An Overview of the New Gas Flow Measurement Facility at the INMS/NRC

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Abstract

Accurate measurement of gas flows is critical to many industrial processes. To meet the requirements of many clients, a new gas flow measurement facility for calibration of gas flow meters has recently been established at the Institute for National Measurement Standards at the National Research Council, Canada. Presently, the calibration service is provided over a flow range of 5 sccm to 50 slm. Two types of devices are used: one is a mercury sealed piston prover and the other is a laminar flow based transfer standard. In this paper, we will describe these two systems and present the calibration uncertainty associated with these systems.

1. Introduction

The devices used to control and measure gas flows in many industrial processes include Thermal Mass Flow Controllers, Rotameters, Turbine Flow Meters etc. For accurate and credible measurements as well as to conform to formal quality assurance program, it is necessary that these devices be calibrated against a traceable standard regularly. Flow is a derived quantity, and such the flow standards provide measurements that are traceable to fundamental standards of length, mass and time. A gas flow calibration facility usually consists of the following:

1. A source of gas flow such as a regulated compressed gas cylinder.

2. A test section into which the test flowmeter can be installed such that the flow and fluid conditions can be appropriately controlled.

3. A flow measurement system.

There are several fundamental methods exist, where reference flow rates can be derived from measurements that are traceable to fundamental standards of length, mass and time. In the *gravimetric* method, the flow rate is measured by directly measuring the mass of gas flowed over a period of time. This is the only method available for directly deriving the flow rate from the base units of mass and time and is independent of the thermodynamic properties of the gas.

Other fundamental methods of determining mass flow rates, such as *volumetric* and *rate of rise* methods, do not derive mass flow directly from the base unit of mass and time and require the knowledge of gas thermodynamic properties at actual operating conditions of temperature and pressure. In the *volumetric* method, the gas is flowed into a variable volume and the time required to collect a known volume is measured yielding a volumetric flow rate. The volumetric flow rate is converted to massflow rate by deriving the gas density from the measured gas temperature and pressure and gas thermodynamic properties. In the *rate of rise* of method, the gas is flowed into a fixed volume and the time required for the gas pressure to rise by a certain amount is measured. The total mass of the gas flowed into the volume can be calculated from the temperature, pressure and gas thermodynamic properties.

Another method of determining mass flow is using the *critical flow venturis.* A *critical flow venturis* is a nozzle of specific geometry and dimensions so that a gas flowing through it accelerates to sonic velocity at the throat. This condition is commonly referred to as *choked* flow and under choked flow conditions, the mass flow rate depends only on the upstream temperature and pressure and is easily calculable.

We have established a gas flow calibration facility at the Institute for National Measurement Standards to provide calibration services over a range of 5×10^{-6} m^3/min to 5×10^{-2} m^3/min. At present we are using a commercially available piston prover, MKS CALIFLOW A200 as a primary standard and a calibration system based on laminar flow elements from DH Instrument.

2. Piston Prover

The CALIFLOW A200 determines gas flow rates by volumetric method. It uses the principle of measuring time required to fill a known volume. Also, the gas temperature and pressure are measured to convert the volume flow rate to mass flow rate at standard conditions of 0° C and 760 Torr.

2.1 Theory of Operation

A typical system for flow rate calibration is illustrated in fig.1, showing various control volumes representing flow meter under test, connecting piping and collection volume. The conservation of mass for this can be represented by the following equation:

$$\frac{\partial}{\partial t}\int_V \rho\, dV \quad + \int_A \rho \bar{v} \cdot d\bar{A} = 0 \tag{1}$$

where, ρ is the gas density, $\partial/\partial t$ is the partial derivative with respect to time and V is the control volume comprising of all the volumes in fig.1, $\bar{v}$ is the vector velocity of fluid and A is the area enclosing the control volume V.

Application of equation 1 to the piston prover, provides a mass flow rate, $\dot{m}$, as:

$$\dot{m} = \frac{\rho_c \cdot V_c}{\Delta t} + \frac{\Delta \rho_a \cdot V_a}{\Delta t} \tag{2}$$

Here, V_c is the volume of gas collected in the piston prover during the time Δt and ρ_c is the mean density of collected gas, calculated from the temperature and pressure measurements during the run. V_a is the remaining volume in the system including volume of the test flow meter and connecting piping and $\Delta\rho_a$ is the change in gas density during the collection time.

The first term in equation 2 is the mass flow rate in the piston prover, while the second term accounts for any change in the gas density in the remaining system volume during the run. The change in gas density could result from changes in the system temperature or pressure. For the piston prover to measure the same flow rate as is passing through the flow meter, it is necessary that the second term be reduced to a minimum. This can be achieved by allowing the system to reach a steady state so that changes in density during the run are zero. Steady state can be reached by allowing the temperature to stabilize at the given flow condition before the calibration run is made.

