Inter-Comparability Tests of Gas Flow Measurement Standards

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Abstract

This paper describes the proficiency evaluation of the low-pressure air-flow national standards at Center for Measurement Standards (CMS). Three sets of gas flow standard facility, namely, a Brooks five-tube piston prover, a 60liter small bell prover and a 600liter large bell prover, were verified and quantified of those uncertainty sources based on the ISO Guide to the Expression of Uncertainty in Measurement (GUM). The expanded uncertainties for mass flow rate measurement are 0.1%, 0.19%, and 0.14%, for piston, small bell and large bell, respectively.

In order to validate the claimed uncertainties and to check the measurement consistency among these standards during calibration services, three different sizes of Laminar Flow Elements (LFE) and two Critical Flow Venturies (CFV) were taken as transfer standards for comparison tests. The En value, namely the difference of measurement errors of unit under test (UUT) from two standard systems against the root-sum-squares of systems and individual UUT measurement uncertainties, is taken as check parameter. Test results show that all En values lie within 0.63, indicating the measurement consistency among various flow standards.

Furthermore, an inter-comparison test using two LFE was conducted between CMS and National Measurement Center/SPRING of Singapore. Within the test flow rate of 0.2liter/min to 24liter/min, the overall measurement difference is within 0.2% and the En value lie within 0.8, showing the measurement comparability between the two National Measurement Institutes.

1. Introduction

Low-pressure gas flow measurement is commonly observed in semi-conductor manufacturing processes, medical drug delivery, chemical analysis and environmental residues detection. Among the various industrial applications, flow meters based on thermal mass, laminar flow, critical flow principles and turbine elements have been utilized as measurement tools. Furthermore, recent development in MEMS technology has prompted the design and manufacture of fluidic devices for sub-micro liter fluid flow measurement. Numerous research efforts have also been carries out for precise fluid flow measurement, utilizing thermal, pressure difference, or force sensing techniques [1]. The trend has prompted the need for higher measurement accuracy in lower flow rate applications.

The work of Nakao[2] compared gas composition effect of small-sized CFVs with the G-H theoretical model with more than ten different gases at Reynolds number (Re#) down to 200. A comparison test with LFE in low flow application by Lin and Choi[3] showed the second order dependency of CFV discharge coefficient for Re# below 1000. The implementation of toroidal throat venturi nozzle as transfer standard was reported by Delajoud et al[4] and, the practical implementation of CFV and LFE for BIPM comparison activity was assessed in details by Wright[5]. It is now common practice that a flow standard is continuously scrutinized in a more stringent fashion to meet industrial development.

For such purpose, intra-comparison or inter-comparison tests are usually adopted to find out and remove systematic measurement difference, and to validate uncertainty evaluation of a measurement system. Through these activities, consistency among NMI's measurement standards can be guaranteed or differences are further harmonized [6]. In the end, technical barrier for trade (TBT) can be reduced.

According to Wright [5], CFVs are generally used for higher flows, while LFEs are generally preferred for small flows. Between a flow range of 0.04L/min to 30L/min, both meter types have been used successfully, but with a typical break point of 1L/min. Thus, three LFEs were chosen for comparison among 5 measurement tubes of the same piston prover from 0.05L/min to 6L/min. A CFV is used for crossing-over from tube 5 to small bell for flow range of 6.8~17L/min and a second CFV for crossing-over from small bell to large bell for flow range of 22-75L/min. The same LFEs were used for inter-comparison tests between CMS and NMC/SPRING for flow range of 0.2~24L/min. And finally, following the work of Nakao, both meter types were tested at N2, dry air, He, and Ar.

