The middle range gas flow standard of SPRING Singapore

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Abstract An auto-bell prover was set up at SPRING Singapore for the calibration of gas flow meters in the flow range of 3 m/h^3 to $100m/h^3$ or 1 to 33g/s (dry air). The gas flow rate of the bell prover was determined by a primary method based on pressure, temperature, time and displaced volume measurements. The evaluations of the measurement uncertainties were carried out at the Gas Flow Laboratory of SPRING Singapore. The relative expanded measurement uncertainty was estimated to be less than ±0.2% of readings. The performance of the auto-bell prover was checked using two transfer standards that were calibrated at National Institute of Standard and Technology (USA). The results are satisfactory.

Keywords: Bell prover; Gas flow; Measurement uncertainty

1. Introduction

The National Metrology Centre of SPRING Singapore established a gas flow calibration system in 1998, in order to meet industry's requirement for the calibration of various types of gas flow meters. An auto-bell prover, made by Flow Technology Inc (USA), was acquired as the standard for the calibration of gas flow meters in the range of volume flow rate of 3 to 100 m^3/h or mass flow rate of 1 to 33g/s (dry air). The measurement uncertainty of the system, as described below, was evaluated under SPRING's controlled laboratory conditions. The performance was checked by comparison with the two turbine flow meters calibrated at NIST.

2. The gas flow standard of SPRING

The bell prover of SPRING, shown in Fig 1, consists of a cylindrical bell with nominal cross-sectional area of 762mm and a $0.4m^3$ double-walled cylindrical tank, in which the bell moves in its annulus space. The maximum displacement of a stroke is 750mm. Two counterweights for the balancing of the bell weight and correction of the buoyancy force allow the bell prover to collect gas at constant and low pressure. The density of gas in the bell prover was calculated by measuring the temperature and pressure of the gas with temperature and pressure sensors located at the central position of the bell prover.

The flow meter is installed at the upstream of the bell prover. As soon as the stable flow is established through the piping, flow meter and regulators, the three-way valve at the bottom of the bell is closed so that all of the flow is diverted into the prover causing the bell to rise at a constant speed for the gas collection.

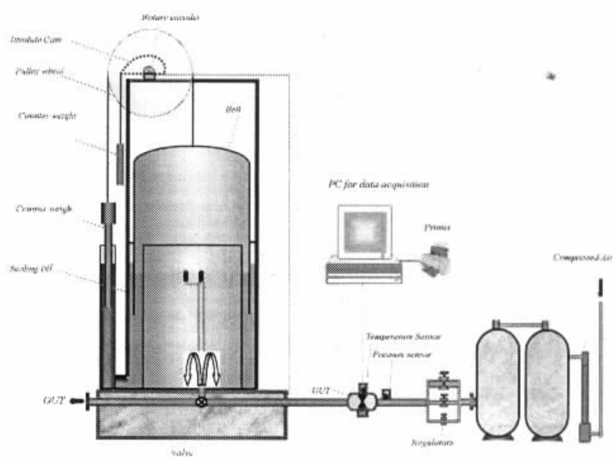

Fig. 1 The schematic representation of the SPRING auto-bell prover gas flow standard

The bell prover calibration system is based on the principle of measuring the time interval required to collect a known volume of gas at measured temperature and pressure. The mathematical models for the calculation of the volume flow rate and mass flow rate are as shown :

$$Q_V = v*A(p,T) \quad (1)$$

$$Q_m = Q_V*\rho_{bell} \quad (2)$$

where v is the average moving speed of bell; $A(p,T)$ is the average area of bell at temperature T and pressure p in bell; ρ_{bell} is the density of gas in the bell prover.

