

CALIBRATION OF GAS FLOW RANGING 1 TO 45 SLM AT THE STANDARDS AND CALIBRATION LABORATORY

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Abstract – This paper demonstrates different configurations of the SCL's reference flow standard used in calibrating a mass flow controller at various line pressures, and elaborates on methods to improve the calibration efficiency and accuracy by using a back pressure regulator. This paper also studies the sensitivity of the reference flow standard to various line pressures. It is revealed that the deviation of relative reading errors is less than the uncertainties of the reference flow standard.

Keywords: reference flow standard, back pressure regulator, flow measurements

1. INTRODUCTION

The flow calibration system which serves as the reference flow standard at the SCL comprises a flow terminal and various flow elements covering different flow range. The flow calibration system provides a user friendly, compact and precise tool for calibrating a wide variety of flow measuring devices including: mass flow controllers, mass flow meters, rotameters, turbine meters, bubble meters and others [1]. The flow terminal is a controller equipped with two pressure transducers and a temperature measurement system for pressure and temperature measurement of the flow elements. The flow terminal then calculates and displays the measured flowrate. The flow calibration system at the SCL can provide flow measurements from 1 to 45 slm (standard litres per minute). The measurement range can be flexibly extended with addition of appropriate flow elements and other supporting instruments.

Flow measuring devices are sensitive to the line pressure. Correction factors for change of line pressure are applied [2]. Error due to line pressure variation is intolerable for instruments such as mass flow controllers which play a major role in the success of the semiconductor manufacturing process. Customers who need lower calibration uncertainties may wish to have their flow measuring devices calibrated at their working line pressure.

This paper firstly demonstrates how a mass flow controller is effectively calibrated at various working line pressures with the aid of a back pressure regulator connected with the flow calibration system. Measurements of the accuracy of the mass flow controller at various working line pressures will be conducted. The measurement results show that the reading error of a flow meter is significant related to

working line pressure. That illustrates the need for a flow calibration system capable of calibrating a flow measuring devices at various working line pressures.

There are three different pressure dependent calibration types for the flow elements of the flow calibration system used in this paper, namely Low pressure, High pressure and Downstream. This paper demonstrates how a mass flow controller can be calibrated at different working line pressure while the flow element is calibrated with only one calibration type with the aid of the back pressure regulator. Last but not least the sensitivity of the reference flow standard to various line pressures deviated from the calibration verification pressure but within the valid indicated pressure ranging from 200 to 325 kPa for low pressure calibration type will also be studied.

2. CALIBRATION OF A MASS FLOW CONTROLLER AT VARIOUS LINE PRESSURES

A typical calibration setup for calibrating flow measuring devices such as a mass flow controller is shown in Fig. 1. It consists of the following components (from left to right): an air compressor for supplying dry filtered air as the flow medium, a pressure regulator for adjusting the operating pressure ranges, a bellows shut-off valve for allowing the gas supply to be shut off for configuration changes, a flow element of the reference flow standard, a metering valve for manually regulating the flow, a pressure gauge for monitoring the line pressure to a device under test (DUT) and the device under test, which is a mass flow controller.

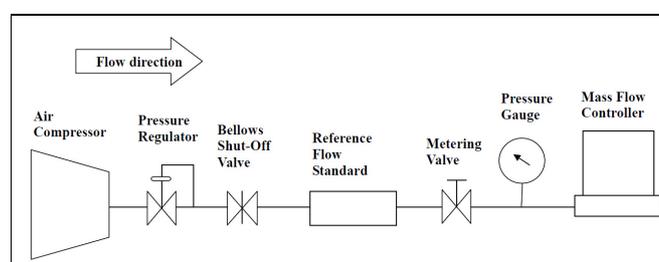


Fig. 1. The typical calibration setup for calibrating a mass flow controller.

The flow rate of the flow element is determined by measuring the differential pressure across it, as the mass flow rate is proportional to the differential pressure [3]. The flow

rate changes with the differential pressure. Hence, the flow calibration point can be easily set by adjusting the metering valve to vary the differential pressure across the flow element.

2.1. Calibration of a mass flow controller at various line pressures

A back pressure regulator is connected with the flow calibration system when a mass flow controller is required to be calibrated at a specific working line pressure. The calibration setup is shown in Fig. 2. The back pressure regulator connected at downstream of the mass flow controller controls the upstream pressure of the mass flow controller. The back pressure regulator functions like a relief valve i.e. it closes to increase the upstream pressure, and opens to reduce the upstream pressure. Once the upstream pressure of the mass flow controller is set at the desired pressure, a metering valve connected at the downstream of the flow element can adjust the flow rate to the desired calibration point easily. Although metering needle valve instead of the back pressure regulator could be used to maintain the working line pressure for the mass flow controller, the adjustment and tuning process is time consuming and requires a lot of effort because it involves numerous tuning steps to alternatively adjust two valves: one for maintaining the mass flow controller at the desired line pressure and another one for maintaining the desired flow rate.