2. Measurement System Evaluation

2.1 Piston Prover, Bell provers

The piston prover at CMS is PVTt based system consisting of five high-precision made glass tubes as standard volume. A mercury-sealed piston is equipped for volume traverse and triggering of time device. For each glass tube, a cube corner is placed on top of the piston as a movable reflector for the laser interferometer system located at the top of the prover. The distance traversed by the piston and the volume determined by triggering of two optical switches are measured and synchronized with the counter of the interferometer system. Based on the measured distance, collection time, averaged temperature and pressure at both the standard and UUT, and the pre-measured glass tube diameter, the standard mass flow rate, or the volume flow rate after conversion, can be determined based on equation (1).

$$
\begin{aligned}
& q_{\mathrm{m},s} \\
& \equiv \rho_s \times V_C / t + \Delta\rho_{CV} \times V_{CV} / t + \rho_s \times q_{V,l} \\
& = \pi \times \rho_s \times D_S{}^2 \times L_S / (4t) + \Delta\rho_{CV} \times V_{CV} / t + \rho_s \times q_{V,l} \\
& = f(D_s, L_s, \rho_s, t, \Delta\rho_{CV}, V_{CV}, q_{V,l})
\end{aligned} \tag{1}
$$

In equation (1), V_C is collection volume between two optical switches, D_s is the averaged diameter of the glass tube; L_s represents traversed distance, t as the collection time; and V_{CV} is the control volume between the UUT and the standard system. Furthermore, ρ_s represents the density, and $\Delta\rho_{CV}$ is the density change inside the control volume during calibration. Finally, $q_{V,l}$ is the estimated leakage rate.

The working flow range of the prover is 0.04L/min ~ 24L/min, with standard conditions set at 296.15Kelvin and 101.325kPa. According to the ISO GUM, every uncertainty sources pertinent to the above influencing factors is calculated. The relative standard uncertainty for each measuring tube is provided in Table 1. The porver system is designated with an expanded uncertainty of 0.1%.

For NMC/SPRING, the piston prover consists of three measuring glass tube and the traversed distance is measured with ultrasonic transducers located on top of the prover. The working range is similar to that of CMS with standard temperature condition set at 273.15Kelvin. Both standard systems are shown at Fig. 1 with the LFE transfer standard.

For the two sets of Bell provers, the working principle is also PVTt based and the equation for mass flow calculation, as well as uncertainty sources are similar to those of the piston prover. However, particular difference lies in measurement of exterior diameter of the bell and oil residue on the surface of the bell is estimated. The expanded uncertainties, following ISO GUM, are estimated to be 0.19% for small bell and 0.17% for large bell, respectively; and uncertainty budget is listed in Table 2.

Table 1. Uncertainty evaluation of piston prover

	Piston1	Piston 2	Piston 3	Piston 4	Piston 5
$2u(D_s)/D_s$ (traceability, T control)	0.012%	0.010 %	0.008 %	0.006 %	0.006 %
$u(L_s)/L_s$	0.0004%	0.0002%	0.0002%	0.0002%	0.0001%
$u(\rho_s)/\rho_s$	0.04%	0.04%	0.04%	0.04%	0.04%
$u(T_s)/T_s$	0.034%	0.034%	0.034%	0.034%	0.034%
$u(P_s)/P_s$	0.015%	0.015%	0.015%	0.015%	0.015%
$u(Z(P_s,T_s))/Z(P_s,T_s)$	0.015%	0.015%	0.015%	0.015%	0.015%
$u(t)/t$ (traceability, time trigger)	0.01%	0.01%	0.01%	0.01%	0.01%
$V_{CV} \times u(\Delta\rho_{CV})/(V_C \times \rho_s)$	0.014%	0.004%	0.017%	0.005%	0.005%
$\Delta\rho_{CV} \times u(V_{CV})/(V_C \times \rho_s)$	0.006%	0.003%	0.003%	0.002%	0.002%
$t \times u(q_{V,l})/V_C$	0.012%	0.012%	0.012%	0.012%	0.012%
$u_C(q_{m,s})/q_{m,s}$	0.05%	0.05%	0.05%	0.05%	0.05%