3. The measurement uncertainty

The bell prover's uncertainty depends on the pressure, temperature, speed and volume measurements. The analysis of uncertainty was based on several experiments and calibrations that were carried out under the laboratory condition of 20±1°C. The standard deviations of uncertainty components are quantified as follows:

3.1. Bell travel length *L*

The collection volume is generated by the displacement of the bell, and measured by a rotary encoder which is attached to the shaft of the pulley. The chain suspending the bell is connected to the pulley so that the pulley rotates as the bell rises. The pulley is machined concentric to the shaft so that the linear movement of the bell is proportional to the rotary encoder pulses. The relationship between the travel length of bell L and the reading of rotary encoder can be written as:

$$L = R*\theta = R*(k*N) \quad (3)$$

where R is the radius of the wheel with nominal value of 270mm; L is the length of bell travel; θ is the rotate angle of pulley wheel; k is the coefficient factor; N is the number of pulses (encoder counter).

A HP 5529A laser interferometer was used to calibrate the travel length of bell. The setup of the calibration is shown in Fig 2. The laser beam for measuring the bell travel distance is parallel to the vertical part of the chain. The mirror for the reflecting the beam sits on the centre of the bell top and moves with it.

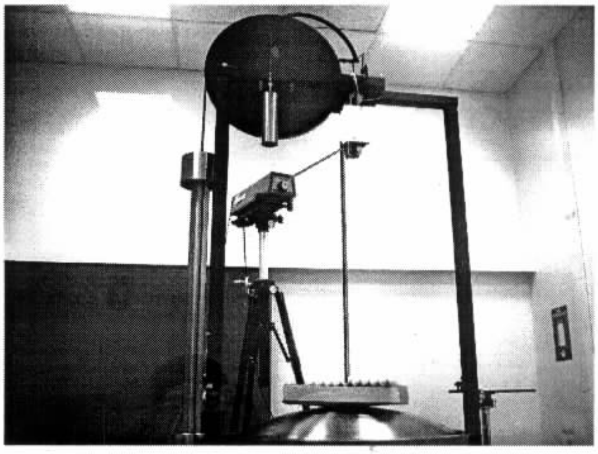

Fig.2 Setup for the calibration of the length measurement

The stress caused by the force releasing along the chain gave an error of about 0.67mm, when the bell rose in the first 100 pulses. The collection of gas therefore only starts from 100 pulses or thereafter. The error of encoder output value versus the actual bell travel distance in the range from 100 to 1100 pulses is limited within 0.15mm, as shown in Fig 3. The uncertainty of calibration using the HP laser interferometer and associated optical system was less than ±0.04mm at 95% level of confidence.

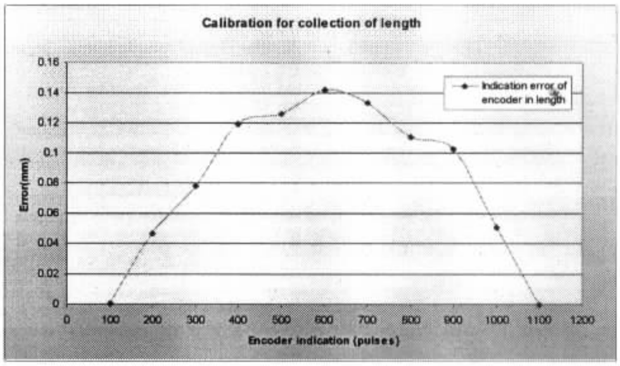

Fig.3 Error in length output from rotary encoder

The pulley wheel is made from stainless steel with 270mm in radius and thermal expansion rate of 19×10^{-6} per kelvin (K). The variation in the length measurement due to the radius of the pulley wheel changing with fluctuation of ambient temperature was estimated to be less than ±0.026mm.

The counterweights provided for buoyancy force correction swings when the bell rises up from the sealing liquid that leads to the vibration of bell during the collection interval. The maximum vibration of bell arising from the counter weight swing is shown in Fig 4. The deviation was limited to within ±0.03mm when the counterweight swung at maximum rocking wave.

