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Model-based solution for multigas mass flow control with pressure insensitivity

OVERVIEW Relentless advances in semiconductor manufacturing have placed extreme performance demands on gas delivery systems. Along with higher levels of accuracy and reliability, material delivery solutions are growing more complex while low cost remains a challenge. A model-based solution for multigas mass flow control promises to address these requirements with pressure-transient insensitivity and greatly improved flow-error corrections for multiple gases.

Thermal sensor-based mass flow controllers (MFC) have been deployed extensively in gas delivery systems throughout wafer fabs, and yet traditional approaches to thermal mass flow-control systems suffer from drawbacks, including slow transient response times, outlet flow deviations in closed-loop configurations, and calibration limits for different gases. In fact, one of the main challenges facing any flow sensor in an MFC is so-called "multigas" capability. Using calibration data for only one gas (usually N_2), a technique is required to manipulate the calibration data to obtain accurate flow measurements for any other gas.

To address these issues, a model-based solution has been developed for highly accurate mass flow-control capability with pressure-transient insensitivity and multigas functionality. Tests have demonstrated improved performance for multigas mass flow-control applications based on the model-based solution.

An MFC is comprised of at least a flow sensor and a control valve. In thermal MFCs, thermal flow sensors are effectively temperature-to-voltage converters. These thermal sensors tend to exhibit low noise and high steady-state accuracy. But thermal MFCs also show the following disadvantages:

- **Slow transient response.** A step change in flow achieved by commanding the valve to a different position results in the flow sensor voltage converging to a steady-state value typically in 5–7 sec. As a result, a control solution that only uses this raw voltage signal will exhibit a slow transient response.
- **Transient pressure dependence.** Pressure transients at the inlet can result in severe flow transients across the thermal sensor placed upstream of the control valve. While a portion of the flow transients may be filtered out by the internal MFC volume, the closed-loop control system responding to the thermal sensor transients will produce unacceptable outlet flow deviations. It should be noted that the controlled process variable is the MFC outlet flow. Furthermore, mounting the thermal sensor downstream of the control valve is inadvisable because of limitations in range and accuracies for most practical applications.
- **Gas dependence.** In the absence of specific gas-calibration data, an MFC that has been calibrated for N_2 will not accurately report or control the flow of a lighter gas such as He or a heavier gas such as SF_6.

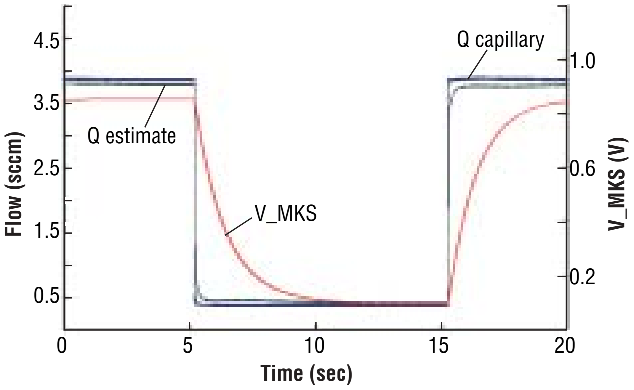

Figure 1. Step response with the inverse model with comparison to the anemometer data.

The model-based mass flow-control solution discussed comprises a thermal flow sensor, pressure transducer, and proportional control valve. Specifically, a physical model-based algorithm [1] executing in real time constitutes an integrated solution with a speed-up algorithm, pressure-transient dependencies, and multigas functionalities.

Some of the salient features of the model-based mass flow-control solution include high accuracy (better than ~1% reading, with 100-to-1 turn-down ratio) and insensitivity to inlet and outlet pressure perturbations to the MFC. Another key feature is a fast step response of ~1 sec for setpoint changes in all ranges and for all gases without any control parameter tuning. Full multigas capability is also achieved by using only N_2 calibration data for all gases.

Flow measurements

A typical thermal flow sensor consists of inlet and outlet coils with a high thermal coefficient of resistance wound around a capillary sensor tube. A change in the capillary flow Q_c causes the capillary wall temperatures to change. Due to the thermal contact with the capillary tube, the coil temperatures T_{ci} and T_{co} change, resulting

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in a change in coil resistances. The high thermal coefficient of resistance in the coil material increases the sensitivity of coil resistance to temperature changes. For example, with the application of a fixed current, the change in coil resistance results in the sensor voltage output varying with the flow.