Table2. Uncertainty evaluation of two bell provers

	Small Bell Prover	Large Bell Prover
$u(V_C)/V_C$	0.031 %	0.018 %
$2u(D_s)/D_s$	0.030%	0.016%
$u(L_s)/L_s$	0.007%	0.007%
$u(\rho_s)/\rho_s$	0.030%	0.030%
$u(T_s)/T_s$	0.024%	0.024%
$u(P_s)/P_s$	0.007%	0.007%
$u(Z(P_s,T_s))/Z(P_s,T_s)$	0.015%	0.015%
$u(t)/t$	0.004%	0.004%
$V_{CV} \times u(\Delta\rho_{CV})/(V_C \times \rho_s)$	0.028%	0.024%
$u(\Delta V_{CV})/V_C$	0.067%	0.043%
$\Delta V_{CV} \times u(\rho_{CV})/(V_C \times \rho_s)$	0.001%	0.001%
$\Delta\rho_{CV} \times u(V_{CV})/(V_C \times \rho_s)$	0.000%	0.000%
$(\rho_s \times u(q_{V,l}) + q_{V,l} \times u(\rho_s))/(q_{m,s})$	0.038%	0.019%
$u_C(q_{m,s})/q_{m,s}$	0.10%	0.07%

2.2 Transfer standards

Both the LFEs and CFVs were commercial available standard equipments. The former utilizes thermodynamics principle together with temperature and differential pressure measurements, as laminar fluid flow passes through a conical passage. The later is basically a toroidal shape convergent-divergent nozzle with flow speed reaching sonic condition at the narrowest throat section. Both meter types meet the criteria of robustness, well developed flow model and calibration stability.

For LFE the equation for mass flow is given as

$$q_m = \frac{P \times (P_1 - P_2) \times \rho_N \times T_N \times Z_N}{T \times Z_{(P,T)} \times \eta_{(P,T)} \times P_N} \times C_G \qquad (2)$$

Where

q_m =Mass flow [kg/s]
P_1 =Upstream absolute pressure [Pa]
P_2 =Downstream absolute pressure [Pa]
$P = \frac{(P_1 + P_2)}{2}$ [Pa]
T =Absolute temperature of gas [K]
T_N =Standard temperature, 273.15K
ρ_N =Standard gas density [kg/m^3]
$\eta_{(T,P)}$ =Dynamic gas viscosity under P,T conditions [Pa•s]
P_N =Standard pressure, 101325Pa [Pa]
Z_N =Gas compressibility factor under standard conditions [-]
$Z_{(P,T)}$ =Gas compressibility factor under P,T conditions [-]
C_G =Experimentally determined geometrical constant [m^3]

For CFV the equation for mass flow is given as

$$q_m = \frac{A \times C_d \times C^* \times P_0}{\sqrt{(R / M \times T_0}} \qquad (3)$$

Where

q_m =Mass flow [kg/s]
C_d =Discharge coefficient [-]
C^* =Critical flow function [-]

P_0 =Stagnation pressure [Pa]
R =Ideal gas constant [j/kg/K/mole]
M =Molecular mass [kg/mole]
T_0 =Stagnation temperature [K]

When using LFE as transfer standard, relative instrument error was used for comparison, while discharged coefficient *Cd* was used for CFV. Definitions are given in equation (4) and (5).

$$\text{Error} = (q_{\text{m,LFE}} - q_{\text{m,s}}) / q_{\text{m,s}} \quad (4)$$

$$C_{\text{d}} = q_{\text{m,s}} / q_{\text{m,th}} = q_{\text{m,s}} \Big/ (A^* C^* P_0 \Big/ \sqrt{R T_0 / M}) \quad (5)$$

In equation (4) and (5), $q_{\text{m,s}}$ is the standard mass flow rate, $q_{\text{m,LFE}}$ is the LFE mass flow rate. A^* *is the nozzle throat area*, C^* *is the* Critical Flow Function, P_0 *nozzle upstream* Stagnation Pressure, T_0 *nozzle upstream* Stagnation Temperature, R *universal gas constant*, and M *gas molecular weight*。

