Model-Based Multi-Gas/Multi-Range Mass Flow Controllers With Single Gas Calibration and Tuning

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A model has been developed that accurately predicts the behavior of the flow sensor combined with the laminar flow element whereby only a single reference gas is sufficient to characterize a multi-gas / multi-range mass flow meter.

Introduction

In semiconductor applications, the required mass flows are typically within a range of 10 ml_n/min up to 25 l_n/min, for all kinds of gases. Hundreds of different single gas mass flow controller (MFC) models may be necessary to cover this flow range, leading to an undesirable large stock for both production and service. Furthermore, most MFCs are calibrated and tuned using a reference gas instead of the actual gas, which may have a detrimental effect on both the accuracy and the dynamic behavior of the instruments.

A first order approximation of the actual gas flow through an instrument calibrated with a reference gas can be obtained by the ratio of specific heats (c_p) between the calibration gas and the actual gas. Many MFCs still use this simple scalar approach to calculate the conversion factor (CF). However, this method has been found to be an inadequate oversimplification, causing a dramatic decrease in the accuracy of the instruments.

Settling times are becoming increasingly important in mass flow controllers as new process technologies—such as atomic layer deposition (ALD) and deep reactive ion etching (DRIE)—are demanding both fast dosage rates as well as accurate and repeatable measurements. The controller (PID) settings of most MFCs are tuned with a reference gas; therefore, their speed of response is not optimized for a specific process gas and operation conditions.

In this article, a new generation of model-based multi-gas/multi-range instruments is presented that is able to cover the typical semiconductor flow range of 10 ml_n/min to 25 l_n/min with only 10 different MFC models. In addition, the flow range of 1 ml_n/min up to 1670 l_n/min can be covered with only 18 different MFC models. Such instruments can be accurately calibrated and tuned using only one reference gas.

> *It is possible to determine the boundary values in between which the actual full scale value of the instrument can be changed.*

First, a definition of multi-gas/multi-range is given, followed by a description of the flow sensor structure, its basic operating principle, and the sensor model. Then, the valve structure, its basic operating principle and the valve model are described. Some measurement results are presented and discussed, and finally, conclusions are drawn.

Multi-Gas/Multi Range: Conventional mass flow meters have a fixed full scale flow range, set according to the value as specified by the customer. However, multi-gas/multi-range (MGMR) mass flow meters have a nominal full scale value of 100%; the actual full scale value can be altered between certain boundaries.

For instruments of the Bronkhorst High-Tech Select series, these boundaries are based on air; note that the boundaries are dependent on the physical properties of the gas used.

Multi Range: The range of the full scale flow rate can be changed to anywhere between 40% and 150% of the nominal value (air). When the instruments are calibrated with

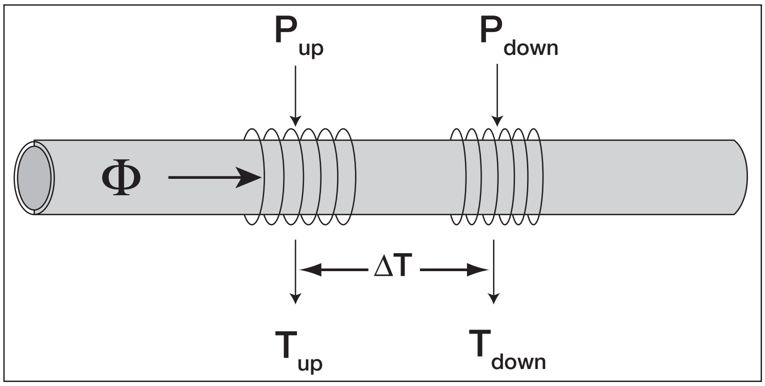

Figure 1. Flow sensor comprising a stainless steel flow tube with two active elements around it

air, the primary calibration curve is taken up to at least 150% of the nominal value of the instrument. From the primary calibration curve, curves for all different gases can be calculated and stored in the instrument.

Multi Gas: Up to 8 different gas calibration curves that have been calculated from the primary calibration curve (air), can be stored in and selected from the instrument.

Sensor Structure and Basic Operating Principle

The actual flow sensor consists of a stainless steel flow tube with two active elements around it, as shown in Figure 1. The measurement principle applied is the constant power (CP) method.

