Establishment of a force balanced piston gauge for very low gauge and absolute pressure measurements at NPL, India

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Introduction

- The force-balanced piston gauge is a primary vacuum standard developed by Ooiwa A [1] during 1990s.
- This new non-rotating force-balanced piston gauge is based upon a mass comparator that determines the force applied to a nominal effective area of 980 mm^2.
- The major difference from traditional rotating piston gauges is that the FPG measures the force generated from a given gas pressure against a force balanced load cell to which the piston is attached.

[1] Ooiwa A 1994 *Metrologia* 30 607-610

Introduction

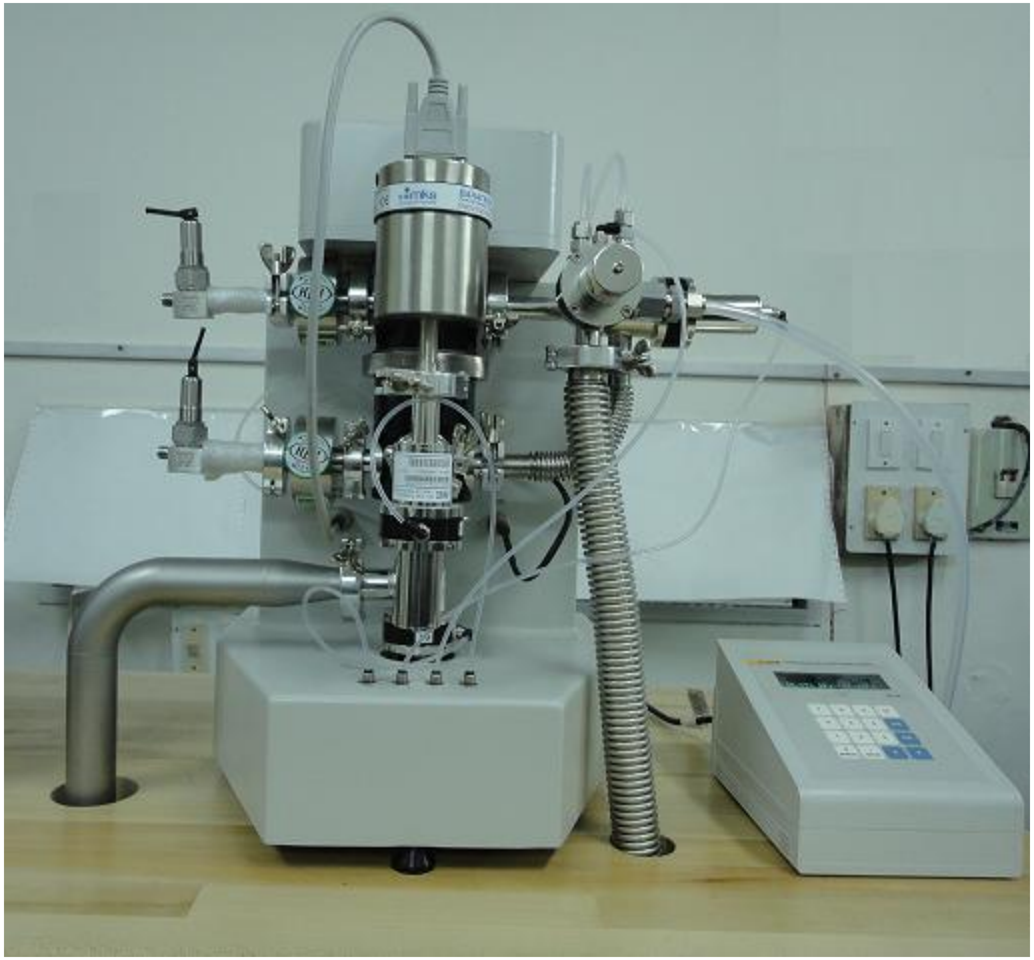
- The non-rotating piston is connected to an electronic dynamometer and centered by means of transient gas flow in the tapered gap between piston and cylinder. The load cell is zeroed with high and low pressure chambers connected.
- Pressure of gas in the upper chamber is adjusted by an automated very low pressure controller (VLPC) that is equipped with two parallel mass flow controllers for coarse and fine adjustment and a PC, which calculates and keeps generated pressure on a chosen value.

