

Digital Mass Flow Controllers

History, Advantages, and Multi-Gas Selection Capabilities

For the past quarter of a century, analog mass flow controllers have served as the most effective means of precisely controlling gas flow in semiconductor processes. MFCs are an essential component of many process tools, but users have generally felt that analog MFCs have limited flexibility and require an excessively large spares inventory to cover the various needs of a wafer fab. The development of digital mass flow controllers (DMFCs), with circuitry that contains a microprocessor chip to provide memory and other digital functions, has overcome many of the limitations of analog MFCs. One of the most important advantages is that the user can program the MFC to run various gases without recalibration. This capability significantly reduces spare MFC inventory because it eliminates the need to stock MFCs dedicated to specific gases. This article discusses DMFC history and development, as well as the advantages and limitations of DMFCs. It also describes a digital MFC that allows an unlimited number of gases to be programmed on site by the user.

Twenty five years ago, most process engineers relied on flow meter tubes and needle valves to control gas flow into reactors and furnaces. It took a lot of persuasion to convince the industry that an MFC was more accurate and repeatable than a ball bouncing in a tube and that the electronic display of flow rate was indeed representative of the actual flow. In fact, the early versions of MFCs were notorious for a variety of problems, creating an enduring love-hate relationship between the customer and the instrument. The increasing demand for MFCs with improved performance and reliability and with new capabilities, combined with increasingly stringent process requirements, has been an unrelenting stimulus for suppliers. Our response has been the development of the digital MFC.

Driving Forces for Digital Control

Conventional MFCs receive an analog input signal and provide an analog or contact closure output signal. Digital MFCs contain a microprocessor—allowing them to receive an analog or digital input and provide an analog, digital, or contact closure output—and memory capability. The flow components, such as the sensor, base, flow bypass, and control valve component structure, have remained stable.

Digital mass flow controllers were developed as a significant evolution in mass flow technology (Figure 1). The inclusion of an internal CPU and digital electronics provides a number of process control advantages over analog MFCs, including data acquisition and diagnostic functions. Additionally, digital MFCs have memory capability

to store multiple gas calibration curves with numerous calibration points that transform accuracy and linearity into a single parameter. An immediate benefit to the user is that the accuracy specification of $\pm 1\%$ for digital MFCs is a function of set point for most of the operating range in contrast to being a function of full scale as in the case of analog MFCs. A digital MFC can typically be operated from full scale down to 25% of full scale without degradation of accuracy. The accuracy specification below 25% of full scale reverts back to a function of full scale, but at $\pm 0.25\%$ of full scale is still a factor of four better than that of an analog MFC (Figure 2). The ability to maintain tight accuracy and linearity throughout the flow range is an obvious benefit for applications that require a high and low set point for a specific gas.

