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Fundamentals of Mass Flow Control

Critical Terminology and Operation Principles for Gas and Liquid MFCs

A mass flow controller (MFC) is a closed-loop device that sets, measures, and controls the flow of a particular gas or liquid. These devices are essential to most thermal and dry etching processes. Advanced Energy®'s Aera® MFCs provide the most precise flow control at the most cost-effective price.

This paper defines critical flow control terminology, describes basic MFC operation, and illustrates Aera MFC design solutions to common mass flow control challenges. The last section introduces the liquid mass flow controller (LMFC) and describes design solutions specific to flow control of liquids.

Elements of an MFC

Base

The base provides the platform on which all other components of the MFC are mounted and contains the channels that form the main flow path of the gas. The base of an Aera MFC is constructed of type 316L stainless steel and is precision finished. Metal or elastomer seals, depending on the application, are provided between the base and other components.

Sensor

The thermal sensor is designed for quick response, long-term stability, and high reliability. The sensor tube in an Aera mass flow product has a very small diameter and mass to ensure the fastest response to any change in gas flow conditions.

Bypass

Also known as the *flow splitter*, the bypass maintains a constant ratio of gas flow through the sensor and main flow path, dividing the gas stream precisely over the entire calibrated flow range. As a result, the total flow can be determined by measuring just the portion of gas that passes through the sensor.

Figure 1. Inside an Aera® MFC

Control Valve

The control valve establishes the flow of gas by responding to a signal that compares the actual flow to the set point. Actuators driving the control valve in Aera MFCs are either piezoelectric, solenoid, or thermal actuators, depending on the model.

Printed Circuit Board

The printed circuit board is designed for optimum stability. Aera MFCs use the minimum number of electronic components and only the highest-reliability components available.
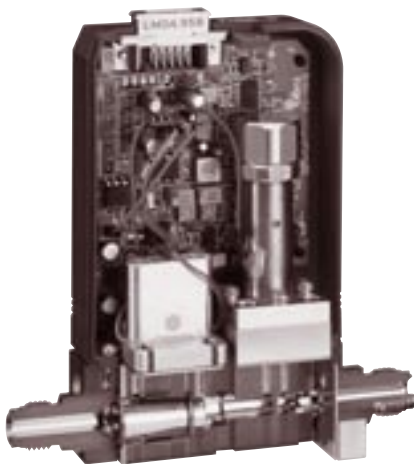
Operating Principle

The heart of a mass flow controller is a thermal sensor. It consists of a small bore tube with two resistance-thermometer elements wound around the outside of the tube. The sensor tube is heated by applying an electric current to the elements. A constant proportion of gas flows through the sensor tube, and the cooling effect creates a temperature differential between the two elements. The change in the resistance due to the temperature differential is measured as an electrical signal.

The temperature differential created between the elements is dependent on the mass flow of the gas and is a function of its density, specific heat, and flow rate. Mass flow is normally displayed in terms of volume of the gas either in standard cubic centimeters per minute (sccm) or in standard liters per minute (slm). The electronics of a mass flow controller convert mass flow into volume flow at standard conditions of 0°C (32°F) and 1 atmosphere. Because the volume of 1 mole of an ideal gas at 0° C (32°F) and 1 atmosphere occupies 22.4 liters, a set point of 22.4 slm will cause 1 mole of gas to flow during 1 minute.