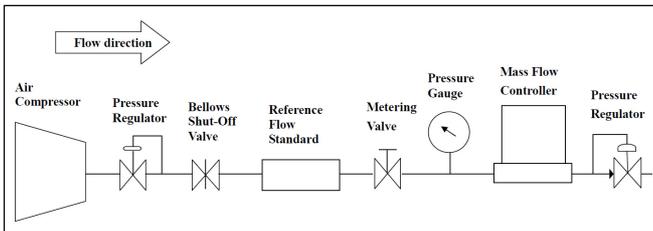


Fig. 2. The calibration setup for calibrating a mass flow controller at specified line pressure of 2 bars (gauge pressure).

To verify the sensitivity of a mass flow controller to line pressure, calibration setups as shown in Fig. 2 and Fig. 3 are set up for measuring the flow rate from 5 LPM (litres per minute) to 45 LPM while the line pressure of the mass flow controller is maintained at 2 bars, 4 bars and 6 bars (gauge pressure) respectively. The measurement results will be compared with that where the mass flow controller is not connected with pressure control and downstream of the mass flow controller is at atmospheric pressure.

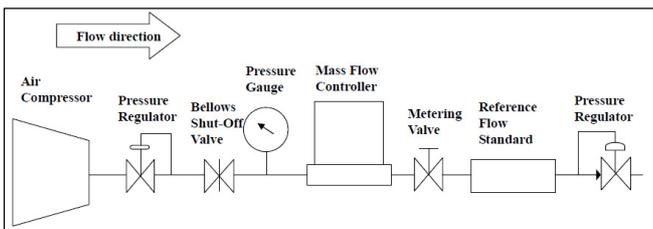


Fig. 3. The calibration setup for calibrating a mass flow controller at specified line pressure of 4 bars or 6 bars (gauge pressure).

The relative reading error of the MFC when it is maintained at various line pressures is shown in Fig. 4. The measurement results reveal that the relative reading error can be up to 2 % when the nominal flow rate is at 45 LPM.

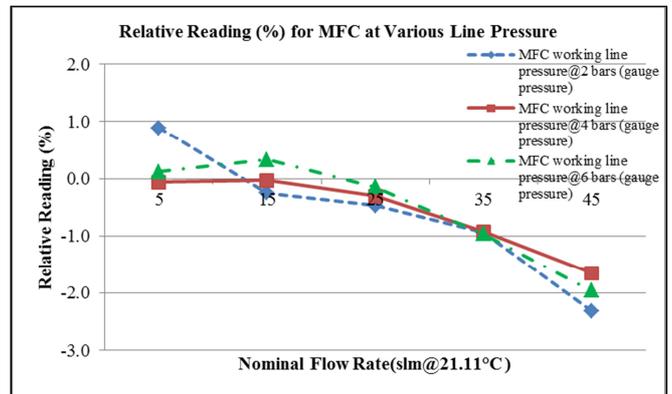


Fig. 4. The relative reading error (%) of a MFC at various line pressures.

2.2. The calibration types of the flow elements

There are three different pressure dependent calibration types for flow elements, namely low pressure, high pressure and downstream. The calibration types determine the operating pressure ranges and mass flow measurement specifications of the flow element. The calibration types would also affect the flow element's flow range and the differential pressure associated with the flow range. The calibration types, operating pressure range and the differential pressure over the flow elements are summarised in Table 1.

Table 1. Pressure Dependent Calibration Types.

Calibration Type	Operating Pressure	Nominal Differential Pressure
Low pressure (LOP)	200 to 325 kPa absolute upstream of flow elements	50 kPa
High pressure (HIP)	325 to 525 kPa absolute upstream of flow elements	50 kPa
Downstream (DOWN)	Atmospheric pressure downstream of the flow elements 85 to 105 kPa	80 kPa

The flow elements have been characterised over the indicated pressure range for the actual calibration type(s) specified in the calibration certificate provided with the flow elements. The operation of the flow elements are bounded by the specified calibration type and the corresponding operating pressure range. To revolve this, a DUT can be connected at upstream or downstream of the flow elements. By doing so, the flow elements can be operated within the pressure limits of its calibration type while the DUT can be calibrated at a specified line pressure. At low working line pressure up to 200-300 kPa, the DUT can be connected at downstream of the flow elements as the configuration shown in Fig. 2, while for high working line pressure, it is necessary for the DUT to be

connected at upstream of the flow elements as the configuration shown in Fig. 3.

