

New Primary Low-Pressure Gas Flow Standard at NIMT

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Abstract: To establish the traceability chain of low-pressure gas flow measurement within Thailand, a primary standard with the capacity of 0.005 L/min to 24 L/min (at 296.15 K and 101.325 kPa) was established at National Institute of Metrology (Thailand); NIMT. The standard facility is a mercury-sealed piston prover consisting of three precision-machined glass cylinders. With the positive displacement technique, the facility measures gas flowrate by determining the displaced volume, time, and pressure and temperature of the gas. Flow measurement can be carried out manually or semi-automatically. The electronics were installed in a separate console to minimize the heating effect on the gas temperature. Furthermore, special care was taken in designing the facility to ensure that gas pressure and temperature can be measured as accurate and representative as possible. The relative expanded uncertainty of gas mass flow measurement, evaluated according to ISO GUM, was less than 0.13 % of reading.

Keywords: Piston Prover, Gas Flow Measurement, Uncertainty Analysis

1. Introduction

To support the needs of gas flowmeter calibrations and establish the traceability chain to SI units of gas flow measurement in Thailand, National Institute of Metrology (Thailand); NIMT has established a mercury-sealed piston prover as a primary standard for low pressure gas flow. The facility was designed and manufactured by Center for Measurement Standards, Industrial Technology Research Institute (CMS/ITRI), Taiwan. The flow capacity of the system covers the flow of 0.005 L/min to 24 L/min (at 296.15 K and 101.325 kPa) with some overlapped flows between the tubes. The calibration gases are dry air and nitrogen. The detailed uncertainty analyses of the gas piston prover are presented.

2. Gas Piston Prover

Typically, mercury-sealed piston provers of earlier design make measurements based on glass cylinders having uniform diameters and graduated scales to determine, usually facilitated by optical switches installed in pairs, the collection volumes. When the incoming gas pushes the piston upward, the light reflected by the mercury ring generates signals to start and stop the timing. System of this kind generally suffers from the following shortcomings.

- (1) Errors due to manual adjustment of the installation positions of the optical switches in correspondence with the graduation marks.
- (2) The distance between the pair of optical switches may differ from the actual distance travelled by the piston since the trigger signals are affected by the mercury surface condition and the reflection intensity, leading to compromised system reproducibility.
- (3) The difficulties in calibrating the graduated scale and the installation effect due to differences between operation and calibration conditions.

- (4) Inappropriate installation position of the thermometer, which problem degrades the correctness of gas temperature measurement.
- (5) All the columns in a set of piston prover generally adopt a common connecting piping which occupies significant proportion relative to the collection volumes of small glass cylinders, resulting in augmented storage effect and increased measurement uncertainty.
- (6) Inappropriate installation position of the pressure tap, which problem degrades the correctness of gas pressure measurement, especially at high flows that cause significant pressure loss in the piping.
- (7) The bypass valve usually opens immediately after the triggering of the second optical switch. This practice affects, in a degree that is difficult to evaluate, the measurements of temperature and pressure at the end of the calibration.
- (8) The environment temperature, when differs considerably from the gas temperature, would affect the temperature of the gas in the glass tube, which is practically difficult to measure, especially at low flows with prolonged calibration time.

The gas piston prover reported in this paper is designed to overcome, to the extent possible, the aforementioned problems. The prover consists of three precision bore glass tubes with the inside diameters of 19.0 mm, 44.4 mm and 143.7 mm and a mercury-sealed piston in each tube. The travelling distance of the piston is measured by a Laser Doppler Scale (LDS) installed on the top of the piston prover body. The axles of the glass tubes are installed collinearly so that the laser beam of LDS can be easily switched among the three cylinders through simple optics for piston travelling distance measurement.

At the steady state condition, the flow is diverted into the tube, causing the piston to rise at a constant velocity. Once the piston moves through the light beam of the first digital fiber photo-sensor, the intensity of the light reflected from the mercury on the piston to the sensor is used as a trigger signal to start the timer and displacement measuring equipment to work. At the end of the stroke, the second digital fiber photo-sensor, at the top of each tube, is triggered to stop the timer and LDS.