Reference Standard - UIM

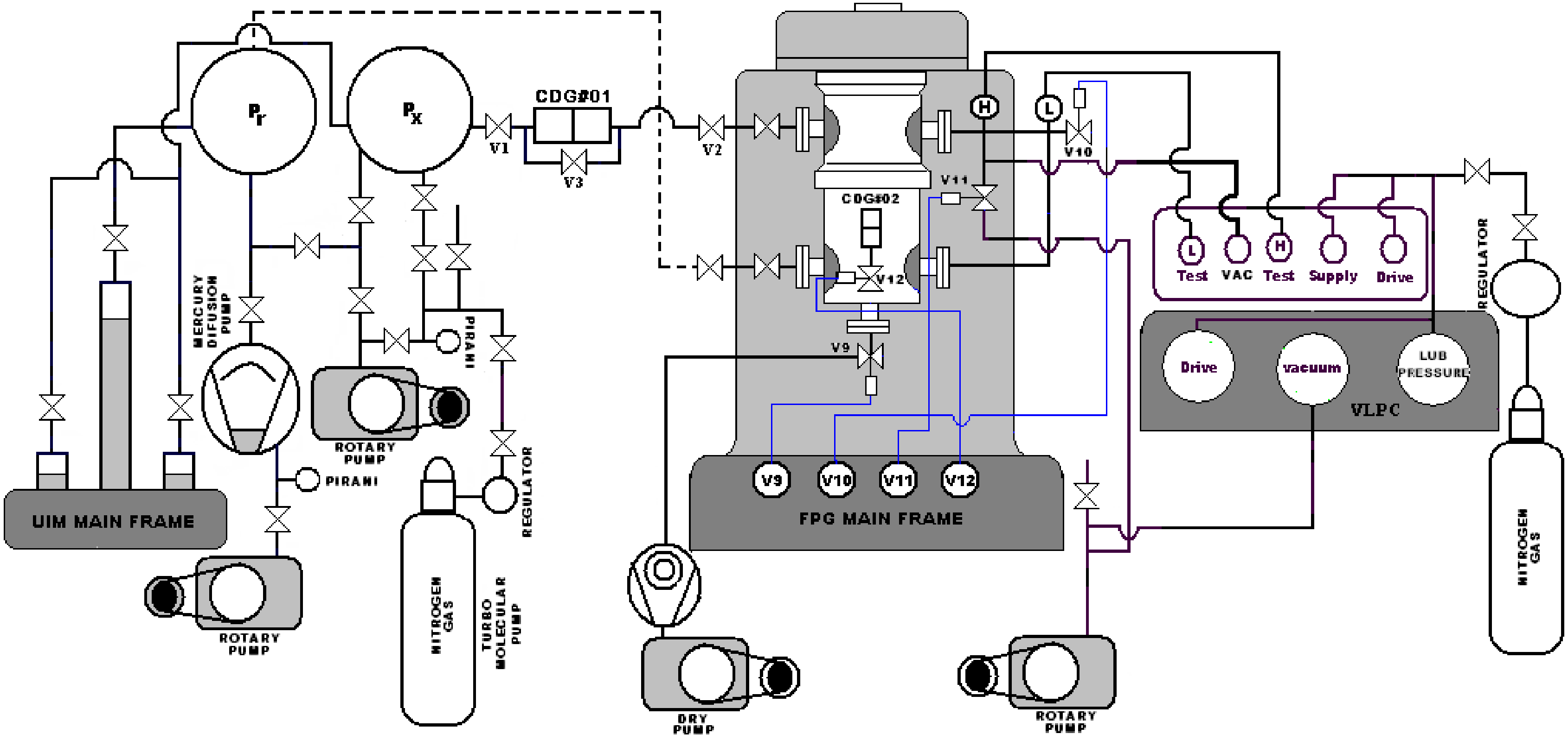
Reference Standard - APG

Force Balanced Piston Gauge

Force Balanced Piston Gauge



Experimental Setup



Experimental Setup

The setup shown in figure 1 is used for our pressure measurements, except for the dashed line used only for gauge mode measurements. The valves V_9 to V_{12} that are associated with the FPG are pneumatically operated for which a continuous supply of 7.0 bar dry air is required; so a separate pneumatic supply is arranged for the same. Since the UIM at NPL, India is a mercury Manometer, a 1.0 torr differential CDG is used as an isolator cum null indicator (CDG#01) to avoid mercury contamination at FPG Piston Chambers as discussed by Hendricks et al [2]. Other added advantages of this isolation CDG is that it keeps away the necessity of thermal transpiration correction arising due to difference in temperatures of UIM and FPG if directly connected and prevented the FPG's VLPC from setting large pressure changes in large volumes of UIM manifold

[2] Jay H Hendricks and Douglas A Olson 2009 *Measurement* 43 664-674

Theory of FPG

$$p_{FPG} = \frac{K_{cal}\left(N + \delta N_1 + \delta N_2 + \delta N_3\right)}{A_{0_{20^o C}}\left[1 + \left(\alpha_P + \alpha_C\right)\left(t - 20\right)\right]} + p_r + p_{head}$$

$$K_{Cal} = \frac{m_{Cal}\left(1 - \frac{\rho_{lcal}}{\rho_{mcal}}\right) g}{N_{Cal}}$$

Where δN_1, $\delta N_2$and δN_3 are the force correction terms in counts, p_r is the reference pressure at the lower chamber (equal to zero when used in gauge mode), p_{head} is the pressure head, k_{cal} is the calibration coefficient and N is the load cell reading in counts. The papers by P Delajoud and M Girard [3, 4] may be referred for detailed discussion.

[3] Delajoud P, Girard M 2002 NCSLI Conference, San Diego
[4] Delajoud P and Girard M 2003 *Vakuum in Forschung und Praxis* 15 24–29

Modes of Measurement

Absolute Mode

The UIM and FPG systems are initialized for absolute mode measurements through their Operating software. After the whole system attained stabilization with a few cycles of purging, FPG is recalibrated and zeroed. Subsequently the CDG#01 is also zeroed with V_2, V_3 open and V_1 closed. In absolute mode the outlet valve of the low pressure chamber of piston cylinder assembly is kept permanently closed and the pneumatic valve (V_{12}) is automatically opened to engage CDG#02 so that the reference pressure at the low pressure chamber could be read and accounted for. With V_3 closed and V_1, V_2 open condition, both UIM and FPG (VLPC enabled) are pressurized to a selected nominal pressure. After establishing the pressure in the UIM and FPG, the measurement system was allowed to stabilize, nominally for 5 to 10 minutes. After stabilization, a set of 8 to 10 pressure readings were recorded for FPG ( ), UIM ( ) and CDG#01 ( ), apart from noting down the drift in FPG zero pressure reading ( ).

Modes of Measurement

Gauge Mode

The UIM system is prepared for gauge mode pressure measurements with V_1 valve in closed condition. The FPG system is initialized for gauge mode measurements through the Operating software (FPG Tools). After the whole system attained stabilization, FPG is recalibrated and zeroed. Subsequently the CDG#01 is also zeroed with V_2, V_3 open and V_1 closed. In gauge mode the outlet valve of the low pressure chamber of piston cylinder assembly is to be kept open to the atmosphere and the pneumatic valve (V_{12}) is automatically closed by FPG Tools to protect CDG#02 from overpressure.