When a DUT is connected at upstream of the flow elements, the use of a back pressure regulator is required. A needle valve can help to regulate and control the flow, thereby maintaining the upstream pressure of the flow elements within the required operating pressure range. The upstream pressure, however, will vary with the flow, which render the adjustment to be more complicated. The back pressure regulator can effectively maintain the upstream pressure of the flow elements within the required operating pressure over a wide range of flow. Once a designated back pressure is set, only minor fine tuning is required for various flows within the flow range of the flow element.

3. SENSITIVITY OF THE REFERENCE FLOW STANDARD TO VARIOUS LINE PRESSURES DEVIATED FROM THE CALIBRATION VERIFICATION PRESSURE

Calibration type of Low pressure is selected for a flow element, with maximum flow capacity up to 5000 sccm (standard cubic centimetres per minute). According to the calibration certificate provided with the flow element, it is calibrated at a pressure of 272 kPa. However, it is mentioned in the calibration certificate that the flow element has been characterised over the indicated upstream pressure ranging from 200 to 325 kPa. In order to validate the performance of this flow element over the indicated pressure range, a high precision flow standard, which is a piston prover, is used as a DUT while the flow element is served as reference flow standard for this validation study. The calibration setup is shown in Fig. 5.

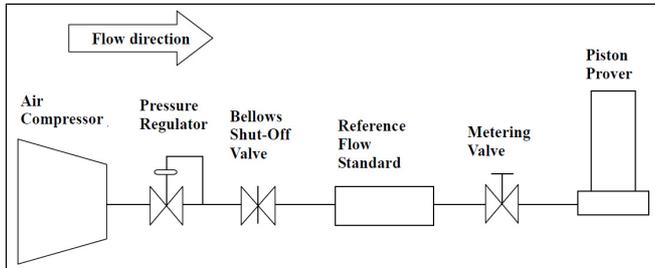


Fig. 5. The calibration setup for calibrating a high precision flow standard.

The accuracy of the DUT is of 0.15 %. The upstream pressure of the flow element is maintained at various line pressures deviated from the verification pressure of 272 kPa (i.e. $\pm 5\%$, $\pm 10\%$ and $\pm 15\%$). The indicated values of the DUT at volume flows of 1000, 3000 and 5000 sccm are compared with the indicated values of the reference flow standard. The comparison results are depicted in Fig. 6.

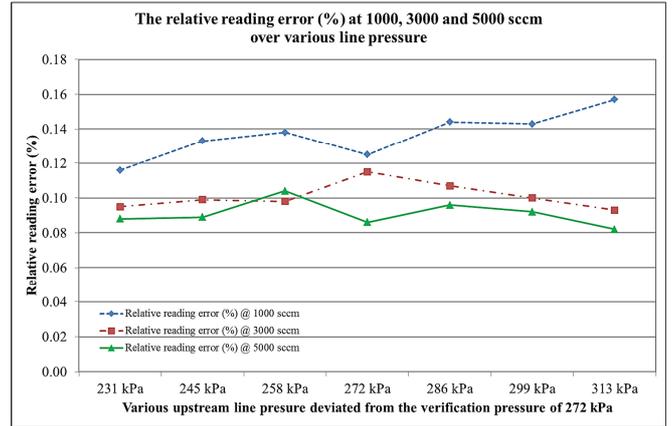


Fig. 6. The relative reading error (%) at 1000, 3000 and 5000 sccm (reference to standard temperature and pressure conditions of 0°C and 101.325 kPa) over various line pressures.

The comparison results between the reference flow standard and the DUT indicated that the maximum relative reading error (defined as value of DUT-value of standard)/value of standard is 0.157 %, which is comparable with the calibration results of the DUT. The maximum deviation of relative reading errors for various line pressures deviated from the calibration verification pressure of the flow element is 0.04 % at 1000 sccm, while the maximum deviation of relative reading errors is 0.02% at 3000 and 5000 sccm. The deviation of relative reading error is within the possible uncertainties of this reference flow standard, that is $\pm 0.2\%$ of reading or 0.02 % full scale, whichever is greater.

4. MEASUREMENT UNCERTAINTY EVALUATION

The estimated expanded measurement uncertainty of the SCL flow standard ranging from 1 to 45 slm is about 0.6 % of reading.