The corresponding collection volumes of each prover are about 103 cm³, 785 cm³ and 8,757 cm³ for the small, medium and large glass cylinders, respectively. The approximate collection time at the maximum flows of each tube is assumed to be 20 seconds. The actual volumetric flow is obtained. During the gas collection period, the absolute pressure and temperature sensors that are installed at the bottom (inlet) of each tube are used to measure the pressure and temperature of the flowing gas into the collection volume; hence, its density is obtained and then used to calculate the flowrate of the gas at the desired conditions.

According to the configuration of the calibration system shown in Figure 1, the mass flowrate of the gas into the system can be expressed as follows.

$$q_m = \frac{\rho_c \cdot V_c}{t} + \frac{\Delta\rho_I \cdot V_I}{t} + q_{m,l} = \frac{\rho_c \times \pi \times D^2 \times L}{4 \cdot t} + \frac{\Delta\rho_I \times V_I}{t} + \rho_c \times q_{v,l} \quad (1)$$

$$= f(D, L, \rho_c, t, \Delta\rho_I, V_I, q_{v,l})$$

Where q_m is the mass flowrate; V_c is the collection volume; V_I is the inventory volume, which is the volume between the exit of the meter under test and the start location of the glass cylinder (see Figure 1); t is the collection time; ρ_c is the density of the gas in the collection volume; $\Delta\rho_I$ is the change in density of the gas in the inventory volume; $q_{m,l}$ is the mass leak rate from the

system; D is the diameter of the glass tube, L is the travelling distance of the piston; and $q_{v,l}$ is the volume leak rate. The photo of the piston prover is shown in Figure 2.

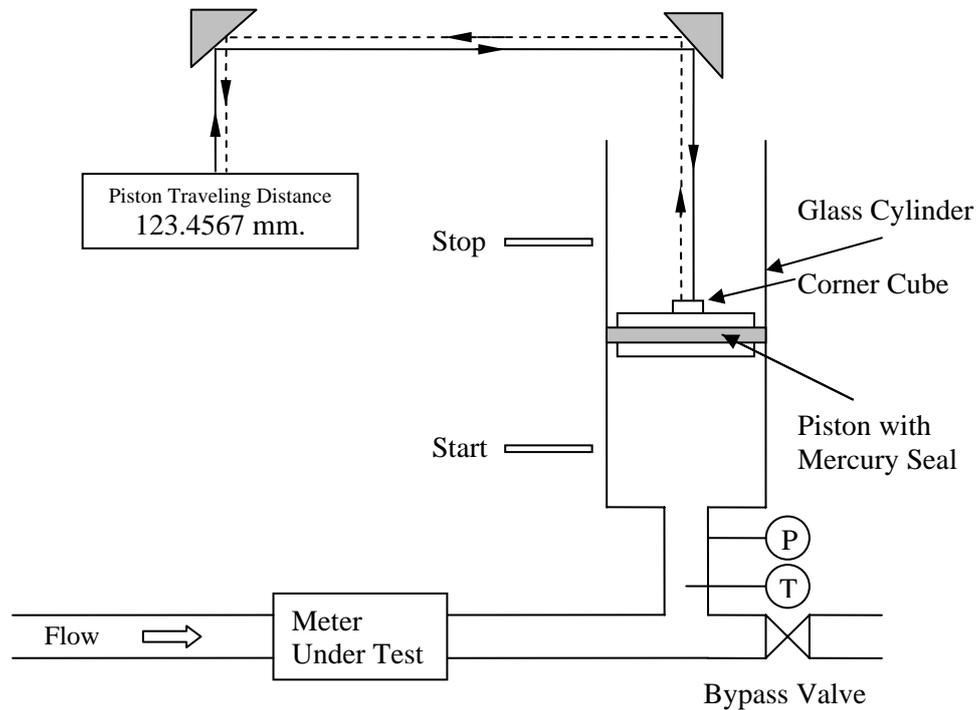


Figure 1. Schematic of Mercury-Sealed Piston Prover



Figure 2. Photo of Mercury-Sealed Piston Prover

3. Sources of Uncertainty

From eq. (1), the relative combined uncertainty of the mass flow measurement can be derived as follows.