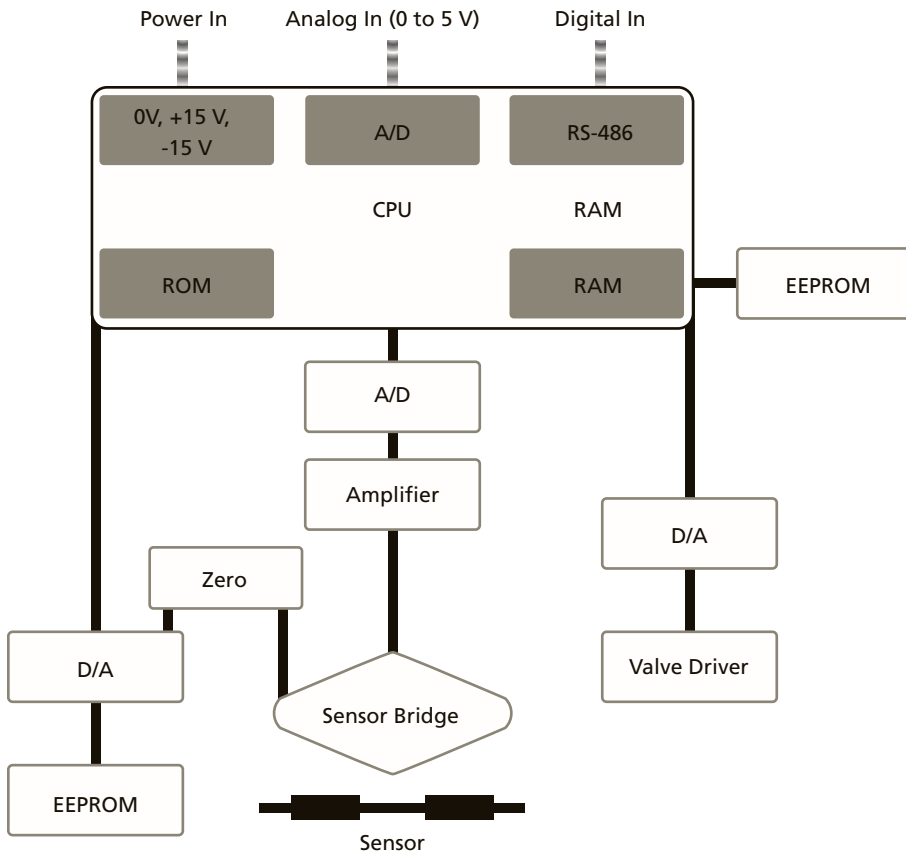


Figure 1. Electrical schematic of a digital MFC

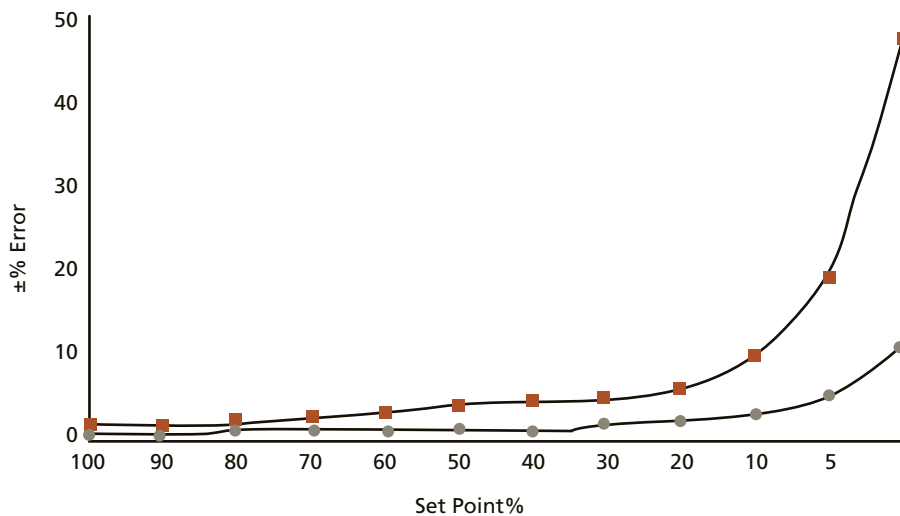


Figure 2. Accuracy: digital vs. analog MFCs

Perhaps the most significant advantage of digital MFCs to an original equipment manufacturer or end user is the potential for lowering the costs of maintaining an inventory of spare MFCs. Spares are necessary for replacement of malfunctioning MFCs or, with analog controllers, to change the gas or flow calibration. Using a digital MFC can substantially reduce the number of spare MFCs kept in inventory.

The useful operating range of an analog MFC is limited because, due to the fixed errors inherent in analog operation, the accuracy and linearity specifications are a function of full-scale flow. The greater the difference between the set point and full-scale values, the wider the possible spread in actual flow. For example, an analog MFC typically has an accuracy specification of $\pm 1\%$ of full scale. The actual flow of an analog MFC with a full-scale flow of 100 sccm could vary by as much as ± 1 sccm in this case. At a set point of 25 sccm, the ± 1 sccm becomes $\pm 4\%$ of the flow. At a set point of 5 sccm, the ± 1 sccm becomes $\pm 20\%$. The same type of relationship between fixed errors and low-end flows exists for linearity, as well. The example illustrates why analog MFCs should be operated as closely as possible to the full-scale flow for optimal accuracy and linearity results.