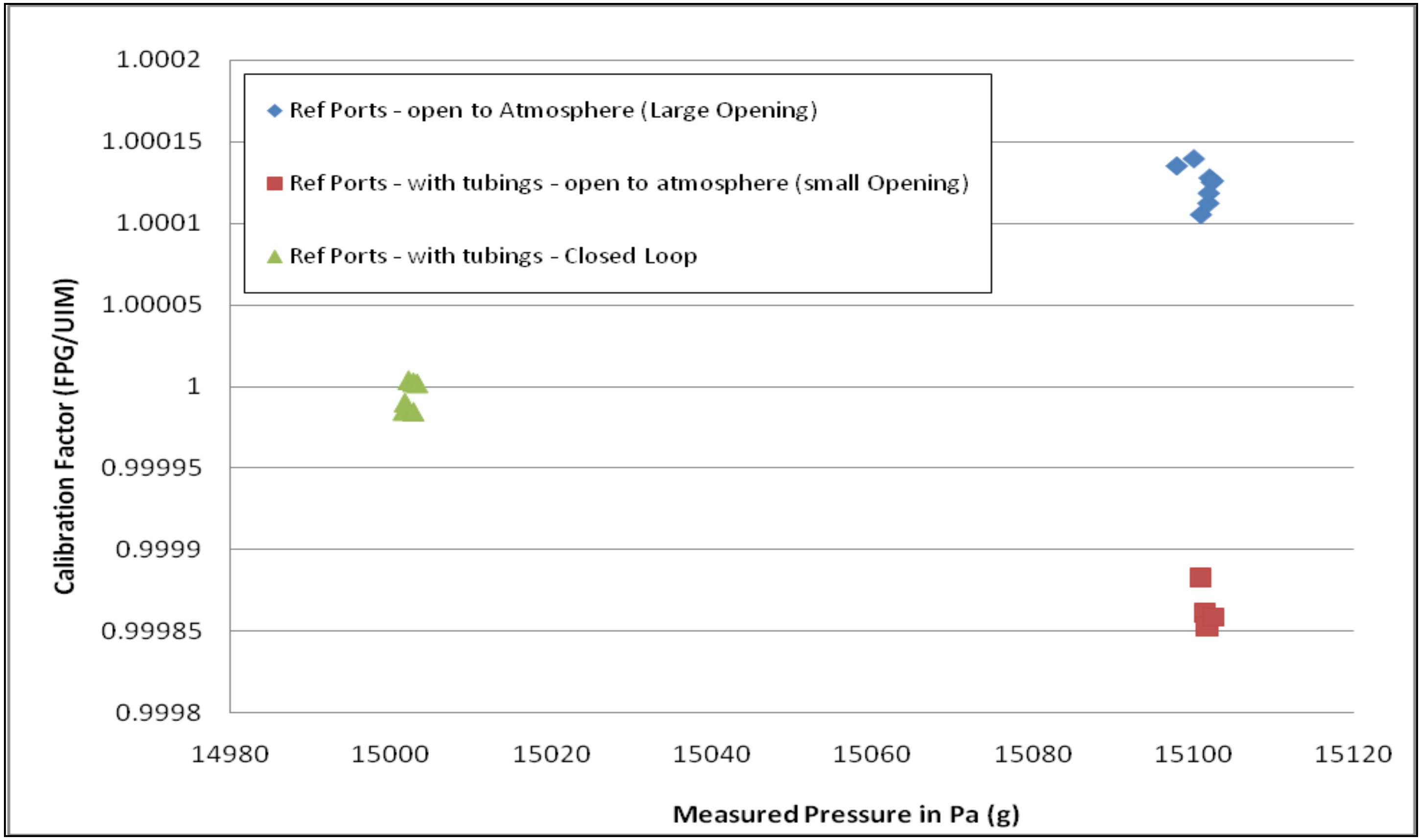
Modes of Measurement

Gauge Mode

Here it would be worthwhile to discuss that in gauge mode, the variations in the ambient conditions affected the readings differently, especially while keeping the ref ports of both UIM and FPG open to the atmosphere through large openings (the opening at UIM reference port is larger than FPG reference port), through small openings using equal length of 6.0 mm dia. tubes and in close loop. Such experimentally observed variations are depicted in figure 2. It is clearly seen that the data collected with closed loop condition are very much comparable. So the data for gauge mode pressure measurement are collected in closed loop condition

Modes of Measurement

Gauge Mode



Methods of Measurement

From the data collected, as discussed by Jay Hendricks et al [5] the corrected FPG pressure reading is arrived at as

$$p_{FPG\,c} = p_{FPG} - p_{ZC}$$

The corrected UIM pressure reading in absolute mode is given by

$$p_{UIM\,c} = p_{UIM} + p_{vp_{Hg}} - p_{CDG\#01}$$

Where is the vapour pressure of mercury. The difference between the corrected readings of FPG and UIM in absolute mode are given by

$$\left\langle p_{FPG\,c} - p_{UIM\,c} \right\rangle = \left(p_{FPG} - p_{ZC}\right) - \left(p_{UIM} + p_{vp_{Hg}} - p_{CDG\#01}\right)$$

[5] **Jay H Hendricks and Douglas A Olson 2009 *Measurement* 43 664-674**

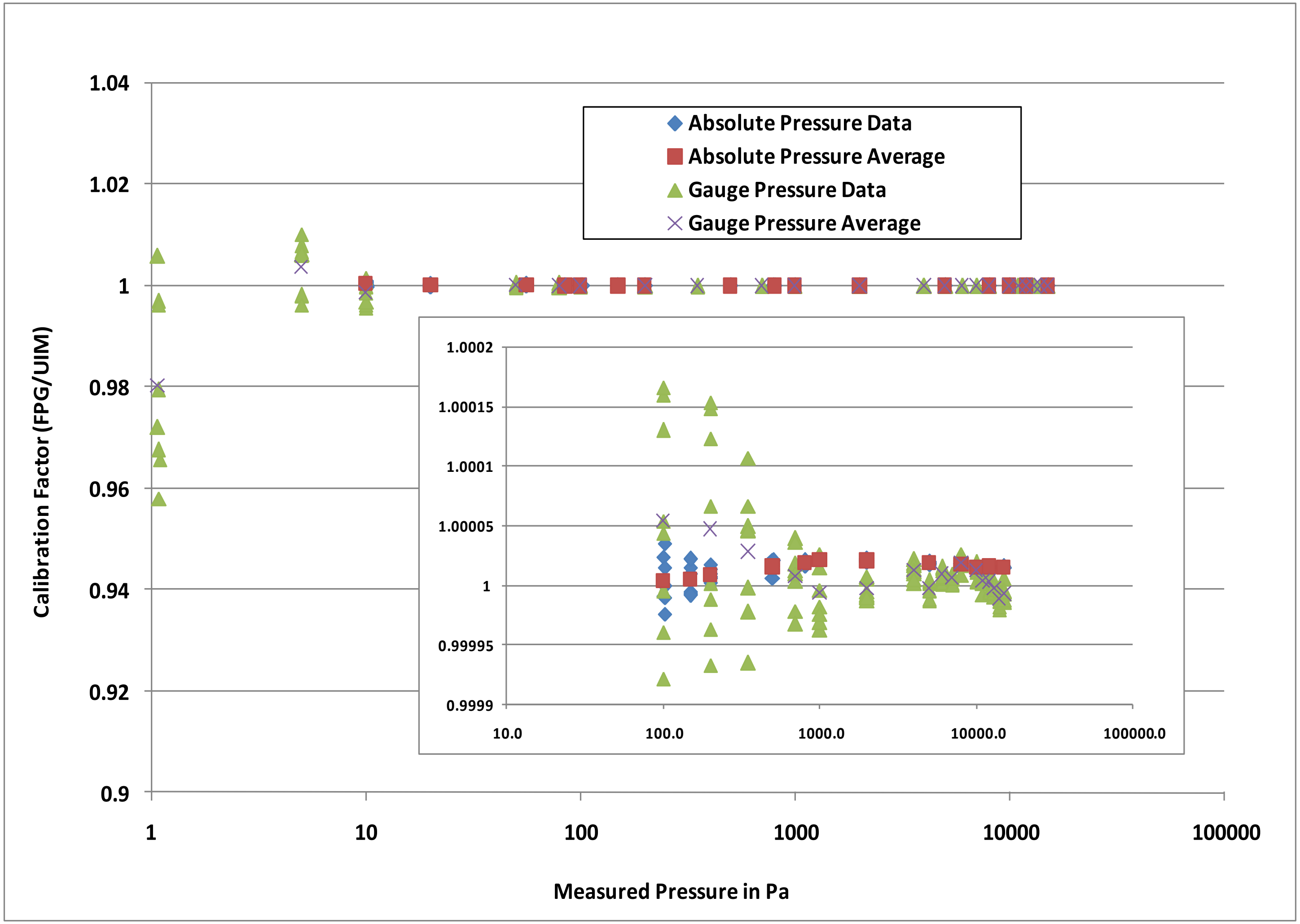
Methods of Measurement

The difference between the corrected reading of FPG and UIM, in gauge mode measurement is given by

$$\left\langle p_{FPG_c} - p_{UIM_c} \right\rangle = \left(p_{FPG} - p_{ZC}\right) - \left(p_{UIM} - p_{CDG\#01}\right)$$

Obviously there is no need to correct for mercury vapour pressure in gauge mode measurements. The plot between measured pressure vs calibration factor ( ) of all data collected in both absolute and gauge mode is depicted in figure 3.

