Hot controllers

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Tac Huynh of Qualiflow S.A. and Pierre Navratil of Xeis, discuss a compensation technique for in situ environmental temperature effects in thermal mass flow controllers

In the semiconductor industry, changes in the accuracy of a mass flow controller (MFC) can directly affect wafer manufacturing processes. For example, since MFCs control the amount of gas used in front-end process recipes, a poorly calibrated MFC can lead to variations in deposition layer thickness or diffusion layer thickness.
The operation of a thermal MFC (TMFC) is based on heat transfer through a temperature sensor. It consists of a sensor, a bypass (flow-splitter), a regulating valve, and a feedback circuit (Fig. 1). The sensor receives, heats, and measures a small proportional part of the laminar flow through the system. Its operation and the accuracy of its measurements are influenced by calibration, surrogate gas correction factors, orientation, and environmental variations. Since it is based on temperature sensing, temperature changes in both the process gas and the process environment have an enormous impact on its operation.

1 Thermal mass flow controller output & calibration

The response of the thermal sensor inside a TMFC can be divided into three ranges. At low flow (i.e., low pressure), the gas remains in a laminar state where the molecules' mean free path (l) is much larger than the characteristic dimension, such as the internal diameter (d), of the flow channel. The Knudsen number, Kn, is defined as

$Kn = l/d$ (1)

and $Kn > 1$ in this type of flow where intermolecular collisions are more or less absent and the gas flow is mostly limited by molecular collisions with the walls of the channel. The sensor response to a free molecular (or laminar) gas flow is approximately linear to the flow rate. At high flow rates (i.e., high pressure), molecule-molecule collisions dominate and the gas behaves as a viscous fluid. For this type of viscous (or turbulent) flow where $Kn < 0.01$, the sensor response is inversely proportional to the flow. In the transition region between molecular and viscous flow (also called Knudsen flow, where $0.01 < Kn < 1$), the sensor response becomes less linear and reaches a maximum before dropping off towards the viscous flow regime (Fig. 2).

The full scale (FS) of a TMFC corresponds to the flow range (low) that generates an approximately linear response and is defined as its effective operational span. The limits depend on the geometry of the sensor as well as the specific gas under study.

A TMFC's accuracy depends primarily on its calibration against specific reference standards and the gas used for the calibration itself. Since most process gases are corrosive and hazardous, a benign, surrogate gas (e.g., N2, H2, O2, SF6, Kr, C2H4, N2O to simulate a wide range of process gases) is usually used instead and correction factors are calculated to account for the difference.

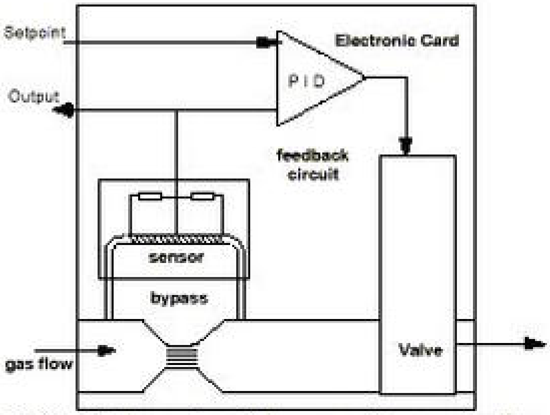

FIG. 1. Schematic of the mass flow controller.

Fig. 1 Schematic of a thermal mass flow controller

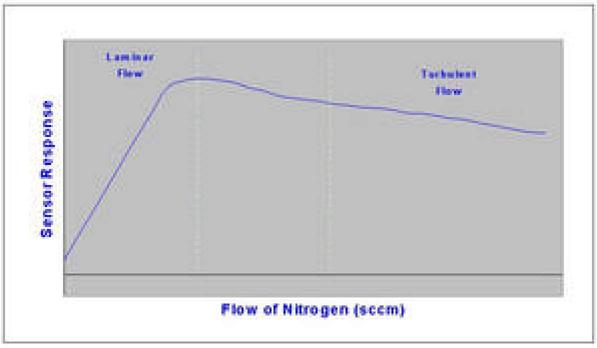

Fig. 2 Response curve of a TMFC sensor

Calibration corrections

2 Surrogate gas

The correction factor for the surrogate gas is defined as the equivalent calibration gas flow divided by the measured gas flow. Until recently, it was assumed to be a constant and simply calculated as the ratio between the heat capacities per unit volume (or molar specific heat) of the surrogate gas and the process gas. Since the linearity of the sensor response decreases with increasing flow rate, a constant factor does not offer the most accurate correction. Moreover, numerical simulations also showed that the correction factor is dependent on the flow rate for gases with a high thermal diffusivity à. Independent studies at the United States' National Institute of Standards and Technology (NIST) showed that as much as a 15% error can exist between the measured correction factor and the manufacturer's recommended values Æ.