However, some end users wish to run MFCs at widely varying flow rates to accommodate a process while keeping the number of MFCs in a gas panel to a minimum. A digital

MFC can be calibrated at many points throughout its operating range, resulting in accuracy and linearity specifications that are a function of set point rather than of full scale for most of the operating range. Any set point can be used without the accuracy and linearity specification becoming a large percentage of the flow rate.

Process optimization for most semiconductor applications that involve the use of gases is heavily dependent on the accuracy and repeatability of gas flow. Therefore, another major driving force for digital processing is the desire to avoid the accuracy and linearity problems that result from the use of various innocuous surrogate gases instead of a customer-specified toxic or corrosive gas when calibrating an analog MFC. Almost every process in the semiconductor industry uses at least one gas that is highly reactive. MFC manufacturers prefer not to handle these highly reactive gases, and each manufacturer has a list of acceptable surrogate gases with conversion factors. However, accuracy and linearity may be lowered by the use of surrogate gases because the curves of set point voltage vs. actual flow differ between the surrogate gas and customer-specified gas, depending on the specific heat, density, and other gas characteristics for each case.

The problem of calibrating with a surrogate gas essentially disappears, however, if the deviation between the flow curves of surrogate and customer-specified gases is determined at multiple points and the offsets are programmed into the memory of a digital MFC. Alternatively, if the flow curves of customer-specified gases have been determined by live gas testing, these calibration points can be directly programmed into memory instead of the calibration points for surrogate gases.

Digital MFCs enable other advanced capabilities, such as alarm functions for flow and valve position; ramped flows; totalized gas flows; storage of and access to MFC operating data; automatic zeroing; self-calibration; and diagnostic functions.

Aera® DMFC Capabilities

A digital version of an Aera® MFC has the following capabilities:

- *Accuracy within $\pm 1\%$ of set point from 25% to 100% of full-scale flow*
- *Accuracy within $\pm 0.25\%$ of full-scale flow below 25% of full-scale flow*
- *Wide dynamic control range from 2 to 100% of full-scale flow*
- *Memory programmable with calibration curves for up to eight different gases*
- *Calibration of up to 11 points for each curve (thereby combining accuracy and linearity into a single parameter)*
- *Unlimited gas selection capability*

Additionally, the calibration points for the curve of sensor output vs. flow for any process gas can be programmed into memory if the offsets between the points for the process and surrogate gases have been determined.

With these capabilities, a single MFC can be used for a multitude of gases and a wide variety of full-scale ranges. It can be used effectively for the entire calibrated flow range, allowing the users to maintain a greatly reduced inventory of spares because of the variety of possible gas and flow calibrations as well as for the wide effective range of set point flows. Many process control enhancements can also be provided.

These include:

- *Automatic zeroing*
- *Operation in the analog or digital mode*
- *Flow ramping capability*
- *Gas flow totalizing*
- *Alarm functions for flow and valve voltage*
- *Flow data acquisition diagnostics capability*

For digital operation, there is no need to modify the flow components of an MFC. In fact, any analog MFC can be converted into a digital version by substituting digital circuitry for analog circuitry on the PC board and implementing an appropriate software protocol.

Multi-Gas Selection Capability

Analog MFCs are calibrated to a dedicated gas and full-scale flow by the manufacturer. If the user wishes to select a different gas or full-scale flow, it is necessary to remove the MFC from the system in which it is installed and do a bench recalibration using a primary or secondary standard. This procedure entails considerable downtime, particularly if the MFC had been used with a reactive gas, because extensive purging would be required before removal and after reinstallation of the MFC.

An analog MFC should be operated close to full scale for optimal accuracy and linearity because fixed errors in an analog MFC cause these parameters to be a function of full-scale flow. This is a limitation when a user wishes to use an MFC at a high- and low-flow set point, because the possible error at the low set point would then be a larger percentage of the set point flow. As an example, an analog MFC calibrated for a full scale of 100 sccm with the typical accuracy specification of $\pm 1\%$ of full scale will have a possible error of ± 1 sccm. The possible error is ± 1 sccm at a set point of 100 sccm, or $\pm 1\%$ of flow, and is also ± 1 sccm at a set point of 10 sccm, but is now $\pm 10\%$ of flow. In applications where this tolerance in accuracy and linearity is not acceptable, a user would need to install two analog MFCs with different full-scale flows, one for the higher flow and another for the lower flow.