Methods of Measurement

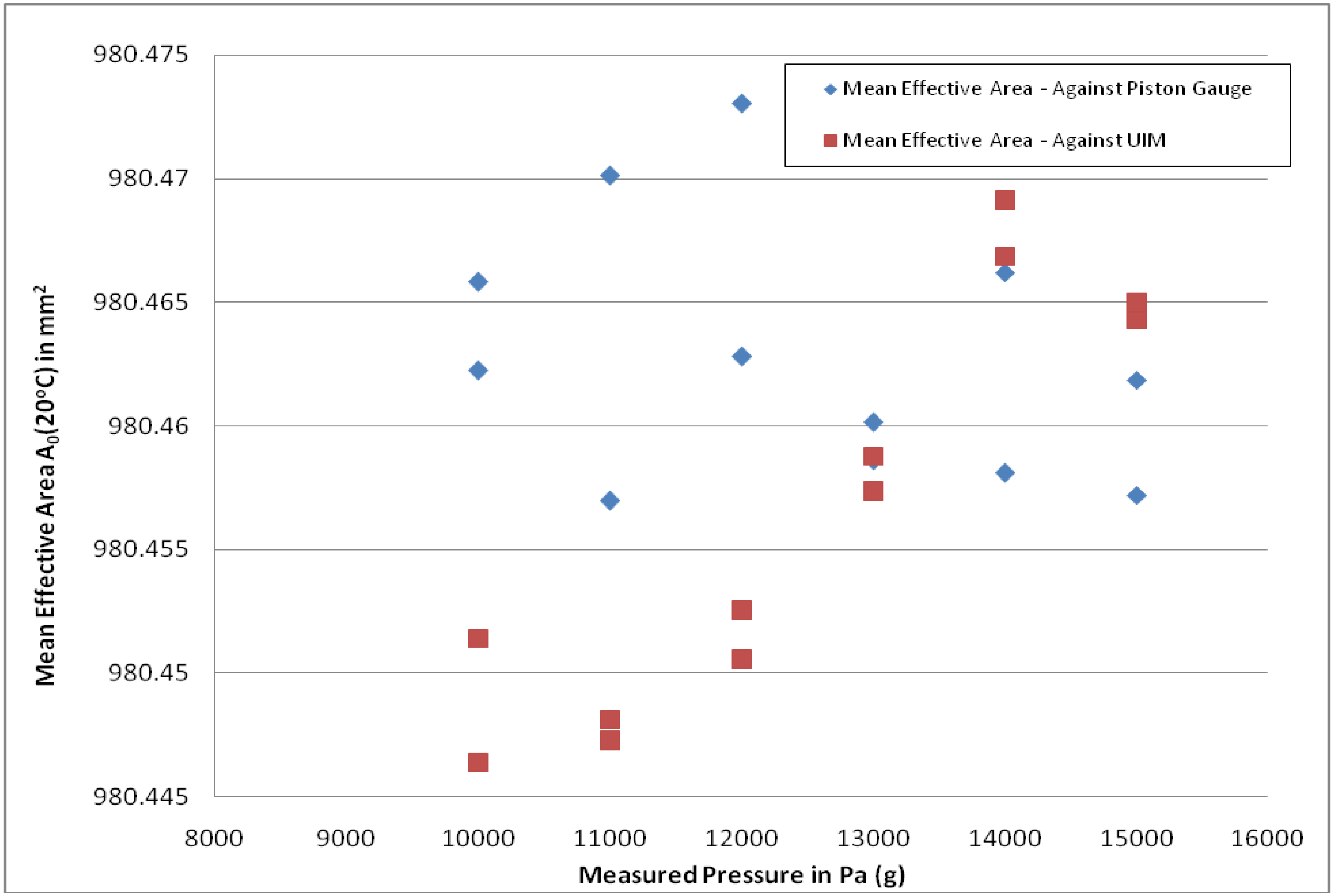


Effective area of Piston cylinder assembly of FPG

$$A_{0(20^{o}C)} = \left(\frac{m_{cal}g}{N_{cal}}\right)\left(1-\frac{\rho_{lcal}}{\rho_{mcal}}\right)\left[\frac{\left(N+\delta N_1+\delta N_2+\delta N_3\right)}{\left(p_{Std}-p_{head}\right)\left(1+\left(\alpha_P+\alpha_C\right)\left(t-20\right)\right)}\right]$$

Where p_{Std} in above equation may be UIM measured pressure at 20°C or Piston Gauge measured pressure at 20°C, as in our study UIM and Air Piston Gauge were used as reference standards. The effective area data thus estimated in the overlapping pressure region (gauge mode) are depicted in figure 2.