For digital TMFCs, we obtained much more accurate calibration by using a number of points from the data curve and a numerical model of laminar flow in a finite volume â, and calculating a polynomial function for the best fit of the measured data ª. A digital TMFC can then be calibrated with different stored curves for different gas species.

These correction factors can also be adjusted using known physical properties, such as molar specific heat and thermal diffusivity, of the gas and vary from one gas species to another.

3 Environmental effects

A TMFC's accuracy is also affected by changes in environmental parameters during calibration and real process applications. Ideally, in situ calibration of a TMFC in an operating process chamber allows for the most accurate operations. Pressure and temperature of the gas flowing through the TMFC, ambient temperature, humidity, and mounting orientation of the device can significantly change during the time between calibration and actual system operation.

Unfortunately, not all environmental parameters are known when design of the controller system or gas handling system takes place. For example, if the gas panel exhaust system is changed, it is difficult to estimate the complex fluid dynamics inside the gas panel enclosure when the house scrubber is connected to the gas box. Most gas boxes are also generic in design, with a lot of empty space for optional features that will be added with time. Sometimes, the gas handling system remains half empty, with only a few options. The volume occupied by these components affect the environmental temperature.

Many studies have focused on ways to improve TMFC accuracy by accounting for pressure transients that affect the sensitivity of the sensor. Also available are techniques to measure heat transfer in controller installation configurations that determine the reference reading at zero gas flow. Our studies show that corrections for the environmental temperature that can substantially enhance the meter performance are now possible.

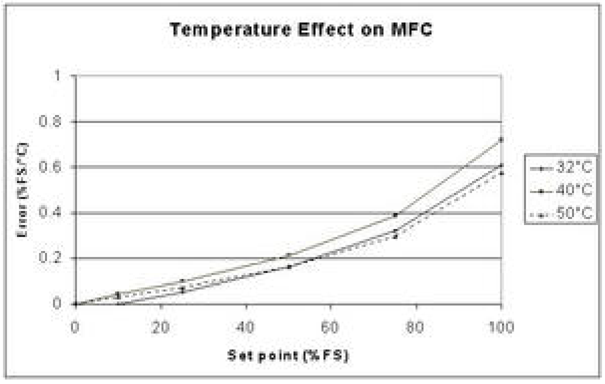

Fig. 3 Temperature effect on thermal mass flow controllers at 32°C, 40°C, and 50°C

4 Fluctuations in environmental temperature

Rising and falling ambient temperatures (in heating and cooling chambers, furnaces, etc.) affect the electronic zero and amplifier gain of the TMFC, the molar specific heat of the gas used, the TMFC sensitivity, and the TMFC span. Some of these temperature fluctuations can be attributed to the power supplied to electronics components and sensors as well as heat given off by the transistor for the control valve.

In processes such as TEOS LPCVD, silicon nitride LPCVD, and tungsten CVD, some of the effluents can condense along their path. Therefore, selected sections are heated to prevent buildup of condensates that can lead to clogged forelines, damaged pumps and valves, and corrupted transducers. As a result, heated gas lines and mass flow controllers may share the same environment with the unheated ones. Sometimes, additional insulation to gas lines at various locations and components can create a temperature effect to individual mass flow controllers.

To study the effect of environmental temperature on TMFCs, we set up a test using a reference flow standard called Molbloc/Molbox from DH Instruments. We used Compass, the Molbox software to capture the experimental data. After recording the flow setpoint, the program compared the value with the reference standard flow to yield the percentage full scale (%FS) error. The temperature of the chamber in which the TMFC was installed could be controlled to –1°C. Programmed by Compass, the flow through the controller stepped through setpoints between 0 and 100%FS, in increments of 5%FS. The program also recorded the dynamic temperature within the chamber at each mass flow set point.