In this method, the two elements are used as both heater and temperature sensor, as shown in Figure 1. Both elements are provided with an equal amount of constant power; the temperature difference ΔT [°C] between them is a measure for the flow:

$$\textit{Sensor Signal} \propto \Delta T \qquad \textbf{Equation (1)}$$

Where:

Sensor Signal = output signal of the flow sensor [V]
ΔT = temperature difference [°C]

Sensor Model: Van der Graaf Curve

A sophisticated calculation model has been developed that accurately predicts the behavior of both the thermal and hydrodynamic flow characteristics of the flow sensor (bypass) combined with the flow restriction in the main channel; the laminar flow element (LFE)[1]. It incorporates the effects of the physical gas properties such as density, specific heat, viscosity and thermal conductivity. Thanks to this combination, calibration with only one single reference gas is sufficient to characterize a multi-gas/multi-range mass flow meter or controller for both its entire flow range (multi-range) and all other process gases to be used (multi-gas).

A simplified equation that expresses the relationship between the flow of a certain gas and the corresponding output signal of the flow sensor is:

Equation (2)

Where:

$$\textit{Sensor Signal} = k_1 \cdot \rho_n \cdot c_p \cdot \Phi_v \left[1 - \frac{k_2}{\lambda} \cdot \Phi_v - k_3 \cdot \Phi_v\right]$$

Sensor Signal = output signal of the flow sensor [V]
k_1 = sensor constant
ρ_n = mass density [kg/m³] at T = 0 °C and p = 1 atm.
c_p = specific heat capacity [J/ (kg·K)]
Φ_v = volume flow [m³/s]
k_2 = sensor constant, including physical properties of the applied gas
λ = heat conductivity [W / (m·K)]
k_3 = sensor constant, including physical properties of the applied gas

The first order approximation of Equation 2 is:

$$\textit{Sensor Signal} = k_1 \cdot \rho_n \cdot c_p \cdot \Phi_v \qquad \textbf{Equation (3)}$$

Which leads to the commonly used but inaccurate equation for the conversion factor (CF) between the reference gas (REF) en the actual gas (ACT) as applied by the customer:

$$CF = \frac{\rho_{n,REF} \cdot c_{p,REF}}{\rho_{n,ACT} \cdot c_{p,ACT}}$$

Equation (4)

With the sophisticated calculation model, the flow characteristics for all gases and flow ranges can be calculated and displayed in the Van der Graaf curve. An example of this curve for air and argon is shown in Figure 2.

In both the air and Ar curve, the (linear) tangent from zero flow is drawn. The nominal full scale flow range (100%) is defined as the flow where a nominal deviation, with value nom%, between the tangent and the flow curve exists. Analogously, the maximum full scale flow range is defined as the flow where a maximum deviation, with value max%, between the tangent and the flow curve exists. The minimum full scale flow rate is determined by the minimum required value minSig of the sensor signal.

Example: an instrument for nominally 1 l_n/min air can have its range changed between the following boundaries:

Full Scale:	Minimum	Nominal	Maximum
Air	40%	100%	150%
	0.40 l_n/min	1.00 l_n/min	1.50 l_n/min
Argon	(minSig at 45%)	100%	135%
	0.50 l_n/min	1.10 l_n/min	1.50 l_n/min

It is possible to determine from the Van der Graaf curve for each gas, the specific boundary values in between which the actual full scale value of the instrument can be changed. Please note that the boundaries are dependent of the physical properties of the gas used.

From only one reference curve, the flow characteristics for all other gases can be derived. This way, it is possible to cover the air flow range of 1 ml_n/