It is also worth noting that Q_c is only a fraction of the total flow that is adjusted by incorporating a mechanical flow bypass.

The speed-up algorithm

The dynamic relationship between capillary flow Q_c and the coil temperatures T_{ci} and T_{co} referred to as the "forward model" can be defined in the following generalized form:

$$T_{ci} = F_i(Q_c) \text{ and } T_{co} = F_o(Q_c) \qquad (1)$$

The nonlinear dynamic functions F_i and F_o are associated with the inlet and outlet coils, respectively. The physical model under consideration constitutes the following:

- heat conduction equation along the tube in conjunction with the heating source due to the coils; and
- heat convection equation for the compressible gas flowing inside the tube.

The coil temperatures are related to the sensor voltage output as follows:

$$V_{\text{sense}} = F_b(T_{ci}, T_{co}) \qquad (2)$$

F_b is a linear function of the coil temperatures.

To determine the capillary flow Q_c for a given sensor voltage V_{sense}, we solve the inverse of the model given in Eqns. 1 and 2. The technical challenge lies in obtaining an accurate and fast estimation of the capillary flow. The results of the inverse model solution are shown in Fig. 1, where one can observe that while the voltage V_{sense} takes more than 5 sec to reach steady state, the estimated capillary flow Q_c converges on the order of milliseconds. For comparison, the actual flow measured by an anemometer that also converges in milliseconds is superimposed. Note that an artificial offset has been introduced to distinguish the actual data.

The need for a speed-up algorithm is driven by the fact that the thermal sensor voltage takes in excess of 5 sec to reach steady state. A simple approach widely employed in systems is to use an "inverse" first-order infinite impulse response filter that is not model-based. This filter-based technique is incompatible with the multigas technology, however, resulting in inaccurate measurements for large changes in flow. It also shows extremely high sensitivity to noise in the sensor voltage signal.

Multigas solutions

The problem of calibration for multigas capability has challenged the MFC industry for decades. One widely employed approach is the application of a constant thermal correction to N_2 calibration data.

Based on a 3D sensor model [2] and the flowing gas properties, we obtain gas corrections at every calibration entry point for N_2. Specifically, this model constitutes the following:

- energy balance in the form of heat conduction in all solid materials; and
- compressible Navier-Stokes equations [3] in conjunction with the energy balance equations for the flowing gas.

The accuracy of the model-based technique can be deduced from Fig. 2, where the error between the model-based flow estimate for the three gases — He, CF_4, and SF_6 — and the calibration data for the particular gas is plotted.

The model-based gas correction technique has proven far superior to the constant thermal correction technique. In the case of SF_6, whereas the constant thermal mass correction technique results in flow estimation error >8–10% of reading, the model-based gas correction technique results in a significantly smaller flow estimation error of ~1%.

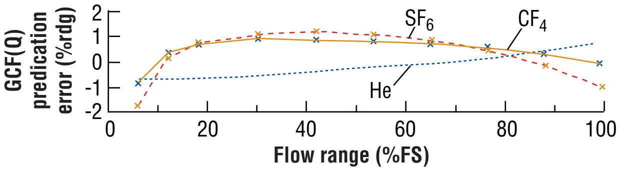

Figure 2. Flow error with model-based gas correction function for a 500sccm unit.

Model-based control

The proportional valve control also presents unique challenges. Specifically, the transfer function that relates the valve current to the flow through the valve is nonlinear and exhibits magnetic hysteresis. The transfer function also varies depending upon gas properties and operating pressure.

Typical industry-standard solutions assume a linear transfer function between the valve current and the flow. These solutions use proportional-integral-derivative (PID) control techniques. While PID control-algorithm parameters can be optimized for a specific gas within a small range of operating pressures, the performance suffers severe degradations as the gas and operating pressures are changed.