$$\frac{u_c(q_m)}{q_m} = \left[\left(\frac{2u(D)}{D} \right)^2 + \left(\frac{u(L)}{L} \right)^2 + \left(\frac{u(\rho_c)}{\rho_c} \right) + \left(\frac{-u(t)}{t} \right)^2 + \left(\frac{4V_I}{\pi \times D^2 \times L} \frac{u(\Delta\rho_I)}{\rho_c} \right)^2 + \left(\frac{\Delta\rho_I}{\rho_c} \frac{4u(V_I)}{\pi \times D^2 \times L} \right)^2 + \left(\frac{4t \times u(q_{v,I})}{\pi \times D^2 \times L} \right)^2 \right]^{1/2} \quad (2)$$

Where u represents the standard uncertainty. The flow measurement uncertainty of the gas piston prover depends on the diameters of the glass tube, travelling distance of the piston, density of the flowing gas, time, the storage effects of the inventory volume and the leakage. The analysis is as follows.

3.1 Inside Diameters of the Glass Cylinders

The inside diameters of the glass cylinders were measured at various cross-sections, each 50 mm apart, along the length of collection volume by bore gauges which are traceable to ring gauges calibrated by Dimension Laboratory of NIMT. At each of the cross-sections, 5 measurements were taken in each of two directions, namely, X and Y, which were perpendicular to each other, resulting in 10 diameter readings for the cross-section. The average of all the diameter readings at various cross-sections was used as the estimation of the diameter of each cylinder.

The environmental conditions of laboratory is controlled at (296.15 ± 1.5) K and (55 ± 15) % of relative humidity. The thermal expansion coefficient of the glass tubes and ring gauges are $0.000006/^\circ\text{C}$ and $0.000018/^\circ\text{C}$, respectively. The effects of thermal expansion to the diameters of the glass cylinders were considered small and negligible.

The uncertainty contributions of the diameter measurements to the standard uncertainties of the collection volumes are 0.012 %, 0.006 % and 0.004 % for the small, medium and large cylinders, respectively.

3.2 Pistons' Travelling Distance

The He-Ne Laser system; Laser Doppler Scale (Optodyne LDS 1000), is used to measure the travelling distance of the pistons between the 2 digital fiber photo-sensors on each tube. The wave length of the laser was calibrated by Wave Length Laboratory, Dimensional Department of NIMT. The effects of the environmental changes, i.e. pressure, temperature and humidity, and cosine error to the measured distance were also taken into consideration. These uncertainties contribute to the standard uncertainty of the collection volume of 0.001 % [4].

3.3 Gas Density

The gas density is used to convert the volumetric flow to mass flow. The density value is calculated based on the measured pressure and temperature using the following equation.

$$\rho_c = \frac{PM}{Z(P,T)RT} \quad (3)$$

Where P and T are the absolute pressure and absolute temperature, respectively, of the gas in the collection volume; M is the gas molecular weight; R is the universal gas constant; and $Z(P,T)$ is the compressibility of the gas. The uncertainty contributions from these components are elucidated as follows.

(1) Temperature measurement

The temperature sensors were calibrated by the Temperature Laboratory of NIMT. The standard uncertainty of calibration, residuals of curve fitting, resolution, the effects of the environment to the temperature distribution of the gas inside the collection volume in the glass cylinder and the drift of sensors is estimated to be 0.13 K (0.044 %, based on a reference temperature of 296.15 K)

(2) Pressure measurement

The absolute pressure transducers, which were calibrated by the Pressure Laboratory of NIMT, are used to measure the pressure of the gas collected in the glass cylinder. The uncertainty of calibration, residuals of curve fitting, resolution, drift of the transducer and the effect of installation position are combined as the standard uncertainty of 17 Pa (0.017 %, based on a reference pressure of 100 kPa)

(3) The molecular weight and universal gas constant are regarded as constants. According to the published reference [3], the uncertainty of universal gas constant is 0.0002 %, and the uncertainties of the molecular weight of dry air and nitrogen are 0.0001 % and 0.019 %, respectively. The calculation of compressibility factor of dry air and ultra high purity nitrogen over the temperature range of 270 K to 330 K at 100 kPa, which are used as calibration gases, has a relative standard uncertainty of 0.001 % [3].