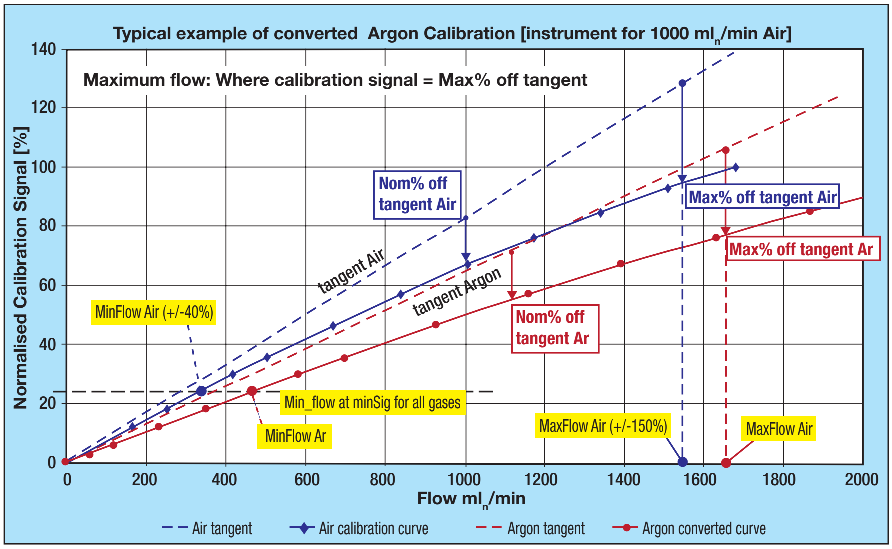

Figure 2. The Van der Graaf curve: flow sensor signal as a function of gas flow

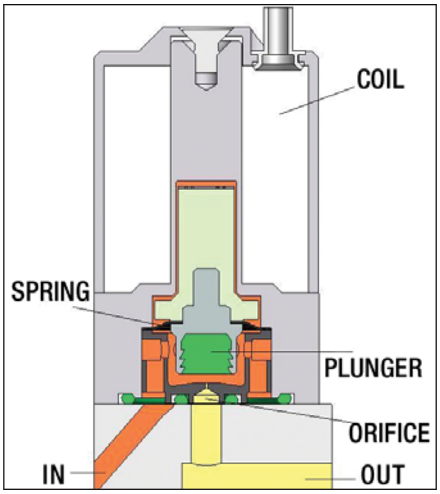

Figure 3. Cross-sectional view of an electromagnetically actuated proportional control valve

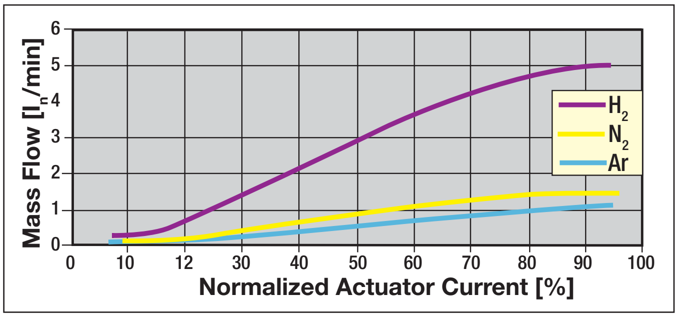

Figure 4. Typical transfer function of an electromagnetically actuated control valve

min up to 1670 l_n/min (100 m^3_n/h) full scale with only 18 MFC models.

Valve Structure and Basic Operating Principle

An example of an electromagnetically actuated proportional control valve is shown in figure 3.

The plunger on top of the orifice controls the flow. The plunger can be controlled at a certain distance above the orifice by applying a certain actuator current to the coil. A typical transfer function of an electromagnetically actuated control valve is shown in Figure 4.

As can be clearly seen from Figure 4, the resulting mass flow as a function of the actuator current is both non-linear and depends on the type of gas that is applied.

Valve Model: Relative Valve Flow

An elaborate tuning model has been developed that accurately predicts the behavior of the non-linear transfer function and flow characteristics of the control valve, in which the effects of the physical gas properties such as density and viscosity are incorporated.

The calculated transfer function and flow characteristics are used to adapt and optimize the PID controller settings (the proportional gain factor K_p) for the specific process gas and operating conditions, once again based upon tuning with only one single reference gas.

The nominal flow capacity of a valve is represented by the K_v value, which is the number that indicates how much gas flow Φ_v [m^3 per hour] flows through the valve at a pressure loss of 1 bar [3]:

$$K_v \propto \Phi_v \cdot \sqrt{\rho_n} \quad \textbf{Equation (5)}$$

where ρ_n [kg/m^3] the normal mass density of the gas (T = 0 °C; p = 1 atm). For nitrogen, hydrogen and argon, ρ_n equals respectively 1.250, 0.08991 and 1.784 kg/m^3 [4].