For the same transfer standard tested at two different standard facilities, #1and #2, and with the calibration parameters defined as MF(#1) and MF(#2), one can determine a non-dimensional E_n value as given in equation (6). Within it, $u(\#1)$, $u(\#2)$ represent the relative standard uncertainty of the standard facilities, while $u(TS)$ belongs to that of the transfer standard。

$$E_n = \frac{|MF(\#1) - MF(\#2)|}{\sqrt{u^2(\#1) + u^2(\#2) + u^2(TS)}} \quad (7)$$

One can justify whether there is significant deviation between two standard systems with the magnitude of the E_n value. For 67% confidence level, E_n value should be less than one, while it should be less than 2 for 95% confidence level。When E_n valued exceeds that pre-defined limit, potential error persists in the uncertainty estimation of the standard system.

3. Results and Discussion

3.1 Intra-Comparison

Laminar flow element (LFE) flow meters were used as transfer standards to compare among five standard flow volumes. Four pairs of comparisons, from small to large flow tubes, corresponding to various flow rates were arranged. A laser interferometer system for measuring the traversing distance of each piston and common temperature and pressure sensors were used during test measurements. By using equation (4), errors of measurement for LFE versus individual flow rates are shown from Fig 2a~2d, for four different parings. As depicted, differences for each pair are within| 0.05%| .

Data calculation shows LFE has repeatability of $u(TS)$ =0.02%. By root-mean-squared combination of $u(TS)$ with system uncertainty of each tube, described in previous section, ($u(\#1)$=0.05%,$u(\#2)$=0.05%), one achieves $\sqrt{u^2(\#1)+u^2(\#2)+u^2(TS)}$ =0.08%. Subsequently, equation (7) is used to render a non-dimensional equivalence E_n value. For four pairs of comparison on the piston prover, *En* values are less than 0.63, far less than the value of two. This indicates no significant measurement differences among five measuring volumes. A brief summary is shown in upper part of Table 3.

Table 3. Summary of intra-comparison results

Facility #1	u(#1) (%)	Facility #2	u(#2) (%)	Flow (dm^3/min)	Transfer Standard	$\sqrt{u^2(\#1)+u^2(\#2)+u^2(TS)}$ (%)	Z (#1) -Z (#2) (%)	E_n
PP Tube 1	0.05	PP Tube 2	0.05	0.05-0.1	LFE	0.08	-0.02 ~ 0.03	0.25~0.38
PP Tube 2	0.05	PP Tube 3	0.05	0.1-0.25	LFE	0.08	0.00 ~ 0.05	0.00~0.63
PP Tube 3	0.05	PP Tube 4	0.05	0.1-1.5	LFE	0.08	-0.05 ~ -0.03	0.38~0.63
PP Tube 4	0.05	PP Tube 5	0.05	0.5-6.0	LFE	0.08	-0.04 ~ 0.00	0.00~0.50
PP Tube 5	0.05	SBP	0.10	6.8-17.4	CFV	0.12	0.02 ~ 0.07	0.16~0.59
SBP	0.10	LBP	0.07	22-75	CFV	0.13	-0.04 ~ -0.03	0.23~0.31

PP: Piston Prover

SBL: Small Bell Prover

LBP: Large Bell Prover

For the comparison between Tube 5 and small bell prover, a miniature-sized sonic venturi nozzle has been used. Measurement errors versus flow rates are depicted in Fig. 2e, with difference in two error measurements among 0.02%~0.07%. Repeatability of nozzle is calculated to be $u(TS)$=0.03%. By similar calculations, En value is less than 0.59, indicating no significant measurement error between the piston prover and small bell prover. For the comparison between small and large bell prover, the En value is less than 0.31, as given in Table 3 and measurement errors shown in Fig. 2f. The intra-comparison activities have shown the measurement consistency among three different types of volumetric flow measurement standards.