Our data shows that a TMFC calibrated at ambient temperature would have reduced accuracy in measured flow rates when subjected to a change in environment. Fig. 3 is a plot of different accuracy profiles at different temperatures. For a TMFC calibrated at 25°C but used in an operating environment at 50°C, we observed errors above 10%FS.

5 Compensation for temperature effects on the thermal sensor

In general, the thermal sensor is well insulated from dynamic changes of temperature in the environment. The static condition at equilibrium is, however, still affected by the overall heating and cooling within the mass flow controller. Our earlier studies â showed that location and length of the temperature sensor is critical to its sensitivity. Table 1 shows the effect of sensor value change at zero gas flow with respect to environmental change within the oven.

In our MFC printed circuit board assembly, we incorporated a solid state temperature sensor close to the thermal sensor to measure the dynamic variations in temperature inside the TMFC. At any given moment, we monitored the environmental temperature and fitted the data into a polynomial equation to describe the flow.

We developed two sets of in situ temperature compensation equations: one for the simple case of a regular thermal sensor, and one for a more precise, fast, thin film sensor â. In both cases, a program running on a computer connected to the calibrated TMFC collected the temperature reading inside the covered TMFC and the gas flow rate recorded by the controller, at ambient and elevated temperatures.

We first set the TMFC at no flow at an ambient temperature of 25°C. This data was then coupled with the flow sensor reading at 25°C. Next, we raised the environmental temperature to 50°C, for example. After the system reached equilibrium, the program recorded a second data point consisting of the temperature sensor and flow sensor readings.

We repeated the measurements for a range of ambient temperatures and used a polynomial equation to fit the data for gas flow at various temperatures within the full range of the TMFC. The polynomial coefficients from the best fit equation was then stored in the non-volatile memory of the computer for a dynamic calculation of gas flow, based on the temperature sensor and flow sensor readings. We can predict the gas flow with an in situ environmental temperature compensation factor as follows:

Flowwith temperature effect = Flowfrom sensor + Kdynamic calculation based on calibration coefficient (2)

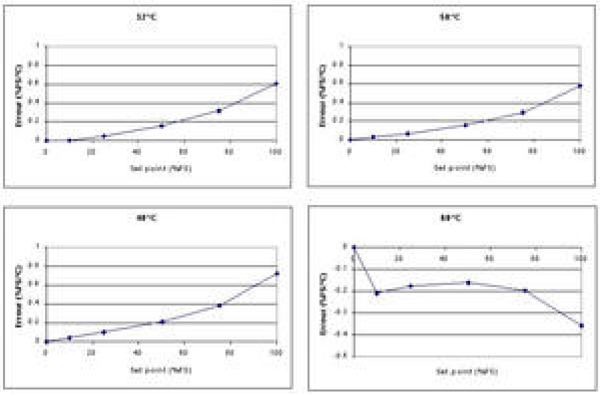

Fig. 4 Sensor response as a function of temperature

6 Precise environmental temperature compensation

Another similar, but more precise, compensation technique calibrated the gas flow as a function of temperature through a range of set points: 0%, 25%, 50%, 75%, and 100% of full scale of the TMFC at temperatures ranging from 25°C to 65°C. Our results (Fig. 4) showed that this technique improved the accuracy of the TMFC significantly.

In addition, the temperature of the TMFC was monitored continuously to provide feedback to the host computer through digital communication such as RS232, RS485, or DeviceNet. The host system could then gather data for different operating conditions in the gas panel down to the component (e.g., TMFC) level.

7 Conclusions

Over the last few years, the semiconductor industry has put much emphasis on ways to improve the accuracy of MFCs. Although issues involving MFC mounting orientation and pressure effects have received much attention, little has been done to address the effect of changes in ambient temperature or process gas temperature. Scientists and engineers at Qualiflow have succeeded to solve the problem using a temperature correction algorithm for digital TMFCs. Using an in situ environmental temperature compensation technique, we calculated correction factors for the temperature effect and obtained satisfactory results with both the traditional sensor and the new, improved thin-film sensors.

We have shown that the compensation technique for in situ environmental temperature effects in TMFCs improves their accuracy by adapting the mass flow controller to the working environment. Incorporating a temperature sensor within the TMFC will set a new standard for the control and monitoring of gas flow in the industry.

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