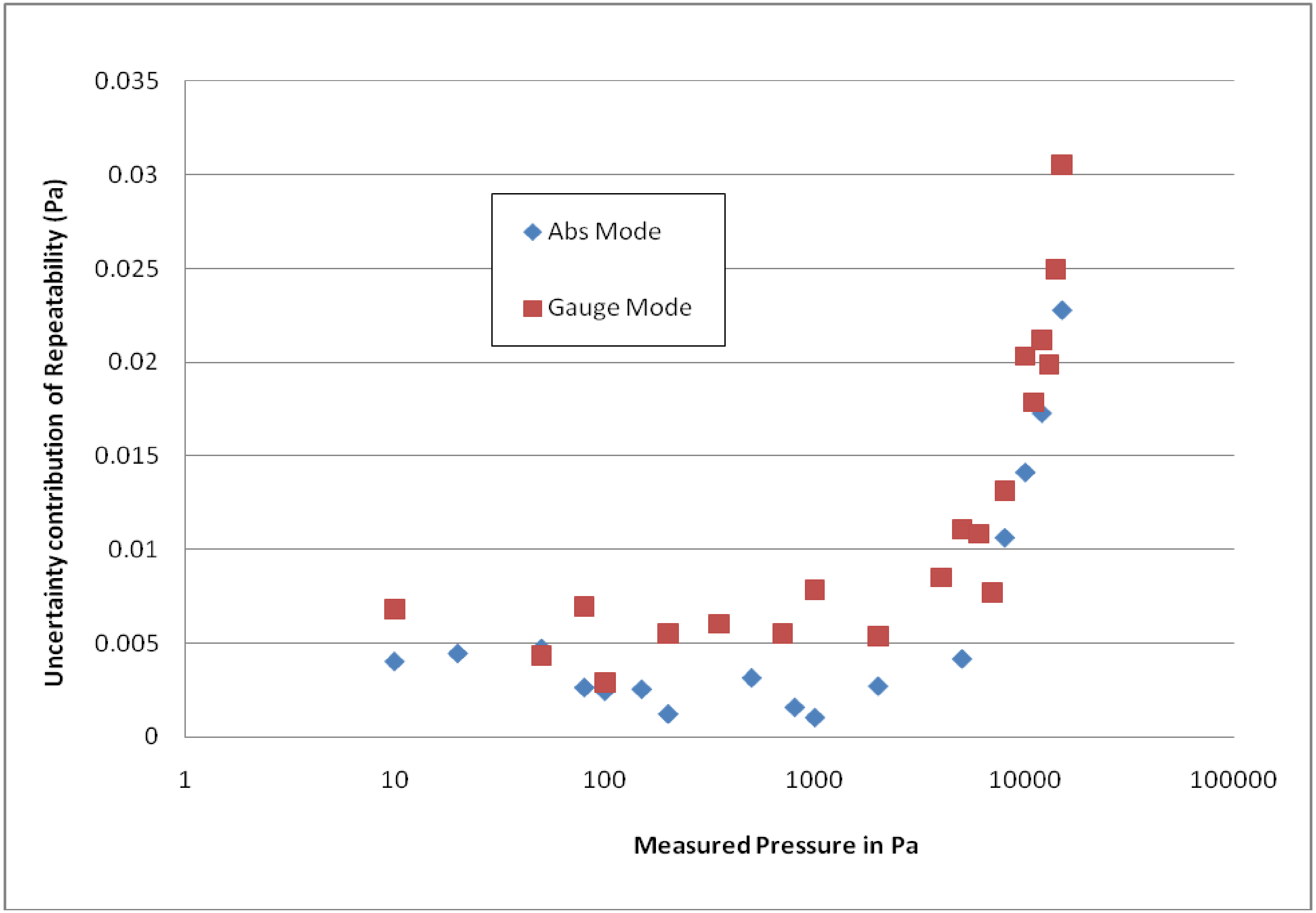
Effective area of Piston cylinder assembly of FPG



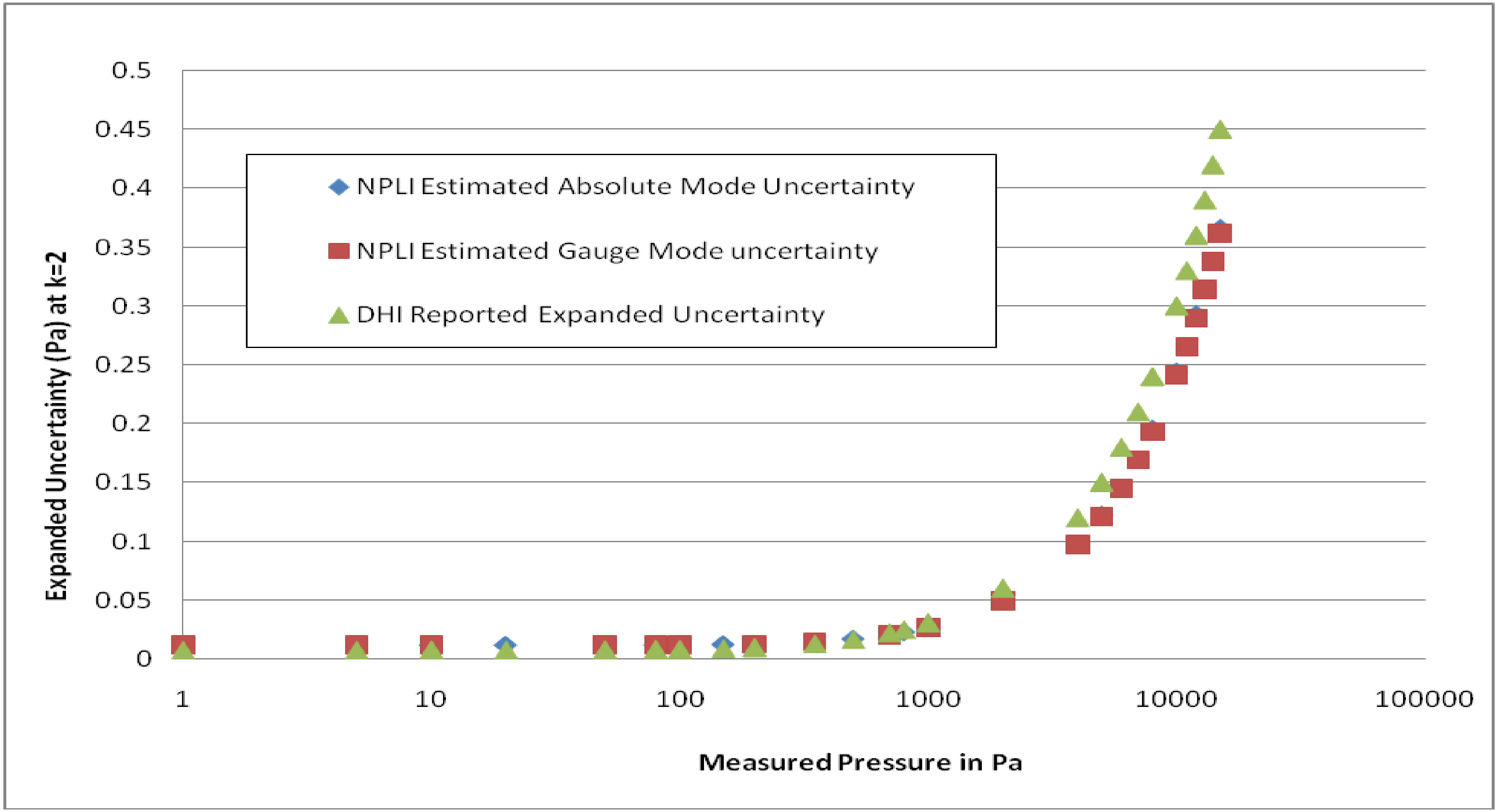
Expanded Uncertainty in Effective area estimation