3.2 Inter-comparison

Results of the inter-comparison using two LFEs between CMS-Taiwan and SPRING-Singapore are listed in table 4, where averaged Meter factors from two sets of data were used to render En value. The claimed uncertainties are 0.1% for CMS and 0.25% for NMC/SPRING. For flow rate below 1L/min, small LFE was used for comparison. The En values for small LFE are quite consistence between the two laboratories, while the En value at 24L/min is bigger than the rest. Possible reasons may be the setting of first triggering position or traceability of secondary instruments. Overall, the difference is within 0.2% for all data and En value well within the limit of 2 under 95% confidence level.

Table 4. Results of inter-comparison

Flow (NL/min)	MF(Lab1#1)	MF(Lab1#2)	MF(Lab2)	U(Lab1)	U(Lab2)	$U(TS)$	E_n
24	0.99669	0.99635	0.99880	0.1%	0.25	0.00072	0.82
18	0.99745	0.99702	0.99876	0.1%	0.25	0.00068	0.51
12	0.99748	0.99715	0.99839	0.1%	0.25	0.00065	0.36
6	0.99696	0.99661	0.99806	0.1%	0.25	0.00072	0.43
1	1.00055	1.00050	1.00226	0.1%	0.25	0.00054	0.63
0.5	1.00071	1.00071	1.00255	0.1%	0.25	0.0078	0.65
0.2	1.00055	1.00052	1.00229	0.1%	0.25	0.00113	0.60

4. Conclusion

Both intra- and inter-comparison tests were conducted during years 2004-2005. Laminar flow element and sonic venturi nozzles were utilized as transfer standards. Flow systems from both NMIs include a five-tubes piston prover, two bell systems with 60 and 600liters measuring volumes and a three tubes piston prover. The En value is used as a comparison parameter. It is shown from system evaluation and comparison test results, no significant measurement difference among CMS flow systems, nor with flow system at Spring-Singapore. For long term measurement consistency, more data collection and participate is regional activities, such as APMP KC is recommended.

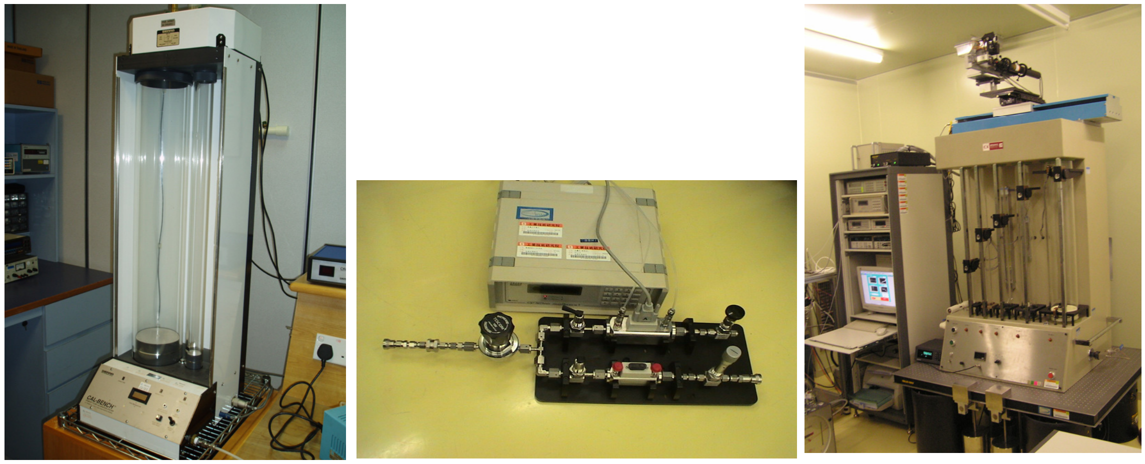

Figure 1. Flow systems for inter-comparison and LFE transfer standards.