A physical model that captures the aforementioned depend-

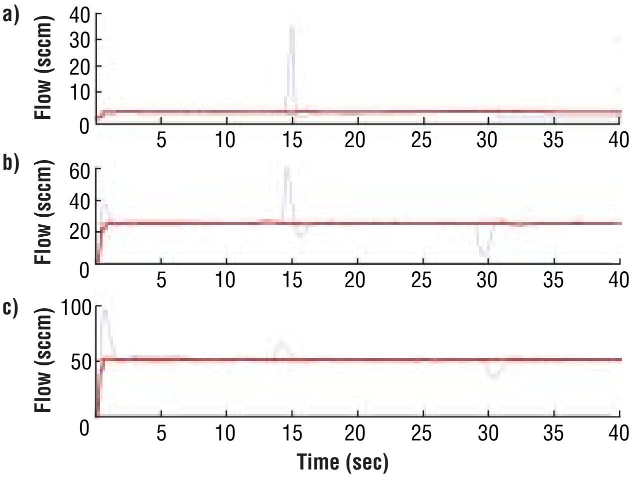

Figure 3. Pressure-transient insensitivity performance of a 50sccm unit flowing N_2 for setpoints of **a)** 2.5, **b)** 25, and **c)** 50sccm. Flow reported by MFC test-bed without (thinner line) and with (thicker line) pressure insensitivity compensation to pressure spikes of 2psia.

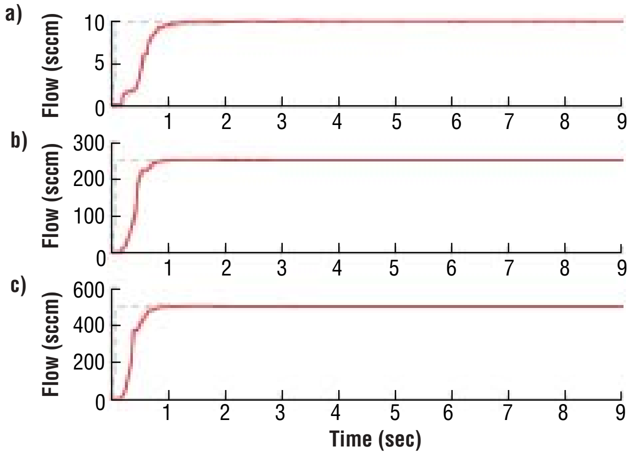

Figure 4. Setpoint regulation of a 500sccm unit flowing N_2 for setpoints of **a)** 10, **b)** 250, and **c)** 500sccm. Flow reported by the MFC (thicker line) and by the MFC test-bed (thinner line).

encies provides the foundation for the model-based control algorithm. The speed-up algorithm operates on the thermal flow sensor voltage to generate an estimated flow. The output flow is computed by compensating the estimated flow for dynamic pressure perturbations. While a trajectory generator ensures a smooth transition between setpoints, the model-based control algorithm uses the setpoint trajectory, pressure-compensated flow estimate, and the pressure within the model-based framework to command the valve so the actual flow tracks the flow trajectory.

Performance testing

Various tests were conducted to validate the performance of the model-based control solution. Setpoint regulation tests for multigas and pressure-transient insensitivity tests for N_2 gas were performed on a 50sccm unit (an MFC with a full-scale N_2 flow), whereas only the setpoint regulation tests for multigas were performed on a 500sccm unit.

All tests were conducted on an off-the-shelf, PC-based MFC test-bed. This test-bed uses a rate-of-rise technique to compute the flow within 1% accuracy of setpoint above setpoints of 15sccm (regardless of the gas). The MFC test-bed software issues a flow setpoint for a predetermined period (default value is 10 sec) followed by a 0sccm setpoint for a few seconds before the next setpoint is issued. Thus, all setpoint commands are preceded and succeeded by 0sccm setpoints for short intervals.

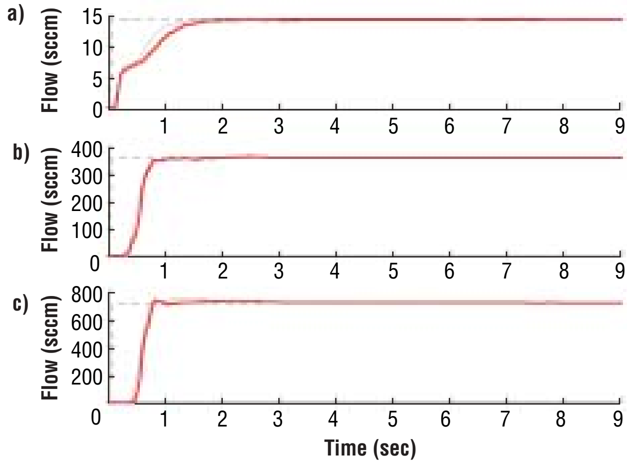

Figure 5. Setpoint regulation of a 500sccm unit flowing He for setpoints of **a)** 14.4, **b)** 360, and **c)** 720sccm. Flow reported by the MFC (thicker line) and by the MFC test-bed (thinner line).