Any MFC will malfunction if various parts in its flow path become contaminated as a result of problems in the gas line. A user will normally have a number of spare MFCs in inventory for immediate replacement of any that are malfunctioning, primarily for MFCs that handle reactive gases and present the greatest risk of becoming contaminated. The number of MFCs held as spares by a user is a function of how many different gas and flow combinations are necessary to minimize the risk of downtime.

Major Advantages of Multi-Gas DMFCs

Because a digital MFC can be reprogrammed for use with multiple gases, the user can select the gas and full-scale flow or change to another gas and full-scale flow without recalibration. This represents a major step in reducing cost of ownership because a user does not need to inventory as many spare MFCs to accommodate the array of various gases and flows of installed MFCs or pay the charges for recalibration of MFCs if a process requires a change of gas or full-scale flow. To select or change the gas or full-scale flow of a multi-gas calibrated digital MFC, the user can select the desired gas and full-scale flow using a personal computer with appropriate software and a communication link to the digital MFC. If the digital MFC is installed in a system that provides an analog control signal, the digital communication link can be served by a parallel line connected to an RJ-11 connector on the MFC.

Cost of Ownership Savings with Digital MFCs

To illustrate the impact of digital MFCs in reducing cost of ownership, the following example is presented. A wafer fab in the U.S. decided to retrofit all of their installed equipment with digital MFCs to replace analog MFCs. They had previously spent approximately \$750,000 for the installed analog MFCs and \$370,000 for spares, a total of \$1.12 million dollars. For the retrofitting of digital MFCs, they spent approximately \$900,000 for those to be installed and \$42,000 for spares, a total of \$942,000. The savings were \$178,000, or 16% (Figure 3). These savings are in addition to cost reductions from increased device yields that result from the process enhancements and diagnostic capabilities provided by digital MFCs.

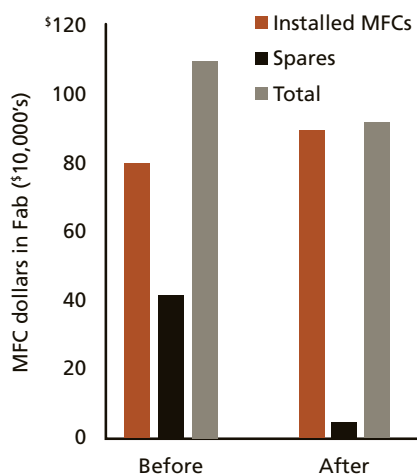


Figure 3. Cost comparison between analog and digital MFCs

When a digital MFC is reprogrammed for a different gas, the full-scale flow range selected is one that can control the gas with the highest nitrogen flow equivalency required by the application or fab group. This will ensure that the selected model is sized to accommodate the set point flows of user-specified gases with various densities. Although accuracy is a function of set point in a digital MFC, for a multi-gas calibrated digital MFC the point at which accuracy becomes a function of full scale will not be as low as 25% of full scale for gases that have a lower nitrogen flow equivalency than the gas with the highest nitrogen flow equivalency. The reason for this is that the gas that has the highest nitrogen flow equivalency determines the accuracy range limits of the particular model (Figure 4).