Assume K_v = 2.235E-03 for a given volume flow of nitrogen. Now, for the same volume flow, using the square root of the densities, the equivalent K_v values for H_2 and Ar are respectively 0.268 and 1.194. For example, when this valve is working at 100% of its transfer function for 1 l_n/min N_2, it will work at 26.8% of its transfer function for 1 l_n/min H_2 and at 119.4% of its transfer function for 1 l_n/min Ar. So, using the K_p value suited for 1 l_n/min nitrogen results in a non-optimum response (either overshoot or a very slow response) when applying 1 l_n/min hydrogen or argon.

Therefore, when changing from one gas to another, in order to guarantee good control performance, the *relative* valve flow should be used to determine the optimum K_p value, instead of the *absolute* valve flow. Moreover, even when the gas has not changed, the optimum K_p changes with the flow rate. An example of the optimum gain settings for the controller for both the absolute and relative valve flow of nitrogen, hydrogen and argon are shown in figure 5.

It is possible to determine from the relative valve flow curve for each gas the specific flow-dependent optimum controller gain settings. So, from only one reference curve, the flow characteristics for all other gases can be derived. This way, it is possible to always have optimum control performance of the multi-gas/multi-range instruments.

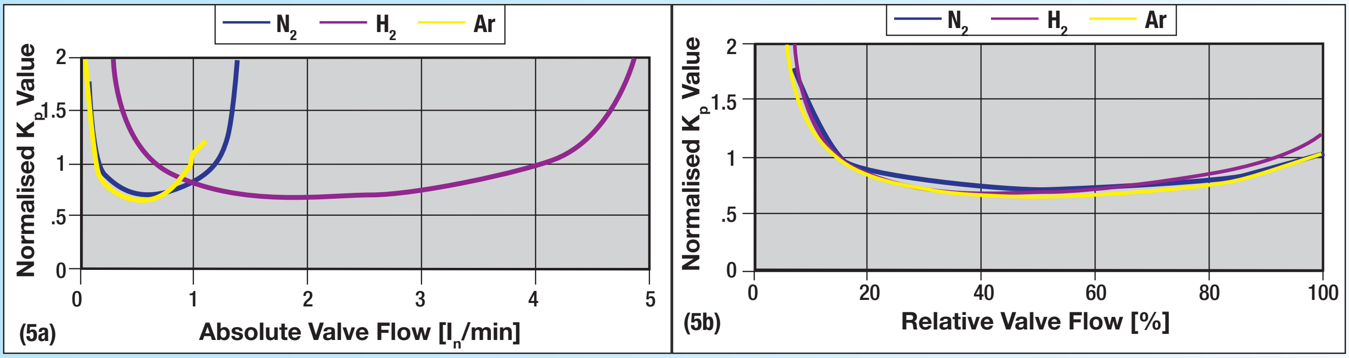

Figure 5. Optimum controller gain settings for nitrogen, hydrogen and argon as a function of (a) absolute and (b) relative valve flow

