from the MFM is compared to a previously established command signal to automatically open or close the servo-control valve.

Several methods are currently used to monitor gas flow [1–4]. Turbine meters, positive-displacement meters, vortex-shedding meters, ultrasonic meters, and magnetohydrodynamic meters all monitor volumetric flow. To obtain mass flow, the volumetric flow is multiplied by the gas density, requiring the separate measurement of gas temperature and pressure. For incompressible flows, orifices, and venturis measure the square of the flow and thus require not only measurement of temperature and pressure but also square-root extraction. Rotameters monitor volumetric flow and respond to temperature and pressure in a complex nonlinear fashion which is different for each flow tube. Flow meters based on the Coriolis force directly monitor mass flow but generally do not have sufficient sensitivity for gases.

Thermal techniques offer the best alternative for direct monitoring of gas mass flow rate. With these techniques, as the gas molecules carry heat away from a hot surface, the rate of heat loss is transduced with temperature sensitive elements in an electronic bridge circuit which directly monitors mass flow.

Mass Flow Monitors

Figure 1 describes two types of thermal MFMs, the immersible type and the capillary-tube type [5,6].

Immersible thermal MFMs have two sensors immersed in the flow: one which is self-heated and monitors mass flow and the other which monitors gas temperature and automatically corrects for temperature changes. Typically, each sensor is a resistance temperature detector (RTD) which is either a single wire, a wire wound on a ceramic mandrel, or a resistive film. The sensors are usually electrically driven as a constant-temperature or constant-current anemometer. For high flows, the dual sensor probe is inserted into a duct or pipe. The wetted surfaces of the sensors are either glass, alumina, or 316 stainless steel. For low flows, the MFM consists of one or more micromachined rectangular channels, each with a separate suspended resistive film mass flow sensor and temperature sensor. In this case, the sensors and flow channels are coated with a ceramic, such as silicon nitride.

Immersible thermal MFMs generally are flow calibrated with the actual gas for which they are deployed. Since many of the gases commonly used in the microelectronics industry are hazardous, the actual gas cannot be used for calibration purposes. Unfortunately, calibrating with non-hazardous reference gases is difficult because the heat-transfer correlations are complex, non-linear functions involving temperature-dependent transport parameters, such as gas viscosity and thermal conductivity.

Capillary-tube thermal MFMs, however, have a simple principle of operation facilitating straightforward calibration with reference gases. The capillary-tube thermal MFM is the one most commonly used in the microelectronics industry.

Capillary-Tube Thermal MFM

Figure 1 shows the flow paths in a typical capillary-tube thermal MFM. The total mass flow (m) enters the MFM and divides into two paths, one (m_1) through the sensor tube, the other (m_2) through the bypass. A pressure-drop ($\Delta P = P_1\text{-}P_2$) is created, forcing a small fraction of the mass flow through the sensor tube that is then monitored. An accurate MFM must have a constant ratio of bypass flow to sensed flow (m_2/m_1). Different flow ranges can be obtained by changing the bypass to effect a higher or lower ratio of bypass flow to sensed flow.

Figure 2 shows the principle of operation of capillary-tube thermal MFMs. The sensor tube has a relatively small diameter and large length-to-diameter ratio in the range of 50:1 to 100:1. Both features are characteristic of capillary tubes. In capillary-tube MFCs, the Reynolds number is sufficiently low (less than 2000) and the length-to-diameter ratio sufficiently high to create a pure laminar flow in the sensor tube. Pure laminar flow is described by the Hagen-Poiseuille equation in which the pressure drop ($P_1\text{-}P_2$) is linearly proportional to the sensor's mass flow rate (m_1), Fig. 2 shows two coils surrounding the sensor. The coils direct a constant amount of heat (H) through the thin walls of the sensor tube into the gas. Also, the RTD coils sense changes in temperature through changes in their resistance. In actual operation, the mass flow carries heat from the upstream coil to the downstream coil; therefore, the latter is hotter than the former. The long length-to-diameter ratio of the tube insures that the entire cross-section of the stream is heated by the coils. This means the first law of thermodynamics can be applied in its simplest form. Figure 2 describes the mass flow through the sensor tube as inversely proportional to the temperature difference ($\Delta T = T_2\text{-}T_1$) of the coils. A full theoretical analysis reveals a more complex relationship, but this simplified description is adequate for a general understanding of the