Combining the above mentioned components with root-sum-of-squares (RSS) technique yields a relative standard uncertainty of 0.051 % and 0.048 % for the calculated density of air and nitrogen, respectively. In this analysis, 0.051 % will be used as the uncertainty of calibration gas density.

3.4 Collection Time

The timer with the resolution of 0.001 s is tested by comparing to the Universal Counter which was calibrated by the Time and Frequency Laboratory of NIMT. The maximum difference of the time measured after applying a fitting function is estimated to be within 0.001 s. The minimum time interval for the high flow of each cylinder is approximately 20 s and is used as the reference value, resulting in a relative standard uncertainty of 0.005 % for the collection time measurement. In addition, the standard uncertainty of the triggering process is estimated, according to the maximum start/stop response time specification of the timer, to be within 0.001 s. The combined relative standard uncertainty is 0.0014 s. (0.007 %)

3.5 Storage Effects

The storage effects account for two parameters that would affect the measurement result, i.e., the variation of gas density in the inventory volume and the inventory volume measurement. The variation in pressure and temperature of the gas in the inventory volume results in a density change, which change in turn affects the mass conservation between the meter under test and the piston prover. The maximum pressure and temperature variations are assumed to be 30 Pa and 0.20 K during the collection time. As a result, the relative standard uncertainty of the gas density variation is 0.045 %. The inventory volumes of the small, medium and large piston cylinders are estimated to be 70 cm³, 200 cm³ and 2000 cm³, respectively. The corresponding ratios of inventory volume to the collection volume are 0.68, 0.26 and 0.23, respectively. These cause contributions of 0.031 %, 0.012 % and 0.010 %, respectively, to the standard uncertainty in flow calibration.

The inventory volume is calculated based on the sizes of the piping, connector and glass tube. The maximum relative deviation is estimated to be 40 %. Therefore, the inventory volume measurement contributes 0.007 %, 0.003 % and 0.002 % for small, medium and large cylinders, respectively, to the standard uncertainty of the mass flow.

3.6 Leakage

The leak is tested by lifting and holding the piston midway in the glass cylinder and monitoring its falling speed. Results show that the leak is less than 0.02 % of the minimum flow to be measured by the piston prover. In practice, the leakage is ignored with a relative uncertainty contribution of 0.012 %.

3.7 Combined Uncertainty

The combined uncertainties of mass flowrate are determined by RSS of all standard uncertainties which correspond to 0.063 %, 0.055 % and 0.054 % for small, medium and large cylinders, respectively. The coverage factor of 2 is then multiplied to the relative standard uncertainties to provide the expanded uncertainties of 0.13 %, 0.11 % and 0.11 % with the level of confidence of approximately 95 % as shown in Table 1.

Table 1. A summary of the piston prover relative uncertainties for mass flow measurement

	Small Piston Prover	Medium Piston Prover	Large Piston Prover
Uncertainty Category	Relative Standard Uncertainty (%)	Relative Standard Uncertainty (%)	Relative Standard Uncertainty (%)
I.D. of Glass Cylinders	0.012	0.006	0.004
Pistons' Traveling Distance	0.00090	0.00089	0.00089
Gas Density	0.051	0.051	0.051
Collection Time	0.007	0.007	0.007
Storage Effects	0.032	0.012	0.010
Leakage	0.012	0.012	0.012
Combined Uncertainty	0.063	0.055	0.054
Expanded Uncertainty ($k=2$)	0.13	0.11	0.11

4. Conclusion

The mercury-sealed piston prover is established as a primary gas flow standard to cover the flow of 0.005 L/min to 24 L/min with the uncertainty of mass flow less than 0.013 % ($k = 2$) in Thailand. The bilateral comparison of the primary low-pressure gas flow standards between the CMS/ITRI and NIMT, which is discussed in a separate paper [5], was conducted to verify the performance of the piston prover of NIMT. The comparison results show a good degree of equivalence of the two primary standards. The absolute values of En ratios are less than 0.4.

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