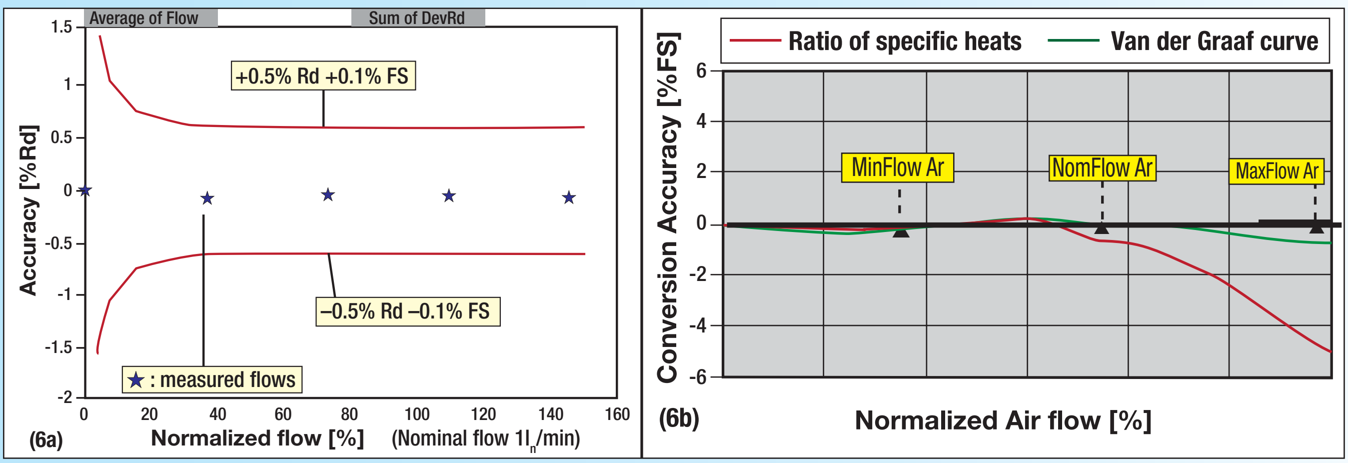

Figure 6. (a) Measured accuracy for the reference gas: air; (b) accuracy of the conversion factor between argon and air: comparison between the Van der Graaf curve and the ratio of specific heats

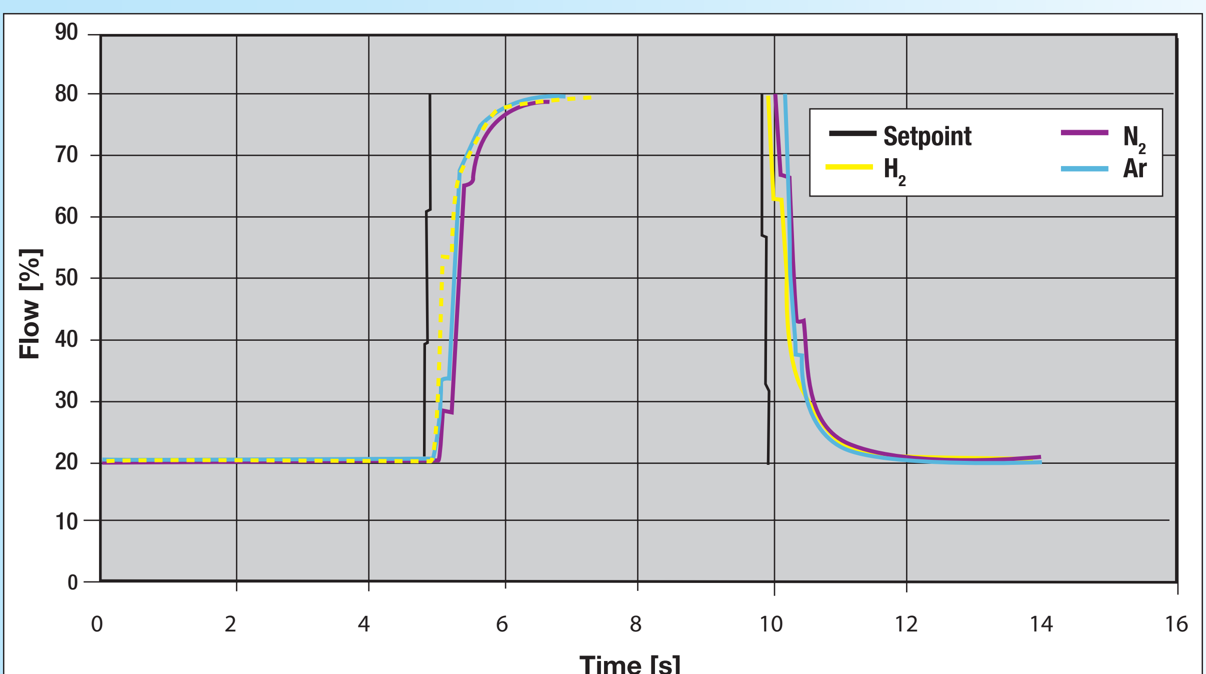

Figure 7. Measured settling times for 1 l_n/min N_2, H_2 and Ar, obtained with an instrument for 1l_n/min air, tuned with reference gas air, with model-based adapted PID controller settings for N_2, H_2 and Ar

Experimental

To demonstrate the principles discussed above, several mass flow meters and controllers were built and thoroughly tested. One of these instruments was an instrument for nominally 1 l_n/min air. The instrument was calibrated up to 1.5 l_n/min air (150% of the nominal value), and the instrument was tuned with air to have a settling time of $t_{98\%}$ of 2 s.