5. References

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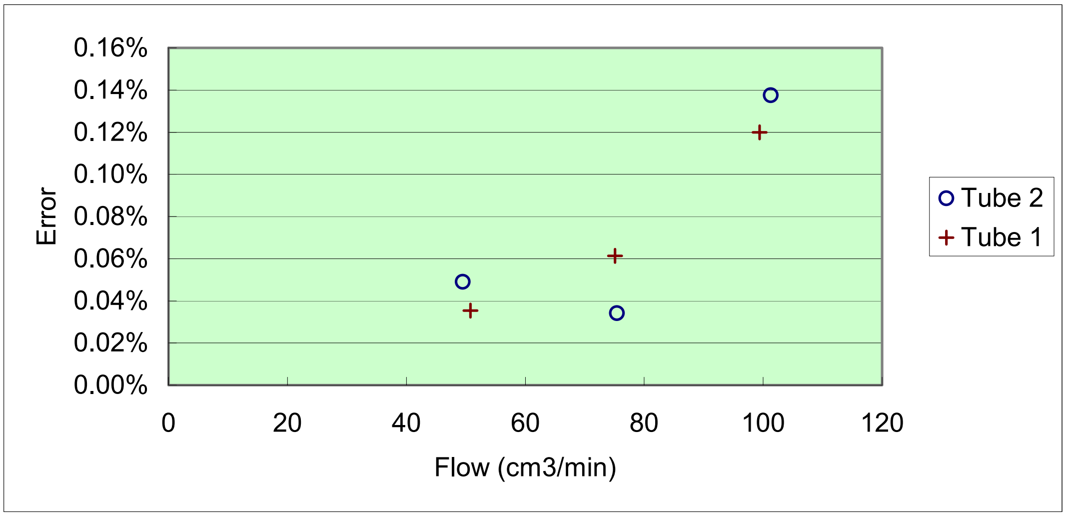

Figure 2a. Piston prover tube 1 vs tube 2.