Sl No	Quantity	Estimate	Limits	Uncertainty	Probability distribution	Type (A or B)	Sensitivity Co-efficient		Degrees of Freedom	Uncertainty Contribution $u_i^2(y)$
	(X_i)	(x_i)		u_{xi}			Equation	Value		
1	Calibration Mass - m_{cal} (kg)	7.79E-01		3.90E-06	Normal	B	A_o/m_{cal}	1.26E-03	∞	2.40E-17
2	Accln. Due to Gravity g (m/s^2)	9.79E+00		1.96E-05	Normal	B	A_o/g	1.00E-04	∞	3.85E-18
3	Lub air Density ρ_{lair} (kg/m^3)	1.61E+00		2.80E-03	Normal	B	$A_o/(\rho_{mcal}+\rho_{lair})$	1.24E-07	∞	1.21E-19
4	Cal Mass Density ρ_{mcal} (kg/m^3)	7.90E+03		9.12E+01	Normal	B	$A_o\rho_{lair}/\{(\rho_{mcal}+\rho_{lair})\rho_{mcal}\}$	2.53E-11	∞	5.31E-18
5	Pressure Medium Density ρ_{mair} (kg/m^3)	4.83E-01		1.06E-07	Normal	B	A_o/ρ_{mair}	2.03E-03	∞	4.65E-20
6	Thermal Expansion coefficient of Piston - α_P (^{o}C^{-1})	4.50E-06		2.59E-07	Normal	B	$A_o(t-t_{ref})/\{1+(\alpha_P+\alpha_C)(t-t_{ref})\}$	2.94E-03	∞	5.79E-19
7	Thermal Expansion coefficient of Cylinder - α_C (^{o}C^{-1})	4.50E-06		2.59E-07	Normal	B	$A_o(t-t_{ref})/\{1+(\alpha_P+\alpha_C)(t-t_{ref})\}$	2.94E-03	∞	5.79E-19
8	Temp.diff from the ref. temp. $(t-t_{ref})$ (^{o}C)	3.00E+00		8.10E-05	Normal	B	$A_o(\alpha_P+\alpha_C)/\{1+(\alpha_P+\alpha_C)(t-t_{ref})\}$	8.82E-09	∞	5.11E-25
9	Measured Pressure- p (Pa)	1.50E+04		5.42E-02	Normal	B	A_o/p	6.54E-08	∞	1.25E-17
10	Fluid Head Correction (Pa)	4.73E+00		1.65E-06	Normal	B	A_o/p	6.54E-08	∞	1.17E-26
11	Verticality (Pa)			1.20E-03	Normal	B	A_o/p	6.54E-08	∞	6.15E-21
12	System Stability (Pa)	0.15	0.075	4.33E-02	Rectangular	B	A_o/p	6.54E-08	∞	8.01E-18
13	Load Cell Precision (Pa)			1.52E-02	Normal	B	A_o/p	6.54E-08	∞	9.88E-19
14	Resolution (Pa)	1.00E-03	0.0005	2.89E-04	Rectangular	B	A_o/p	6.54E-08	∞	3.56E-22
15	Std Dev of Mean Eff Area (m^2)	7.80E-09		2.25E-09	Normal	A	1	1.00E+00	11	5.07E-18
16	Repeatability (m^2)	1.80E-08		5.69E-09	Normal	A	1	1.00E+00	9	3.24E-17
									Total Variance	9.35E-17
									Overall standard uncertainty (m^2)	9.67E-09
									Effective Degrees of Freedom	74
									Relative expanded uncertainty (ppm) at k=2.025	19.98

FPG Measured Pressure Repeatability



FPG Measured Pressure Expanded Uncertainty



Expanded Uncertainty
Theoretical Method (abs)

Quantity		Estimate	Limits	Uncertainty	Probability distribution	Type (A or B)	Sensitivity Co-efficient		Degrees of Freedom	Uncertainty Contribution $u_i^2(y)$	
Sl No	(X_i)	(x_i)		u_{xi}			Equation	Value		Independent	Dependent
1	Calibration Mass - m_{cal} (kg)	7.79E-01		3.90E-06	Normal	B	p/m_{cal}	1.92E+04	∞		5.63E-03
2	Accln. Due to Gravity g (m/s^2)	9.79E+00		1.96E-05	Normal	B	p/g	1.53E+03	∞		9.00E-04
3	Lub air Density ρ_{lair} (kg/m^3)	1.61E+00		2.80E-03	Normal	B	$p/(\rho_{mcal}+\rho_{lair})$	1.90E+00	∞		2.83E-05
4	Cal Mass Density ρ_{mcal} (kg/m^3)	7.90E+03		9.12E+01	Normal	B	$p\rho_{lair}/\{(\rho_{mcal}+\rho_{lair})\rho_{mcal}\}$	3.87E-04	∞		1.24E-03
5	Pressure Medium Density ρ_{mair} (kg/m^3)	4.83E-01		1.06E-07	Normal	B	p/ρ_{mair}	3.11E+04	∞		1.09E-05
6	Thermal Expansion coeff. of Piston - α_P ($^oC^{-1}$)	4.50E-06		2.59E-07	Normal	B	$p(t-t_{ref})/\{1+(\alpha_P+\alpha_C)(t-t_{ref})\}$	4.50E+04	∞		1.36E-04
7	Thermal Expansion coeff. of Cylinder - α_C ($^oC^{-1}$)	4.50E-06		2.59E-07	Normal	B	$p(t-t_{ref})/\{1+(\alpha_P+\alpha_C)(t-t_{ref})\}$	4.50E+04	∞		1.36E-04
8	Temp.diff from the ref. temp. ($t-t_{ref}$) (^oC)	3.00E+00		1.35E-06	Normal	B	$p(\alpha_P+\alpha_C)/\{1+(\alpha_P+\alpha_C)(t-t_{ref})\}$	1.35E-01	∞		3.32E-14
9	Effective Area- A_0 (m^2)	9.80E-04		9.80E-09	Normal	B	p/A_o	1.53E+07	∞		2.25E-02
10	Fluid Head Correction (Pa)	4.73E+00		1.23E-06	Normal	B	1	1	∞		1.51E-12
11	Ref Pressure (Pa)			3.35E-03	Normal	B	1	1	∞	1.12E-05	
12	Verticality (Pa)			1.20E-03	Normal	B	1	1	∞		1.44E-06
13	System Stability (Pa)	0.15	0.075	4.33E-02	Rectangular	B	1	1	∞		1.88E-03
14	Load Cell Precision (Pa)			2.50E-03	Normal	B	1	1	∞	6.25E-06	1.00E-12
15	Resolution (Pa)	1.00E-03	0.0005	2.89E-04	Rectangular	B	1	1	∞	8.33E-08	8.33E-08
16	Repeatability (Pa)	7.21E-02		2.28E-02	Normal	A	1	1	9		5.20E-04
									Total Variance	1.76E-05	3.30E-02
									Overall standard uncertainty (Pa)	4.19E-03	1.82E-01
									Effective Degrees of Freedom	3.62E+04	
										Absolute Value (Pa)	Relative Value (ppm)
									Expanded uncertainty at k=2	8.38E-03	24.2

Expanded Uncertainty Theoretical Method (gauge)