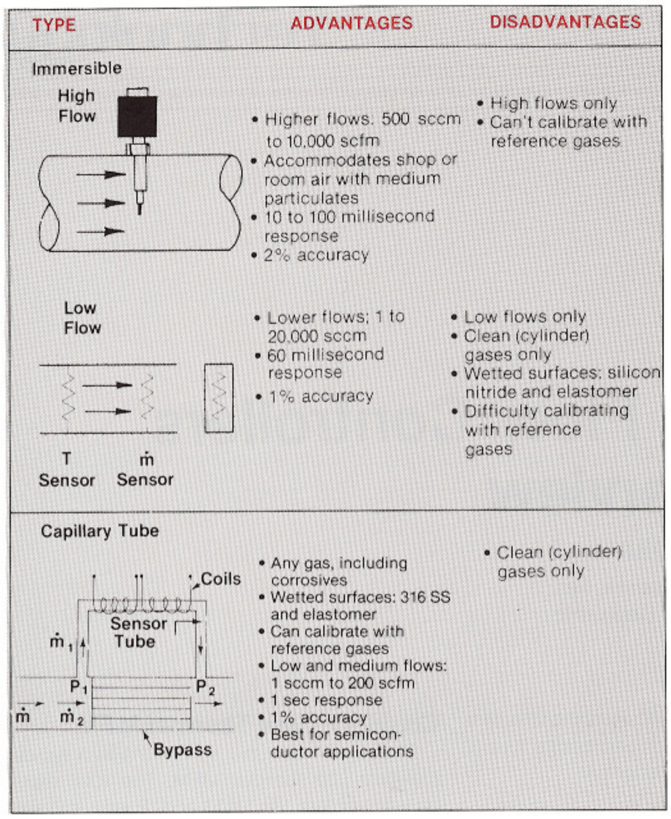


Fig. 1—Types of thermal MFMs. Capillary tube type MFM flow path is shown.

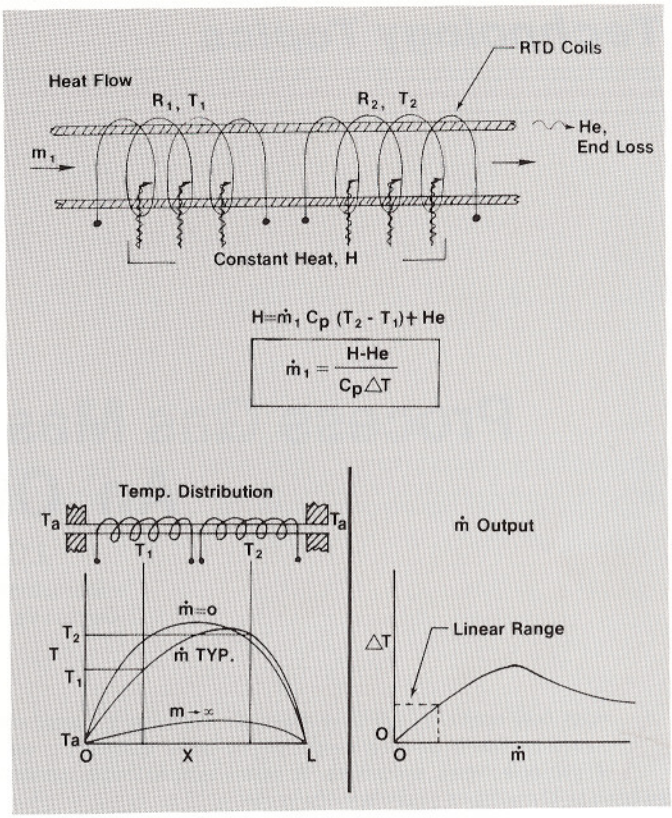


Fig. 2—Principle of operation of capillary tube type MFM.

principle of operation. The coils are legs of a bridge circuit with a constant current input. The output voltage is in direct proportion to the difference (R_2-R_1) in the coils' resistance; the result is the temperature difference (ΔT). The other two parameters, heat input (H) and specific heat (C_P) are both constant. C_P is a desirable transport parameter, unlike gas viscosity and heat conductivity, because it is essentially constant for a given gas over wide range of temperature and pressure. Although the output is not intrinsically linear with mass flow, it is nearly linear over the normal operating range. True linearity is achieved with multiple breakpoint linearization (e.g., 0, 25, 50, 75, and 100 percent of full scale).