2.2 Description of the CALIFLOW piston prover

Figure 1 shows an outline of the CALIFLOW system. The key elements of the system are two precision bore borosilicate glass cylinders, each fitted with a piston with a mercury seal. The mercury sealed piston rises as the test gas flows into the cylinder. The cylinder's uniform cross sectional area provides the collection volume that is proportional to the piston's vertical movement. A tape connects the piston to a counterweight. This tape is looped over an encoder shaft and an idler pulley. The counterweight maintains the tape tension to drive the shaft encoder as the piston rises or falls. The encoder transmits a pulse for each increment of shaft angle rotation, consequently each pulse is related to an incremental change in volume under the piston. This is how the collection volume is defined. The encoder provides 2000 pulses per revolution. On the large cylinder, this translates to approximately 0.55 ml/count. On the small cylinder the resolution is about 0.034 ml/count. Other key components of the system are a crystal clock, a Baratron pressure sensor and a RTD temperature sensor. The clock pulses are accurately synchronized with the encoder output to measure the collection time.

2.3 Sources of Uncertainty

The largest contribution to overall uncertainty in measurement by a piston prover is due to the first term in equation 2. The influence variables are the cylinder volume V_c , the collection time Δt and the gas density ρ. The cylinder volume is calibrated by measuring the cylinder diameter at various cross sections and the piston travel at various heights. The corresponding pulse counts for each piston travel is recorded to obtain an average volume/count for each cylinder. The volume uncertainty is, therefore, due to the uncertainty in the diameter measurement, height measurement and the thermal expansion of the glass cylinder. The uncertainty in the collection time comes from the calibration uncertainty of the clock as well as the error in synchronization of clock pulses with the encoder output. The uncertainty in gas density result from the uncertainty in the measurement of temperature and pressure.

The second term of equation 2 can be a significant contributor to overall measurement uncertainty if the gas density varies during the test run. This can result if the system temperature or pressure changes during the run. Also, if there is any leakage in the system it could add to the overall uncertainty in the flow measurement.

Table 1 summarizes the various uncertainty components for the CALIFLOW system.

Table – 1

Uncertainty Components	Large Cylinder %	Small Cylinder %
1. Collection Volume (V_c)	0.050	0.065
2. Gas Density (ρ)	0.060	0.060
3. Collection Time	0.020	0.020
4. Storage Effects	0.020	0.020
5. Leakage	0.010	0.010
Flow Combined Standard Uncertainty	0.083	0.093
Flow Expanded Uncertainty	0.166	0.186

3. Laminar Flow Elements

3.1 Theory of Operation

The calibration system is based on the well-established laminar flow theory and the known thermodynamic properties of gases. The laminar flow element is designed by centering a precisely machined piston in a cylindrical bore, creating a longitudinal annular passage for the gas flow. The cylindrical bore is machined in a block whose thermal mass is very large relative to the gas in the annular space. Two platinum resistance thermometers measure the average temperature of the block over its working length. Precision pressure sensors measure the upstream and downstream pressures. The mass flow of a compressible fluid in laminar flow through an annular passage is given as:

$$q_m = \frac{(P_1 - P_2) \cdot \rho_{(P,T)} \cdot \pi \cdot R \cdot h^3}{\eta_{(P,T)} \cdot 6 \cdot L} \tag{3}$$

Where, P_1 and P_2 are upstream and downstream absolute pressure, R is the radius of the flow passage, h is the gap between piston and cylinder, ρ is the gas density at the average pressure P =(P_{1+} $P_{2)}/2$, and the absolute temperature of the gas T, η is dynamic gas viscosity, and L is the length of the flow passage. The gas density at the operating temperature and pressure is is given by:

$$\rho_{(P,T)} = \rho_N \frac{P \cdot T_N \cdot Z_N}{P_N \cdot T \cdot Z_{(P,T)}} \tag{4}$$

Where, ρ_N is the gas density at standard pressure P_N and Temperature. T_N. Z_N is the gas compressibility factor under standard conditions and $Z_{(P,T)}$ is the gas compressibility factor under P, T conditions.

The mass flow equation can now be written as:

$$q_m = C_d \frac{P \cdot (P_1 - P_2) \cdot \rho_N \cdot T_N \cdot Z_N}{T \cdot Z_{(P,T)} \eta_{(P,T)} \cdot \rho_N} \tag{5}$$

Where, $C_d = \pi.R.h^3/6L$ is the geometrical constant of the particular laminar flow element that is obtained from calibration with another reference standard.