	Quantity	Estimate	Limits	Uncertainty	Probability distribution	Type (A or B)	Sensitivity Co-efficient		Degrees of Freedom	Uncertainty Contribution $u_i^2(y)$	
Sl No	(X_i)	(x_i)		u_{xi}			Equation	Value		Independent	Dependent
1	Calibration Mass - m_{cal} (kg)	7.79E-01		3.90E-06	Normal	B	p/m_{cal}	1.92E+04	∞		5.63E-03
2	Accln. Due to Gravity g (m/s^2)	9.79E+00		1.96E-05	Normal	B	p/g	1.53E+03	∞		9.00E-04
3	Lub air Density ρ_{lair} (kg/m^3)	1.61E+00		2.80E-03	Normal	B	$p/(\rho_{mcal}+\rho_{lair})$	1.90E+00	∞		2.83E-05
4	Cal Mass Density ρ_{mcal} (kg/m^3)	7.90E+03		9.12E+01	Normal	B	$p\rho_{lair}/\{(\rho_{mcal}+\rho_{lair})\rho_{mcal}\}$	3.87E-04	∞		1.24E-03
5	Pressure Medium Density ρ_{mair} (kg/m^3)	4.83E-01		1.06E-07	Normal	B	p/ρ_{mair}	3.11E+04	∞		1.09E-05
6	Thermal Expansion coefficient of Piston - α_P ($^oC^{-1}$)	4.50E-06		2.59E-07	Normal	B	$p(t-t_{ref})/\{1+(\alpha_P+\alpha_C)(t-t_{ref})\}$	4.50E+04	∞		1.36E-04
7	Thermal Expansion coefficient of Cylinder - α_C ($^oC^{-1}$)	4.50E-06		2.59E-07	Normal	B	$p(t-t_{ref})/\{1+(\alpha_P+\alpha_C)(t-t_{ref})\}$	4.50E+04	∞		1.36E-04
8	Temp.diff from the ref. temp. $(t-t_{ref})$ (^oC)	3.00E+00		1.35E-06	Normal	B	$p(\alpha_P+\alpha_C)/\{1+(\alpha_P+\alpha_C)(t-t_{ref})\}$	1.35E-01	∞		3.32E-14
9	Effective Area- A_0 (m^2)	9.80E-04		9.80E-09	Normal	B	p/A_o	1.53E+07	∞		2.25E-02
10	Fluid Head Correction (Pa)	4.73E+00		1.23E-06	Normal	B	1	1	∞		1.51E-12
11	Verticality (Pa)			1.20E-03	Normal	B	1	1	∞		1.44E-06
12	System Stability (Pa)	0.15	0.075	4.33E-02	Rectangular	B	1	1	∞		1.88E-03
13	Load Cell Precision (Pa)			2.50E-03	Normal	B	1	1	∞	6.25E-06	1.00E-12
14	Resolution (Pa)	1.00E-02	0.0050	2.89E-03	Rectangular	B	1	1	∞	8.33E-06	8.33E-06
15	Resolution of UIM (Pa)	1.60E-02	0.0080	4.62E-03			1	1		2.13E-05	
16	Repeatability (Pa)	9.64E-02		3.05E-02	Normal	A	1	1	9		9.30E-04
									Total Variance	1.46E-05	3.34E-02
									Overall standard uncertainty (Pa)	3.82E-03	1.83E-01
									Effective Degrees of Freedom	1.16E+04	
										Absolute Value (Pa)	Relative Value (ppm)
									Expanded uncertainty at k=2	7.64E-03	24.4

FPG Measured Pressure Comparison Method

As per the comparison method proposed [5], the calibration factors arrived at through comparison is given by

$$Cf_i = \frac{\left(\sum_{j=1}^{m} \frac{p_{FPG_{i,j}}}{p_{UIM_{i,j}}} \right)}{m}$$

Where m is the number of repeat readings taken in an identified ith nominal pressure point and the mean calibration factor is given by

$$Cf_{mean} = \frac{\sum_{i=1}^{n} Cf_i}{n}$$

[5] Arun Vijayakumar D 2006 *MAPAN* 21(1) 23-36

FPG Measured Pressure Comparison Method

Where n is the total number of nominal pressure points identified with in the span of FPG. Using this mean calibration factor, the corrected FPG reading is given by

$$p_{FPG_c} = \frac{p_{FPG}}{Cf_{mean}}$$

Above equation is the model equation for the uncertainty budgets prepared for both absolute and gauge mode measurements. The results of the budgets prepared for the theoretical and comparison methods are found to be very much comparable, thus proving the validity of the comparison method proposed.

Expanded Uncertainty Comparison Method (abs)

Quantity (X_i)	Estimate (x_i)	Limits	Uncertainty	Probability Distribution	Type (A or B)	Sensitivity Coefficient		Degrees of Freedom	Uncertainty Contribution	$u_i(y)^2$	
			u_{xi}			Equation	Value			Independent	Dependent
Repeatability (Pa)	0.0721		2.28E-02	Normal	A	1	1	9	2.28E-02		5.20E-04
Resolution (Pa)	0.009	0.004	2.50E-03	Rectangular	B	$1/Cf_{mean}$	9.999E-01	∞	2.50E-03	6.25E-06	
Hysteresis (Pa)	0	0	0	Rectangular		1	1	∞	0		0
Mean Calibration Factor	1.000015		1.09E-05	Normal	A	P_x/Cf^2_{mean}	1.500E+04	14	1.63E-01		2.66E-02
Normalized Ref. Std. Reading (Pa)	14999.775		5.42E-02	Normal	B	1	1	∞	5.42E-02	2.12E-05	2.92E-03
									Total Variance	2.74E-05	3.00E-02
										$u_i(y)$	
										5.24E-03	1.73E-01

Standard Measurement Uncertainty = Q(0.0052 Pa , 0.00116 % of reading)

Estimated Effective Degrees of Freedom 18

Estimated value of Coverage Factor (k) at Degrees of Freedom =18 and 95.45 % Confidence level 2.15

$U_i(y)$	
1.13E-02	3.73E-01

Expanded Measurement Uncertainty = Q(0.0113 Pa , 0.00248 % of Reading) for k=2.15

Expanded Uncertainty Comparison Method (gauge)

Quantity (X_i)	Estimate (x_i)	Limits	Uncertainty	Probability Distribution	Type (A or B)	Sensitivity Coefficient		Degrees of Freedom	Uncertainty Contribution	$u_i(y)^2$	
			u_{xi}			Equation	Value			Independent	Dependent
Repeatability (Pa)	0.0964		3.05E-02	Normal	A	1	1	9	3.05E-02		9.29E-04
Resolution (Pa)	0.014	0.007	4.00E-03	Rectangular	B	$1/Cf_{mean}$	9.999E-01	∞	4.00E-03	1.60E-05	
Hysteresis (Pa)	0	0	0	Rectangular		1	1	∞	0		0
Mean Calibration Factor	1.000009		1.13E-05	Normal	A	P_x/Cf^2_{mean}	1.500E+04	19	1.70E-01		2.88E-02
Normalized Ref. Std. Reading (Pa)	14999.865		5.42E-02	Normal	B	1	1	∞	5.42E-02	2.12E-05	2.92E-03
									Total Variance	3.72E-05	3.26E-02
										$u_i(y)$	
										6.10E-03	1.81E-01