The bypass forces a constant proportion of the incoming gas to be fed into the sensor. The gas flow through the sensor tube causes heat to be transferred from the upstream resistance-thermometer element to the downstream resistance-thermometer element. This temperature differential is linearized and amplified into a 0 to 5 V flow output signal by means of a bridge circuit. The output signal is compared with the external set point signal to the mass flow controller. The error signal that results from comparing the output signal with the set point signal directs the control valve to open or close to maintain a constant flow at the set point level.
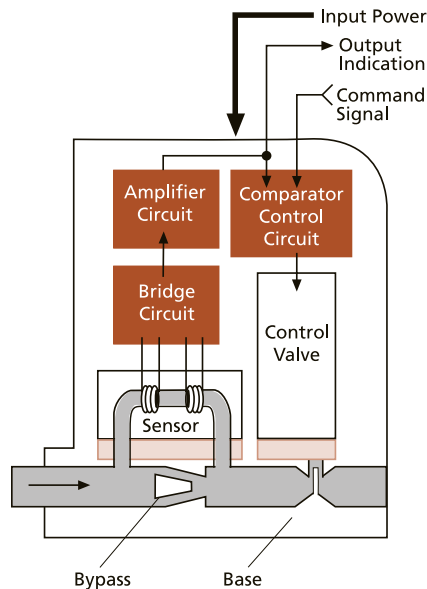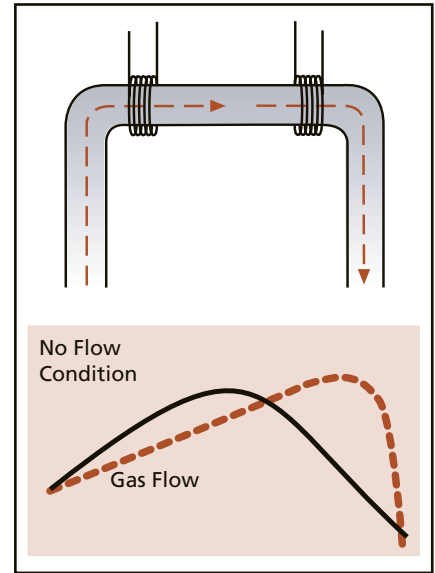

Figure 2. Operational diagram

Figure 3. Sensor temperature profile

Performance and Reliability

MFC manufacturers go to great lengths to explain why their products should outperform others, often focusing on a few design features. But it is not enough to define MFC performance on the basis of a few parameters— today's critical processes demand MFCs that deliver outstanding performance and reliability. The primary factors include:

Accuracy

Accuracy refers to the difference between the actual flow of an MFC and that of a primary standard at any set point.

Repeatability

Another primary factor is the repeatability of actual flow for an MFC or from one MFC to another at any set point.

Linearity

Linearity is the straightness of the curve of actual flow vs. set point, in other words, accuracy over the entire flow range.

Calibration Drift

Calibration drift is the change in the curve of actual flow vs. set point due to aging effects of some of the component parts that make up an MFC.

Stability

Stability refers to the ability of an MFC to maintain stable flow levels through short-term effects such as pressure and temperature changes, and through long-term effects such as aging of the component parts.

Response or Settling Time

The time that it takes for actual flow to stabilize after a set point change is another critical parameter.

Over-shoot and Under-shoot

Over-shoot and under-shoot refer to any spike or dip, respectively, in the response curve of actual flow vs. time.

Pressure Change Response

Pressure change response is the time that it takes for actual flow to stabilize after a sudden change in gas input pressure.

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Temperature Change Effects

This parameter concerns the stability of flow during ambient temperature variations.

Zero Drift

Zero drift is the most common complaint of MFC users. It is a time-dependent shifting of the zero calibration point from its original zero value to an offset value, and is generally caused by aging effects of various electrical components on the PC board as well as by aging of the sensor windings. The aging phenomenon that results in zero drift not only causes a shift in the zero calibration point but also causes a shift of the entire curve of control voltage vs. flow.

Some MFC manufacturers, particularly those with zero drift problems, offer an option of automatic zeroing. Auto zero does indeed correct the shift in the zero calibration point, but it does not correct the shift of the entire calibration curve. Admittedly, the shift in the remainder of the calibration curve is less severe than that for the zero point, but it still represents a degradation of accuracy and linearity.

On the other hand, zero drift has been essentially eliminated in Aera flow products. The typical zero drift of our MFCs is less than 0.5% of full-scale flow over a period of one year. This is the result of using the highest-quality sensor wire and electrical components on the PC board. Perhaps more importantly, the sensors and the assembled MFCs are subjected to extensive burn-in procedures and stringent, multiple QC inspections to screen out all marginal components and assembled MFCs.

In this manner, we do not hide the zero drift problem; we prevent it.

Liquid Mass Flow Controllers

Liquid sources have been used in semiconductor processing for as long as the industry has existed. In the industry's early days, liquids were often chosen as source materials because the proper techniques for handling toxic and corrosive gases were unfamiliar to many development engineers. Gas leaks were the norm, with frequent harm to workers and equipment. Today, handling procedures are well understood, and leaks are generally not a major problem. Nevertheless, liquid sources are now preferred over some gaseous sources because of the appropriateness of liquid reaction characteristics for particular applications.