Using the Van der Graaf curve, the conversion was calculated from Air to other gases: argon, helium, nitrogen, carbon dioxide and hydrogen. Using the relative valve flow model, the optimum controller gain settings were calculated for the other gases as mentioned above.

The measurement program included the determination of the accuracy and the settling time of the instruments for both the reference gas (air) and the other gases.

Results

In figure 6a, the measured accuracy is shown under the reference calibration conditions. The calibration results are within the boundaries of ± 0.5% Reading (Rd) ± 0.1% full scale (FS). In figure 6b, the measured accuracy of the instrument, converted with the Van der Graaf method, is displayed when argon is applied. The measured accuracy is within the boundaries of 1% FS. Please note that the results when using the conventional conversion factor (Equation 4) are far worse; they can be up to 5% FS for argon, and far more for other gases.

In Figure 7, the measured settling times are shown of the instrument that was tuned with air to have a settling time of 2 s. The model-based adapted PID-controller settings for N_2, H_2 and Ar were stored in the instrument, and the measured settling time for these gases was 2 s as well.

CONCLUSIONS

- A sophisticated calculation model has been developed that predicts the behavior of the flow sensor combined with the laminar flow element (LFE). Due to this calculation model, calibration with only one single reference gas is sufficient to characterise a multi-gas/multi-range mass flow meter for both its entire flow range (multi-range) and all other process gases to be used (multi-gas).
- An elaborate tuning model has also been developed that accurately predicts the behavior of the non-linear transfer function and (dynamic) flow characteristics of the control valve. The model makes it possible that from only one reference curve, the (dynamic) flow characteristics for all other gases can be derived. This way, one is enabled to always have the optimum control performance of the multi-gas/multi-range instruments.
- The semiconductor flow range of 10 ml_n/min to 25 l_n/min can be covered with only 10 different MGMR MFC models, and the flow range of 1 ml_n/min up to 1670 l_n/min with only 18 different models.

> *An elaborate tuning model accurately predicts the behavior of the non-linear transfer function and flow characteristics of the control valve.*

- Multi-range: the full scale (FS) flow rate could be changed to anywhere between 40% and 150% of the nominal value (air); the minimum flow rate was 0.8% of the nominal value. Thus, for air, the minimum turn-down ratio is 1 : 50 (0.8%–40%) and the maximum turn-down ratio is 1 : 187.5 (0.8%–150%). But note: the boundaries are dependent on the physical properties of the gas used. This means that, for air, under optimum conditions, the flow range of 1 mln/min up to 25 l_n/min can be covered with only 2 instruments, namely one for nominally 200 ml_n/min (1.06–300 ml_n/min) and another for nominally 20 l_n/min (0.16 –25 l_n/min). The following conclusions are valid for an instrument of nominally 1 l_n/min air:
- For the reference gas calibration, the accuracy was within ± 0.5% Rd ± 0.1% FS.
- Multi-gas: flow characteristics from several gases (Ar, N_2, He, H_2) have been calculated and verified with actual calibration; for all of these gases, the accuracy was within 1% FS compared to e.g. up to 5% FS for Ar when using the ratio of the specific heats.
- Model-based adapted PID controller settings were calculated for several gases, in order to obtain a typical settling time of $t_{98\%}$ = 2 s. Tuned with the reference gas (air), the measured settling times were 2 s for nitrogen, hydrogen and argon. G&I

REFERENCES

[1] H.J. Boer. Precision mass flow metering for CVD applications, EuroCVD Symposium, (1999).

[2] W. Jouwsma. Marketing and design in flow sensing, Sensors and Actuators A, 37 – 38 (1993) pp. 274 – 279.

[3] L. Ebskamp, W. Jouwsma. Device for controlling the fluid flow rate through a pipe, EP0188024, (1984). (European patent)

[4] www.fluidat.com

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