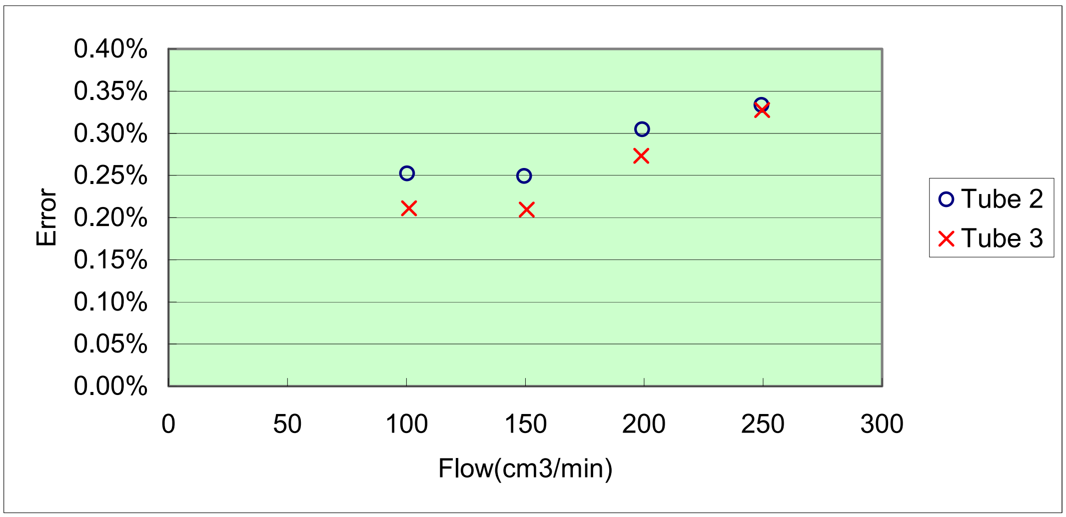

Figure 2b. Piston prover tube 2 vs tube 3

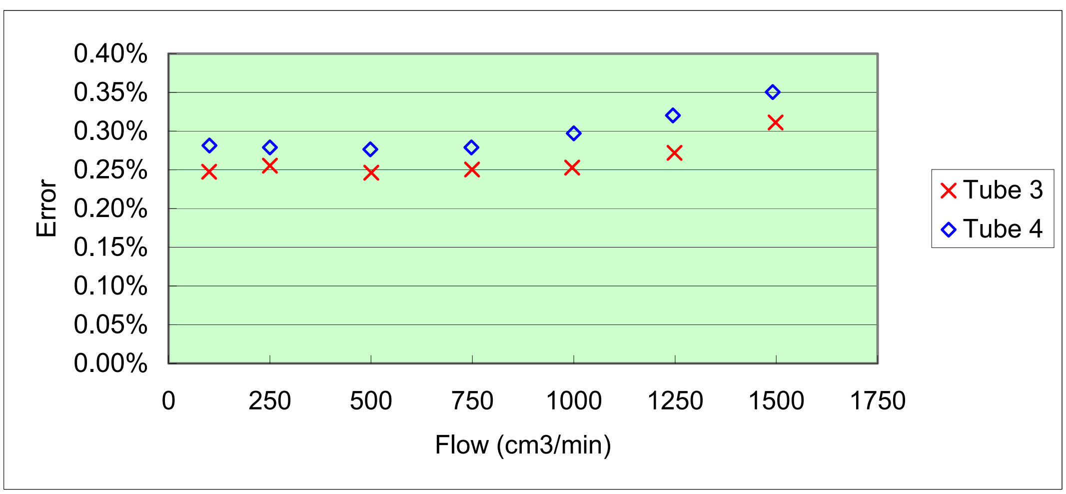

Figure 2c. Piston prover tube 3 vs tube 4

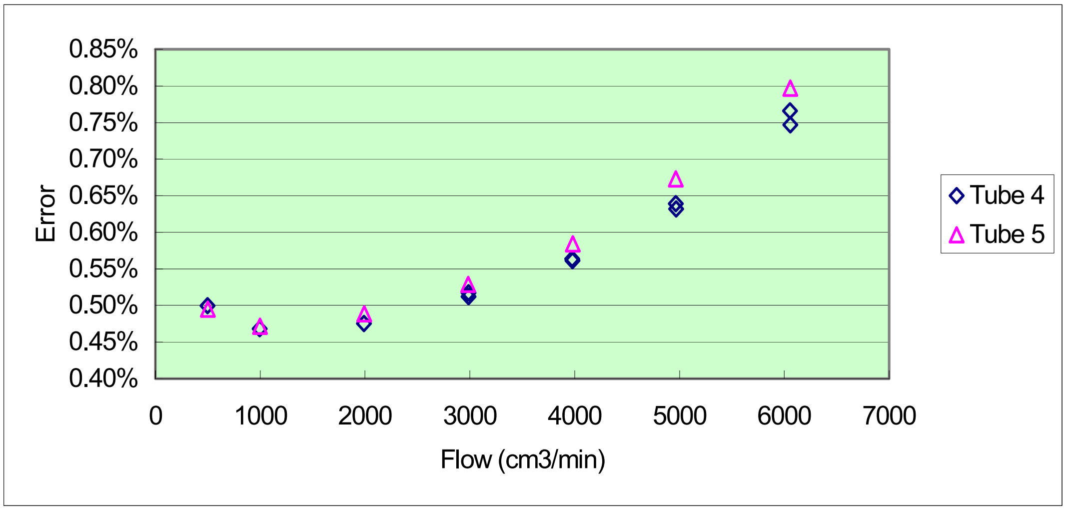