The laminar flow element is associated with an electronic unit that contains the pressure sensors and the readout for PRTs and a microprocessor to solve the mass flow equation 5.

3.2 Sources of Uncertainty

The largest contribution to overall uncertainty in measurement by the laminar flow element is due to the geometrical constant C_d in equation 5, that needs to be determined by calibration using a reference system. Other contributing factors are the pressure, temperature and the density of the gas. We have calibrated the pressure sensors at the INMS using primary reference standard to an uncertainty of 0.01% and the PRTs have been calibrated with an overall uncertainty of 0.1

K. We are currently using three elements of various flow ranges. These elements have been calibrated at DH Instrument as well as at NIST, Gaithersburg. We are currently in the process of determining the geometrical constant C_d by calibrating the laminar flow elements against the CALIFLOW piston prover.   The early calibration results show good agreement between various calibrations. These results will be presented elsewhere when completed.

4 Summary

We have presented a description of the airflow calibration facility recently established at the Institute for National Measurement standards at the National Research Council. We are using a MKS CALIFLOW A200 as a primary flow system and a laminar flow based system from DH Instrument as a transfer standard. The calibration service can be provided over a range of 5×10^{-6} m^3/min to 5×10^{-2} m^3/min. The expanded uncertainty (k=2) of flow measurement by the piston prover is better than $\pm0.2\%$. The future projects in the flow lab include establishing a gravimetric system so that gas flows can be directly traceable to the fundamental units of mass and time with very low uncertainties.

References

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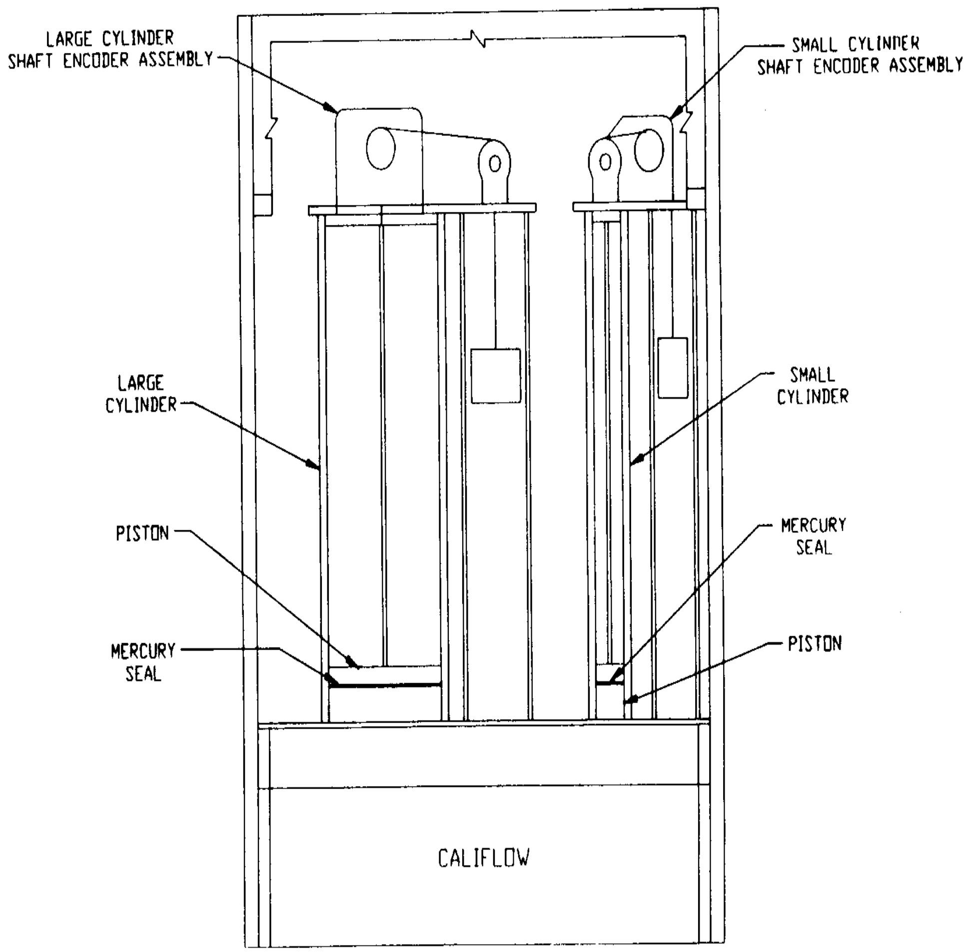
LARGE CYLINDER
SHAFT ENCODER ASSEMBLY
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PISTON
MERCURY
SEAL
MERCURY
SEAL
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CALIFLOW

FIGURE 1