The most common method for introducing liquid source materials into reactors and furnace tubes is to first vaporize the liquid and then pass the vapors through mass flow instruments that have been developed specifically for controlling vapor flow. Liquid sources can be vaporized either by bubbling a carrier gas through the liquid or by heating the liquid to generate an adequate vapor pressure. One major constraint that is common to all vaporization methods is that some liquid sources have too low a vapor pressure to generate adequate vapor pressure at room temperature or moderately elevated temperatures.

Instruments known as *vaporizer controllers* are typically used to control vapor flow generated using the carrier gas technique. One type of vaporizer controller combines an MFC with a ratio detector consisting of thermal conductivity cells that measure the ratio of vapor to carrier gas. The ratio detector provides a signal to the MFC to adjust the carrier gas flow to deliver a constant amount of source vapor per unit time, independent of all variables.

Another type of vaporizer controller is a complex system that consists of an MFC, a minicomputer, and devices for measuring the major variables: bubbler temperature and pressure. All other variables are assumed to be of minor importance. The minicomputer calculates the vapor pressure of the liquid source based on the temperature and pressure measurements and provides a signal to the MFC to adjust the carrier flow to deliver a constant amount of source vapor per unit time. The degree of saturation of the carrier gas may vary depending on bubbler design, liquid level, and bubble size.

Calibration drift is common in vaporizer controllers that use a ratio detector, caused by cumulative contamination of one of the thermal conductivity cells as a result of reaction between the source material and finite concentrations of oxygen or moisture in the carrier gas. There are also accuracy and repeatability limitations. For example, the variable carrier gas flow rate will at least slightly affect the reproducibility of the mainstream flow within a process chamber.

When vapor is generated by heating a liquid source, MFCs are used to control the flow of heated vapor. Re-condensation is prevented by heating the MFC and the lines leading to and from it. For TEOS, a widely used liquid source for medium-temperature oxide deposition, re-condensation is prevented by confining a "high-temperature" MFC and associated plumbing within an isothermal enclosure heated to near 80°C (176°F). This configuration is sometimes known as a *thermal vaporizer system*. To withstand the elevated temperature, the flow components and PC board of the MFC are designed as separate modules, with the flow component module located in the enclosure and the PC board module mounted external to the enclosure.

A thermal vaporizer system is more accurate and repeatable than the carrier gas/bubbler technique, but it requires a very large, expensive system to enclose all of the requisite hardware and maintain an isothermal environment. Re-condensation of the vapor can be a chronic problem with this technique unless stringent precautions are taken to heat all lines leading from the thermal vaporizer system to the reactor or furnace tube.

A New Method for Flow Control

A mass flow control instrument for metering very low flows of liquid source materials into process chambers is now available, offering considerable advantages over vaporizer techniques. This instrument is a liquid mass flow controller (LMFC) and is an adaptation of basic mass flow control technology. The LMFC provides accuracy and repeatability, as well as size and cost advantages.

An LMFC consists of the same flow components found in traditional MFCs. The major difference is that each component must be designed to prevent the most prevalent problem with LMFCs—bubble formation and retention. In an LMFC, a liquid source can gain heat from the sensor tube, which operates at an elevated temperature, and from contact with the internal parts of a control valve if it is of a type that generates heat. If bubbles were consequently generated and retained, their presence would adversely affect accuracy and repeatability and could cause malfunction of the LMFC. The present design uses a vertically configured flow path that prevents retention of bubbles. The inlet fitting is at a lower level than the outlet fitting, and the sensor is S-shaped rather than U-shaped as in conventional MFCs. Additionally, the control valve is of a piezoelectric/ diaphragm type, which has a much cooler operating temperature than other types of control valves and permits no liquid to enter the internal region of the valve. To prevent bubble formation in the heated sensor tube, the LMFC is limited to liquids that have a boiling point of at least 65°C (149°F).

Figure 4. Aera® LX-1200/1200C series LMFC

United Kingdom	Germany	Korea	Japan	Taiwan	China
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F: 44.1869.325004	F: 49.711.7778700	F: 82.31.777.9195	F: 81.3.32353580	F: 886.2.82215050	F: 86.21.58579003