The measurement model is given below:

$$c = f_{std} - f_{uut} \quad (1)$$

where

c = correction

f_{std} = mean of gas flow recorded by standard

f_{uut} = mean of gas flow recorded by unit under test

With reference to the above relationship

Hence c = function (f_{std}, f_{uut})

The combined uncertainty, $u_c(c)$, of the output quantity, c , is the positive square root of the sum of the square of each standard uncertainty of the input quantity multiplying by the square of its sensitivity coefficient as follows:

$$u_c^2(c) = \sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \quad (2)$$

Assuming all the input quantities are independent and uncorrelated, we obtain

$$[u_c(c)]^2 = c^2 f_{std}^2 (f_{std}) + c^2 f_{uut}^2 (f_{uut}) \quad (3)$$

where

$$c_{f_{std}} = \frac{\partial c}{\partial f_{std}} = 1$$

$$c_{f_{uut}} = \frac{\partial c}{\partial f_{uut}} = -1$$

The components contributed to the measurement uncertainty of the reference flow standard are summarised in Table 2.

Table 2. Measurement Uncertainty Components of the Reference Flow Standard

Measurement Uncertainty Components of the Reference Flow Standard	
I	Measurement uncertainty of the reference flow standard, $u(f_{std})$:
(i)	Measurement uncertainty of the flow element used for measurement, $u(f_{std1})$.
(ii)	Measurement uncertainty due to the flow element reading deviated from the reference value, $u(f_{std2})$.
(iii)	Measurement uncertainty due to long term drift of the entire flow calibration system, $u(f_{std3})$.
(iv)	Measurement uncertainty due to variation of calibration pressure during measurement deviated from the verification pressure reported in the calibration certificate of the flow element, $u(f_{std4})$. (Remark: According to the manufacturer's instruction, for real gases there is a change in viscosity with pressure and in some cases is not very well known, there could introduce, because of the limited specific pressure range, systematic variations in flow measurement as high as 0.1% of reading.)
(v)	Measurement uncertainty due to variation of air composition on the accuracy of the flow elements, $u(f_{std5})$. (Remark: According to the manufacturer instruction, when there is an uncertainty as high as 1% change of content of gas component, there could introduce systematic variations in flow measurement as high as 0.1% of reading.)
(vi)	Uncertainty due to systematic offset identified during validation of measurement result, $u(f_{std6})$.
II	Uncertainty due to repeatability of measurement errors, $u(f_{std} - f_{uut})$.
III	Uncertainty due to resolution of unit under test, $u(f_{uut})$.

Taking the flow at 1000 sccm as an example, the measurement uncertainty budgets of the reference flow standard are summarised in Table 3.

Table 3. Measurement Uncertainty Budgets of the Reference Flow Standard at 1000 sccm

Measurement Uncertainty Components	Relative Expanded Uncertainty, %	Relative Standard Uncertainty, %
$u(f_{std1})$	0.20	0.10

$u(f_{std2})$	0.05	0.03
$u(f_{std3})$	0.20	0.12
$u(f_{std4})$	0.10	0.05
$u(f_{std5})$	0.10	0.05
$u(f_{std6})$	0.40	0.23
$u(f_{std} - f_{uut})$	0.05	0.05
$u(f_{uut})$	0.01	0.01
Relative combined standard uncertainty, (%)		0.29
Relative expanded uncertainty, (%)		0.58

5. CONCLUSIONS

The application of a flow calibration system for calibrating a mass flow controller at various line pressures is studied in this paper. Even only one calibration type is available for the flow element, a back pressure regulator enables the flow calibration system to be used to calibrate a mass flow controller at various line pressures. This could be done by connecting the mass flow controller at upstream or downstream of the flow element while keeping the flow element maintained at a line pressure within its operating pressure limits or even maintained at the calibration pressure in any circumstances. This paper also elaborates how the back pressure regulator can help to improve the overall calibration efficiency and accuracy.

The sensitivity of a flow element to various line pressures deviated from the calibration pressure is also studied. The measurement results revealed that the flow element under study is not sensitive to various line pressures deviated from the calibration pressure and the maximum relative reading error is less than the possible uncertainties of the flow calibration system.

More studies on the limitation and accuracy of the flow calibration system such as the sensitivity to temperature changes, dead air and orifice effects and the working principle of the sonic flow elements will be further conducted in the near future. It is expected the further studies would result in better understanding and fruitful outcomes on the practical application of the flow calibration system.

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