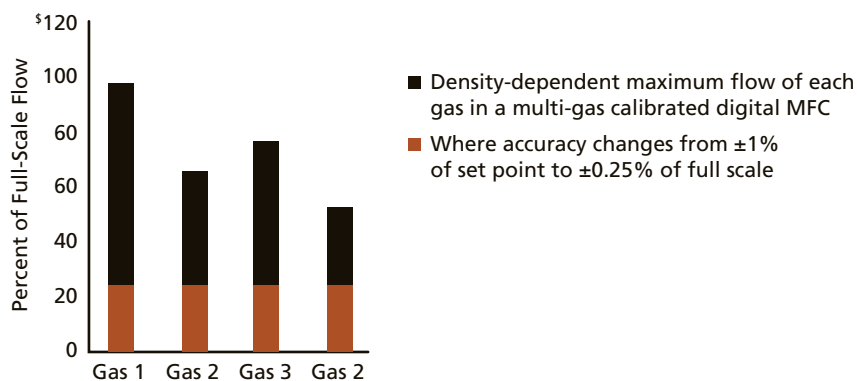


Figure 4. Accuracy range of multi-gas calibrated digital MFCs

Although digital MFCs can be calibrated for a number of different gases, it is not always an advantage to do so. If there is no intention of changing the gas or full-scale flow range of a digital MFC that is to be installed in a system, it may be more appropriate to calibrate the digital MFC for a specific gas and full-scale flow. A digital MFC dedicated to a single gas can be calibrated to any full-scale flow without concern for its own nitrogen flow equivalency or that of other gases. Therefore, the accuracy of a digital MFC calibrated for any single gas will always be a function of set point from full-scale flow down to 25% of full scale. It is typical for users to specify single-gas calibrations for digital MFCs that are to be installed in a system and multi-gas calibrations for digital MFCs that are designated to be spares.

Gas Selection Limitations of a Multi-Gas Calibrated Digital MFC

The internal CPU in a digital MFC allows multiple gas calibration curves to be programmed into memory. The maximum number of gas calibration curves that can be programmed is typically in the range of eight to 15, depending on the brand of digital MFC. If a user wishes to minimize the MFC spares inventory by stocking the smallest number of digital MFCs that can replace any installed MFC, the maximum possible number of calibration curves could still be a limitation considering the large variety of gases that are used in a wafer fab. Ideally, a user would want the capability to change the gas calibration of a spare digital MFC to any other gas, at the user's option, on site, and without recalibration.

Aera developed a digital MFC that has the capability to store up to eight gas calibration curves. Early in the development, it was found that achieving excellent repeatability of flow with gases that had quite different nitrogen flow equivalencies was not a simple matter. Commonly used proportional gain algorithms based on third-order polynomials could not provide satisfactory levels of flow accuracy, repeatability, and stability. It was necessary to generate very sophisticated PID (proportional band, integral, and derivative functions) algorithms in order to instantaneously achieve the desired proportional gain values without over-shoot or under-shoot, while at the same time creating a proportional gain bandwidth with extremely narrow limits.

Unlimited Gas Selection Using a Digital MFC

The development of unique PID algorithms led to a major product evolution. It became possible to use digital MFCs for on-site, unlimited gas selection. This was accomplished by generating surrogate gas calibration templates. The templates were created by calibrating the digital MFC for a limited number of surrogate gases and programming appropriate conversion factors into the setup software for essentially every gas used in the semiconductor industry. The result is that a user can program a multi-gas calibrated digital MFC for any gas, without recalibration, and precisely control that gas over a sufficiently wide flow range.

Limitations of Digital MFCs

The marriage of digital control to mass flow technology certainly provides greater flexibility and optimization of performance. It offers impressive calibration flexibility and validity not attainable with analog MFCs, as well as operational enhancement features that improve the two-way communication capability between the MFC and a control system.

However, users should understand that digital processing cannot solve everything. Digital operation should not be considered a solution to all the problems associated with MFCs. It will not remove any limitations that are the result of poor design or poor quality control. The basic performance of an MFC, such as response time, particle-free operation, and long-term reliability, will still be a function of component design and the level of quality control in the manufacturing process. For example, although digital control may reduce over-shoot in the response curve of an MFC, it will not make the response time any faster in some cases. Nor will digital electronics control make an MFC any cleaner or more resistant to the effects of contamination or corrosion. Long-term reliability will still remain a major issue in comparing MFCs. Digital control should be regarded as an evolutionary step in making an MFC more process friendly rather than a panacea for poor quality. Prospective users of digital MFCs must consider these issues when selecting a supplier.

Summary

The development of digital MFCs has resulted in important process control advantages to the semiconductor industry. This article explained the driving forces behind digital MFC development, as well as the major capabilities of DMFCs. It also conveyed advantages of multi-gas control, including various ways that digital MFCs can substantially lower cost of ownership. Further, the article described a more recent development that allows a user of digital MFCs to change the gas calibration of a spare digital MFC to any other gas, at the user's option, on site, and without recalibration. This capability further reduces the required number of MFC spares and provides an even lower cost of ownership.



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