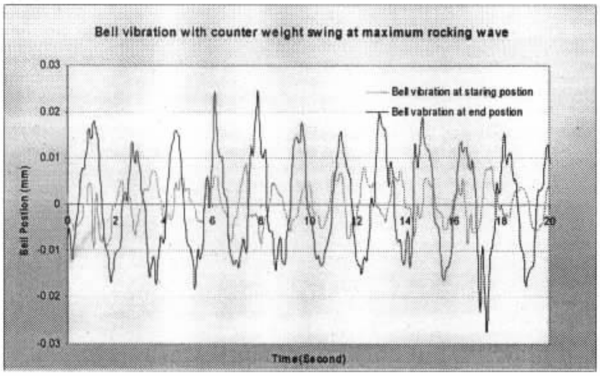

Fig.4 Bell vibration due to the counter weight swing

3.2. Bell rising speed v

The moving speed of bell is determined from: $v = L/t$ where L is the length of collection, t is the time interval between start and stop positions of collection. The collection time was measured by a time counter that was built into the computer of the bell prover. The measurement uncertainty of counter was ±0.005%.

The HP 5529A laser interferometer with the measurement uncertainty of ±0.02% in speed measurement was also employed to calibrate the rising speed of bell. The calibration was performed at the setting flow rates covering the entire measurement range. The maximum error which included the effect of time actuations for stroking at start and stop positions was 0.012%. The measurement uncertainty for the calibration of the bell moving speed was ±0.06% at 95% confidence level.

3.3. Average bell cross-sectional area

The bell is made of stainless steel with a thickness of 1.47mm. A Pi tape, with a measurement uncertainty of ± 0.13mm, was used to measure the outside diameter of the bell. The average diameter was obtained by using the Pi tape to measure the perimeters along the cylinder of the bell at every 25mm height. The maximum difference in the diameters over the entire length of the bell was less than 0.127mm. In addition to the non-uniformity in the diameters, the departure from the circularity of the bell also contributed to the measurement uncertainty of ±0.035% in the bell area. The bell thermal expansion coefficient was 17.5×10^{-6} per kelvin (K). which contributed a measurement uncertainty of ±0.013% under the laboratory conditions. The maximum positive pressure in the bell prover during a collection of gas is 50Pa that makes the bell enlarge in the cross-sectional areas. However, this is insignificant, taking into consideration that the elastic coefficient of bell is only 6×10^{-6} per bar. The combined standard uncertainty of the average cross-sectional area by combining uncertainties of the diameter, circularity, thermal expansion, Pi tape and the thickness of the bell, was ± 0.044%.

3.4. Change of oil level

The bell prover is designed to work in such a way when the bell rises up from the sealing liquid, the counterweight will sink into a small tank that is hydraulically connected to the annulus containing the sealing liquid. This design allows the sealing liquid to maintain at a constant level during the interval of gas collection. However the following reasons may lead to a change in liquid level.

3.4.1 Pressure changes

The pressure increased by not more than 3Pa during the course of gas collection at the highest flow rate of $100 m^3/h$ as shown in Fig.5. This is equivalent to a 0.25mm oil level drop at the inside annular, thereby increasing $12.3 cm^3$ in the collection volume.

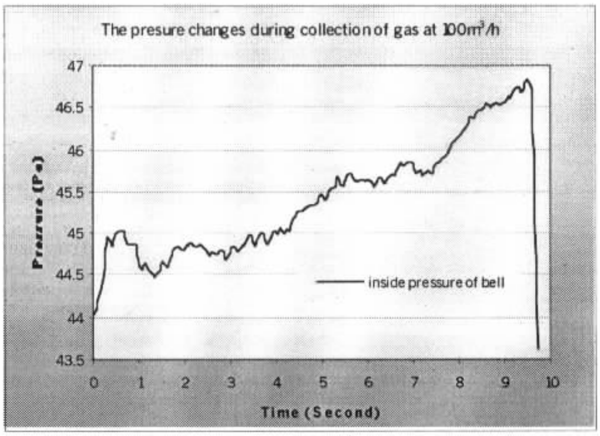

Fig.5 Pressure changes in the bell prover

3.4.2 Oil adherence

The sealing liquid (DIALA AX oil) adhering to the surfaces of the bell was estimated as 0.25kg on the basis of the experiment that was conducted under the laboratory condition. It occupied 0.042% of the collected volume of bell prover.