Figure 2d. Piston prover tube 4 vs tube 5

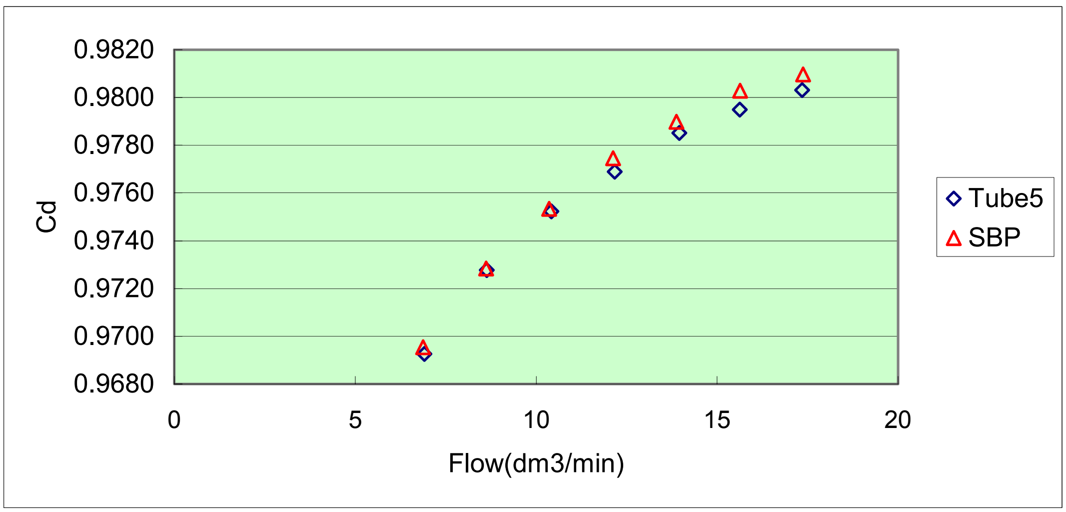

Figure 2e. Piston prover tube 5 vs small bell prover

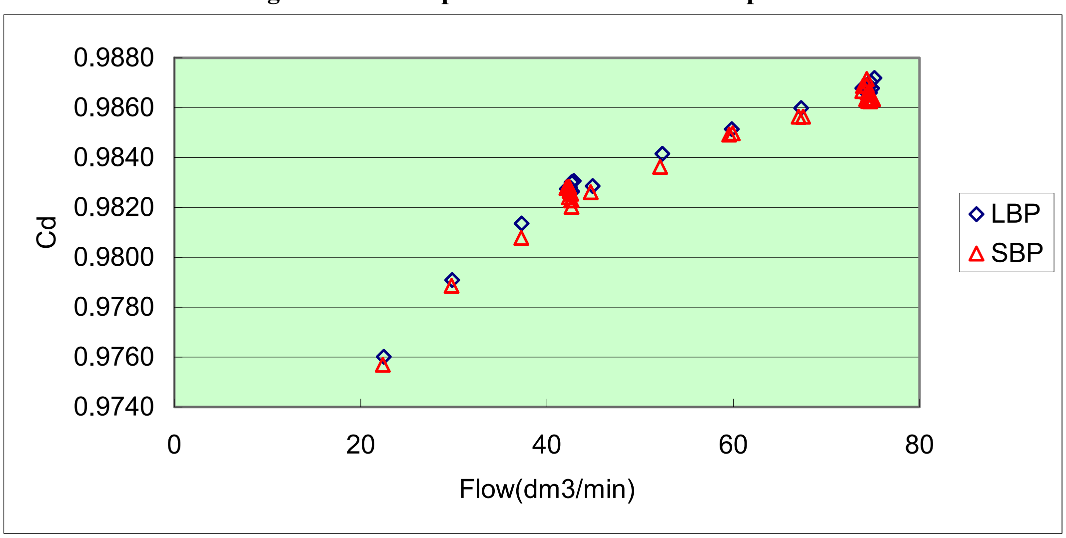

Figure 2f. Small bell prover vs large bell prover