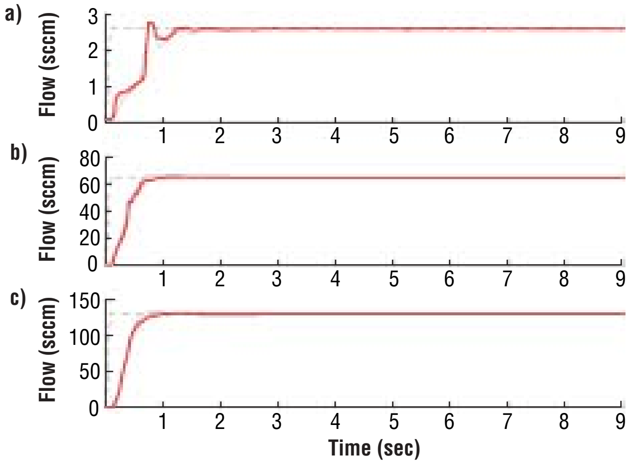

Figure 6. Setpoint regulation of 500sccm unit flowing SF_6 for setpoints of **a)** 2.6, **b)** 65, and **c)** 130sccm. Flow reported by the MFC (thicker line) and by the MFC test-bed (thinner line).

Pressure-transient insensitivity

A step-change in the inlet pressure can result in a spike of inlet flow to the MFC that can be an order-of-magnitude above or below the commanded flow setpoint. A pressure transient of this nature can occur when a high-flow MFC sharing a common inlet feed and located in a gas box is made to rapidly change its setpoint. This flow transient eventually dissipates as the pressure inside the MFC approaches that of the inlet, so long as the MFC is not subjected to any new pressure perturbations.

For low-flow MFC units (10–500sccm), this problem is more acute because the change of flow due to a pressure transient is a higher proportion of the setpoint than that of a high-flow unit. It should be noted that during a pressure transient if the valve is held in a fixed position, the outlet flow would remain approximately constant. In the era of closed-loop control based on inlet flow measurements, however, the feedback loop would respond to an inlet flow spike, causing the valve to change position very rapidly and generate a reverse spike in the actual outlet flow. Such a dramatic deviation of the outlet flow from the setpoint can cause substantial errors to the precise mass delivery requirements (especially critical for applications in the semiconductor industry).

To determine the pressure-transient insensitivity performance, pressure perturbations were introduced in the form of pressure step changes by instantaneously opening and closing a solenoid valve in a line tapped off the inlet to the MFC. With the solenoid valve open, this adjacent connected line registered 1000sccm of N_2 flow. Figure 3 presents the pressure-transient insensitivity results. A 2psia (pounds/sq. in. absolute) pressure perturbation was introduced by opening (referred to as “upward”) the solenoid valve approximately 15 sec after the new setpoint was issued. The closing of this valve (referred to as “downward”) introduced a reverse pressure spike of 2psia at approximately 30 sec. The 2psia pressure perturbations were applied to all setpoints.

Conclusion

Tests were conducted to establish the setpoint regulation performance for N_2, He, CF_4, and SF_6 at setpoints equal to 2%, 50%, and 100% of full scale. The 500sccm unit was tested for full-scale values 500sccm of N_2, 720sccm for He, 210sccm for CF_4, and 130sccm for SF_6. It is noteworthy that He is 36.5× less dense than SF_6 at STP (standard temperature at 0°C and pressure at 1atm, or standard atmosphere). Figures 4–6 present the setpoint regulation performance for gases N_2, He, and SF_6, respectively.

Extensive experimental data demonstrate the overall superior performance of the model-based multigas mass flow-control solution with pressure insensitivity capabilities. ■

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