The sealing oil transfers between the inside and outside of the bell, with the bell rising due to the inconsistent oil film formed on its surfaces. The maximum transferred volume of oil was calculated from the total volume of oil film adhered at the surfaces of the bell. The relative error in collection volume arising from the oil transfer between the inside and outside of the bell was estimated to be less than 0.016%.

3.4.3 Oil adherence to counter weight

The oil, adhering to the surface of the counterweight, increases the oil level. With the counterweight moving down into the small oil tank, the total weight of oil adhered to the counterweight was estimated to be 6cm^3, equivalent to 0.002% of the total collected volume.

3.5 Storage of gas

2.5.1 Storage in the bell

The collection volume expands from the remaining volume which is the volume prior to the commencement of the gas collection. The maximum ratio between the collected volume and the remaining volume was 0.9. The change in pressure and temperature of the gas in the remaining volume during the interval of collection leads to an error in collection volume. The variation of pressure in the bell prover was less than 3Pa during the interval of gas collection at the highest flow rate. The temperature variation, during a cycle of collection, was less than 0.1K. The standard uncertainty arising from storage effect in the bell was estimated to be ±0.03%.

2.5.2 Storage in the piping

The approach piping connecting the meter under test and bell prover is a 3.5 meters long stainless steel tube which is 38mm in diameter, with two elbows. The pressures were measured at three taps located at central positions on the straight pipelines. The pressure at rest positions were estimated from the equation:

$$P = P_{referece} - \rho * f * (l * v^2 / 2D) \qquad (4)$$

where ρ is density of air, f is friction factor, l is the distance to the tap for pressure measurement, v is the average air velocity, D is the diameter of pipe. The pressures at different positions have been computed as a function of the Reynolds number based on the experiments. The computed errors of the pressures in the pipe for the different flow rates were less than 0.01%. The error arising from the pressure change in the pipeline during the interval of gas collection was found to be less than 30Pa, and hence was not significant.

2.6 Gas density

The air density was measured by pressure and temperature sensors. The calibrations of both sensors were carried out against reference standards with the calibration uncertainties of ±0.16mbar and ±0.03K respectively. The samples of pressure and temperature were collected upon the completion of gas collection. The gas used for calibration was sufficiently conditioned to be the same as the temperature of bell prover. The bell prover was put through several cycles prior to the commencement of calibration process, to attain a steady temperature. As a result, temperature changes during the interval of gas collection were kept within less than 0.1K. The PRT that was used to measure the temperature was also placed parallel to the direction of the gas flow so that the error caused by friction was kept minimal. Hence, the air density had an error of less than 0.02%. The standard uncertainty which included the temperature variation and pressure fluctuation in the bell was ±0.049%.

4. Checking the performance

The transfer standards comprising two tandem turbine flow meters with a 25.4mm connecting pipe was used to verify the performance of SPRING's bell prover. They were calibrated against the standards at NIST. Compressed dry air was used for the calibrations. The calibrations were carried out from 2330 cm^3/s to 31150 cm^3/s at NIST and from 2330 cm^3/s to 22263 cm^3/s at SPRING. The results were presented as meter factor versus a viscosity parameter - calculated using the equation: $\mathbf{K} = f / V$, where V is the actual volume flow rate at the meter under test and f is the frequency output by the meter. The viscosity parameter was derived from the expression: $N = f * \rho / \mu$ where ρ and μ are dry air density and viscosity. Both the air density and viscosity were measured by the pressure and temperature sensors located on each meter. The standard uncertainties of calibration were calculated from:

$$u_c = [(V^{-1} * u_f)^2 + (f * V^{-2} * u_V)^2 + u_R^{\,2}]^{1/2} \qquad (5)$$

where u_f is the standard uncertainty of frequency measurement, u_V is the uncertainty of actual volume flow rate of the turbine meters and u_R is the reproducibility of the turbine meters.