Other capillary-tube thermal MFM designs use a single heater coil with separate upstream and downstream RTD coils to measure ΔT. Yet another methodology [7] employs multiple coils with attendant bridge circuitry to maintain a constant temperature distribution in the sensor tube. The principle of operation described in Fig. 2 does not apply to this methodology.

Two critical elements of an MFM are the sensor tube and bypass.

Sensor Tube Design

Probably the most common complaint about MFCs is that they clog with particulates or deposits from reactive gases, causing errors in the measurement of mass flow rate. The sensor tube, with internal diameters ranging from 0.008 to 0.031 inches, is the flow component most prone to becoming clogged. Clogging can be minimized by using the largest internal diameter possible.

There are two shapes of sensor tubes—"U"-shaped and straight. Almost all MFCs have "U"-shaped sensor tubes. This sensor geometry is difficult to clean or to rod-out. For this reason, contaminated "U"-shaped sensor tubes usually are not cleaned, but instead are replaced. Straight sensor tubes are easily cleaned by rodding and washing them out via cleaning access ports [8].

Bypass Design

The bypass is the second critical element in an MFC in terms of sensitivity to clogging or contamination. Figure 3 shows the types of bypasses currently offered by most MFC manufacturers. As shown previously, the ratio of the bypass flow to the sensed flow (m_2/m_1) must be constant. This is only the case if the flow in the bypass is laminar, matching that of the sensor tube. In pure laminar flow, the pressure drop across the bypass is *linearly* proportional to the bypass flow. The single machined element has pure laminar flow and is easily removed and cleaned. Multiple disks and sintered filter elements also have laminar flow but are more difficult to clean. An orifice bypass has nonlaminar flow so that the ratio of total flow to sensed flow is nonlinear and temperature-dependent—two factors that can degrade accuracy. If the bypass is a combination of orifice and screens, then the pressure drop across the bypass is the sum of the orifice and screen pressure drops, the relative weighting of each depending on the Reynolds numbers of each flow. In this case, the total flow is again a nonlinear, temperature-dependent function of the sensed flow.

Valve Design

Figure 4 shows typical MFC servo-control valves. For most microelectronics applications, the electromagnetic valve is the best choice and the one most commonly used. This normally closed valve is similar to an on-off solenoid valve, except that the current to the coil, and hence the magnetic field, is modulated so that the ferromagnetic valve armature assumes the exact height above the valve's orifice necessary to maintain the valve's command flow. The time response of alternative valve designs is discussed in the next section.

Additional Factors in Choosing MFCs

Seven other points should be addressed by the user in selecting the MFC which best satisfies his requirements: (1) maintenance, (2) accuracy, (3) repeatability, (4) time response, (5) anticontamination, (6) safety, and (7) quality assurance.

The ease of disassembling and cleaning an MFC is critical to *maintenance* reduction. The three clog-prone components are the sensor tube, bypass, and orifice. Each should have a maximum flow cross-sectional area to reduce clogging and each should be removable for cleaning either by the user or the manufacturer. Periodic MFC calibration is also an important consideration. It can be performed by the manufacturer or by the user with an available flow calibration system. When the user performs his own maintenance the MFC does not have to be returned to the manufacturer. This puts the user in control of his downtime and avoids stocking spare MFCs.

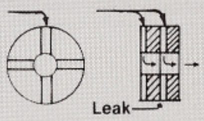
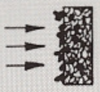
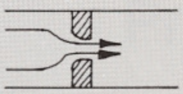
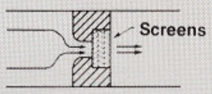
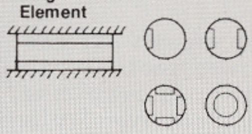
TYPE	ADVANTAGES	DISADVANTAGES
Multiple Discs 	• Laminar flow	• Difficult to clean and install • Leak rate depends on clamping force
Sintered Filter Element 	• Laminar flow	• Collects particulates • Difficult to clean
Orifice 	• Easy to clean	• Not laminar flow
Combination Orifice and Screens 	• Simple construction	• Difficult to clean
Single Machined Element 	• Laminar flow • Single-piece, easily removed and cleaned • Removes with inlet fitting	

Fig. 3—Types of bypasses.