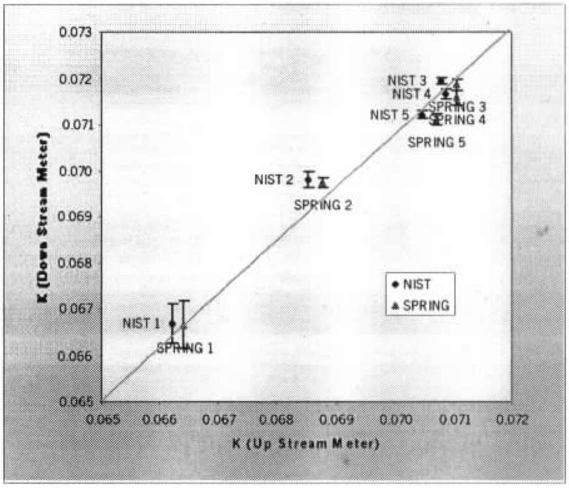

Fig.5 The Youden plot for results of verification

The transfer standards were installed upstream from the bell prover. Both meters were calibrated at SPRING on a set of flow rates and viscosities parameters (N) similar to that of NIST. The results are plotted as a Youden graph as shown in Fig.5. Each pair of meter factors (K) which has the same viscosity parameter (N) is projected onto the 45° line, and the difference of the projected value represents the bias from the results of NIST. The difference ranged from 0.10% to 0.18% of reading

Table 1 Summary of measurement uncertainty

Ref no:	Source of uncertainty	Quantity		Std Deviations *Si* Value	%
1	**Collection Volume**				
1.1	Error in collection length	mm/L		0.150	0.022%
1.2	Calibration of encoder	mm/L	±	0.020	0.006%
1.3	Radius of pulley wheel	mm/L	±	0.026	0.004%
1.4	The swing the counter balance	mm/L	±	0.030	0.004%
1.5	Bell area	M^2/A	±	1.99E-4	0.044%
1.6	Pressure change in bell	Pa/P		3	0.004%
1.7	Oil adherence at bell	g/M		250	0.042%
1.8	Oil transfer	g/M		50	0.017%
1.9	Oil adherence to counter weight	g/M		5	0.002%
1.20	Gas storage in the bell	M^3/V		-	0.030%
1.21	Gas storage in pipe	M^3/V		-	0.010%
				$u_{c(volume)}$	**0.073%**

2	**Collection Time**				
2.1	Timer	Hz/Time	±	5.0E-05	0.005%
2.2	Calibration of bell moving speed	mm/s /v	±	-	0.030%
2.3	Error in speed measurement	mm/s /v		1.11E-03	0.004%
				$u_{c(time)}$	**0.031%**
3	**Gas Density**				
3.1	Pressure sensor	Pa/P		16	0.010%
3.2	Temperature sensor	K/t		0.03	0.016%
3.3	Pressure distribution	ΔPa/P		22	0.022%
3.4	Temperature distribution	ΔK/t		0.1	0.034%
3.5	Density equation	$Kg/m^3/\rho$		0.02%	0.020%
				$u_{c(Density)}$	**0.049%**
	Combined Uncertainty			$\mathbf{u_c}$	0.087%
	Expanded Uncertainty			**U**	0.185%

4. Conclusion

A list of uncertainty components for the SPRING's bell prover is given in Table 1. The expanded measurement uncertainty was estimated to be less than 0.2% under the laboratory condition of SPRING. The comparison with the transfer standards, which were calibrated by NIST, showed agreement to within 0.19%.

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