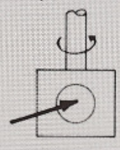
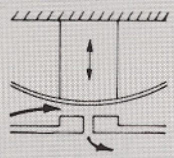
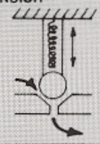
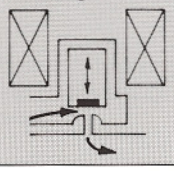
TYPE	ADVANTAGES	DISADVANTAGES
Motor-Operated 	• Large flows (> 10 slm)	• Has "deadband" • Slower response (3 to 30 sec)
Piezo-Electric 	• Fast response (2 sec) • "Infinite" resolution • Packless	• Smaller flows (< 20 slm) • Diaphragm valve—lower pressures (150 psig max.)
Thermal Expansion 	• Low and medium flows (1 sccm to 200 slm) • "Infinite" resolution • Packless	• Slow response (10 sec) • Normally open • Intrinsic overshoot • No shut-off
Electromagnetic 	• Low and medium flows (1 sccm to 500 slm) • Fast response (1 to 3 sec) • "Infinite" resolution • Packless • Normally closed	• Not for higher flows (>500 slm)

Fig. 4—Typical servo-control valves.

Accuracy and *repeatability* are major considerations. Accuracy depends on two factors: flow calibration and repeatability. Accurate factory-performed flow calibration, which is discussed later, assures delivery of an MFC with the correct starting point accuracy. Repeatability guarantees its continuing performance to specification. High repeatability is attained by employing low-drift, highly-stable electronics components and precise internal voltage and current regulation. Furthermore, the sensor tube and bypass must not clog with time, and the resistance of the sensor coils must be stable. Resistance stability requires a highly stable RTD material and stable coil geometry. "U"-shaped sensor tubes can have residual stresses from bending which can cause long-term strains and unraveling of the sensor coils. Both phenomena can contribute to long-term drift in the coils. Straight sensor tubes avoid this problem.

The true way to test the *time response* of MFCs is to use an independent, fast response mass flow meter in series with the MFC test specimen. Two examples are a laminar flow element with a fast response differential pressure transducer and a fast response immersible thermal mass flow sensor. The independent MFM must have a time response which is at least 5 times faster than the MFC test specimen. A desirable electromagnetic time response can be attained by using thin-wall sensor tubes and optimized proportional-integral-differential (PID) control loop design.

Major reductions in particulate *contamination*, a goal so important in the production of VLSI microelectronics, are achieved by assembling MFCs in a cleanroom environment, electropolishing all wetted surfaces, and eliminating most welds such as the spot welds in the inlet screen.

MFC *safety* and *quality assurance* are enhanced by subjecting every MFC to rigorous test procedures such as vacuum leak-checks with a mass spectrometer to better than 1×10^{-9} sccs of helium; pressure leak checks; valve leak checks; time response tests; long-term static burn-in of sensor tubes and fully assembled MFCs; and long-term dynamic cycled valve burn-in.

Flow Calibration

Production MFCs are flow calibrated using either primary standards or transfer standards. Primary standards employ the U.S. National Bureau of Standards (NBS) primary measurements of time and distance and can be used for non-hazardous gases. Most MFCs are calibrated with transfer standards using a production MFM, which has been accurately calibrated with a primary standard. Unfortunately, this method can magnify inaccuracies because a 1 percent transfer standard calibrating a 1 percent production MFC yields a 2 percent production instrument, instead of the 1 percent accuracy required by industry standards.

Conclusion

A process gas mass flow controller satisfying the demanding requirements for many applications in the microelectronics industry should have the following design and performance features: its flow monitor is a capillary-tube thermal mass flow monitor with stable sensor coils; its sensor tube, bypass, and valve orifice have maximum cross-sectional areas and are easy to remove and clean or replace; its valve is electromagnetic and has PID control; its accuracy is 1 percent of full scale; its repeatability is 0.2 percent of full scale; and its time response is 1 second to within 2 percent of set point; it is assembled in a cleanroom environment; it is subjected to vacuum and pressure leak checks and to long-term static and dynamic burn-in; and it is calibrated using primary flow calibration standards.

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