Standard Measurement Uncertainty = Q(0.0061 Pa , 0.0012 % of reading)

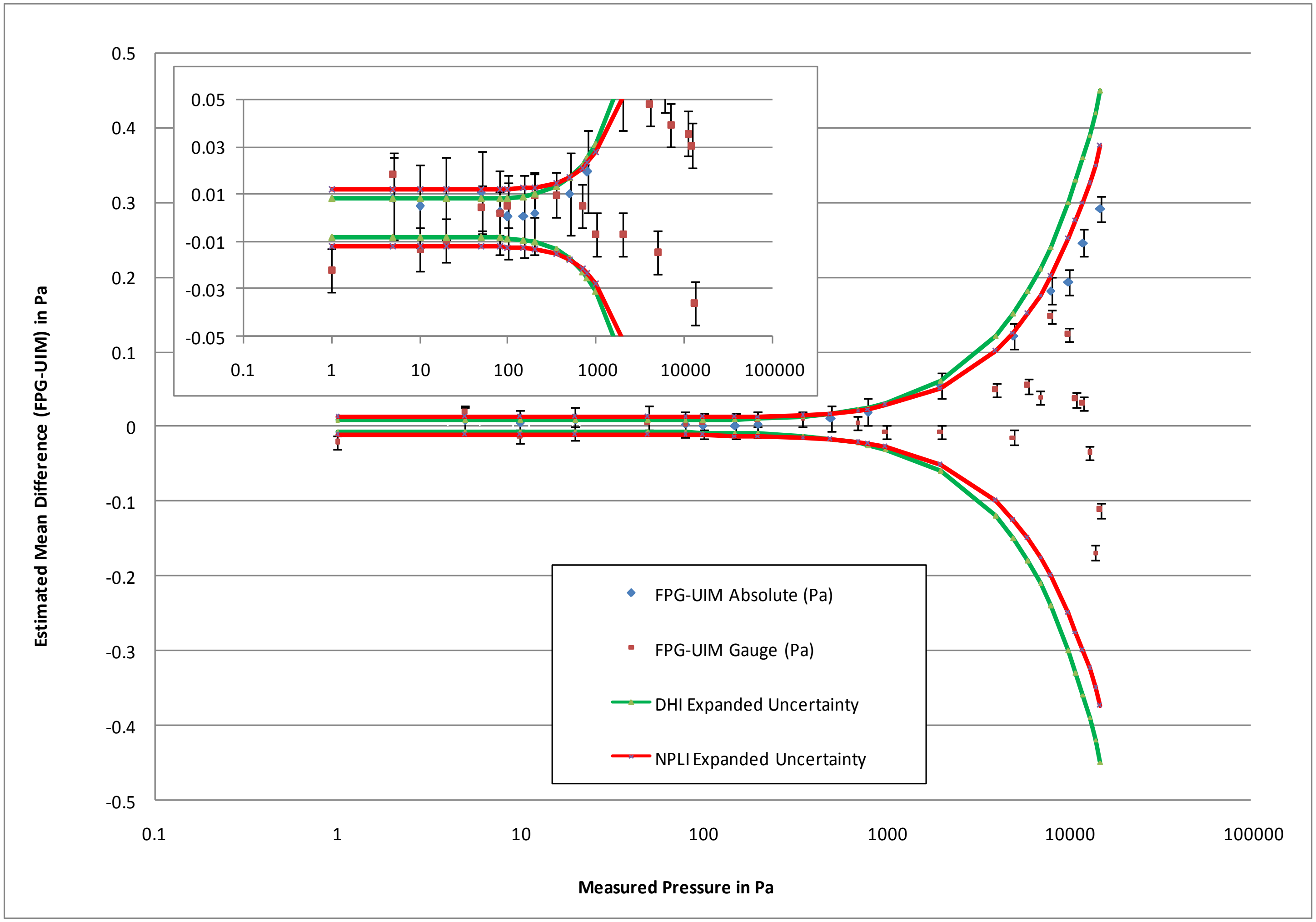
Estimated Effective Degrees of Freedom 24

Estimated value of Coverage Factor (k) at Degrees of Freedom =24 and 95.45 % Confidence level 2.11

$U_i(y)$	
1.29E-02	3.81E-01

Expanded Measurement Uncertainty = Q(0.013 Pa , 0.00254 % of Reading) for k=2.11

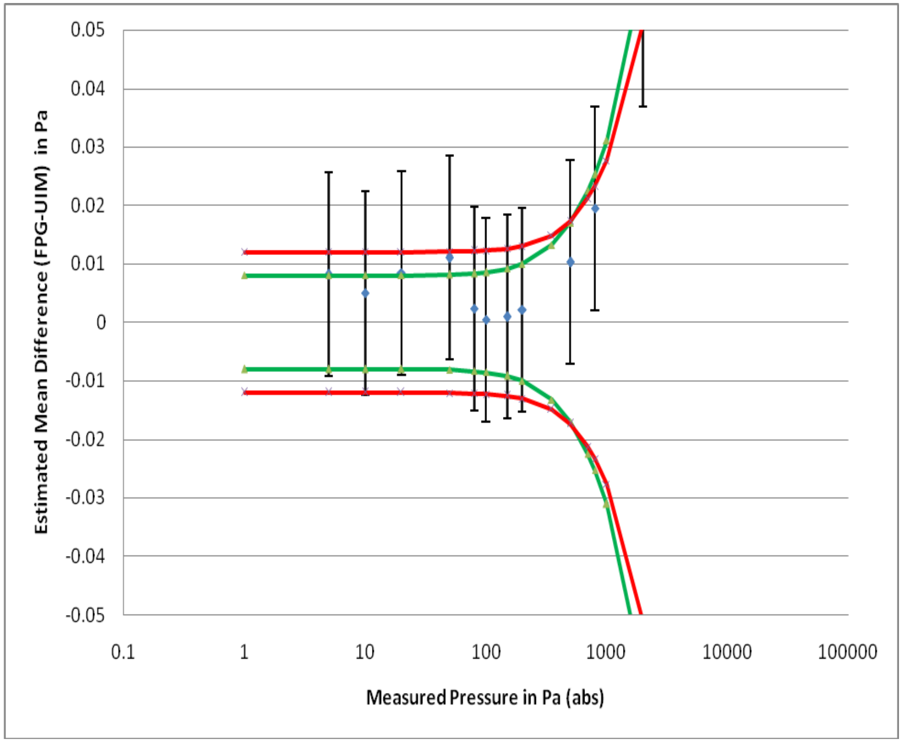
Estimated Mean Differences with in Uncertainty Bands

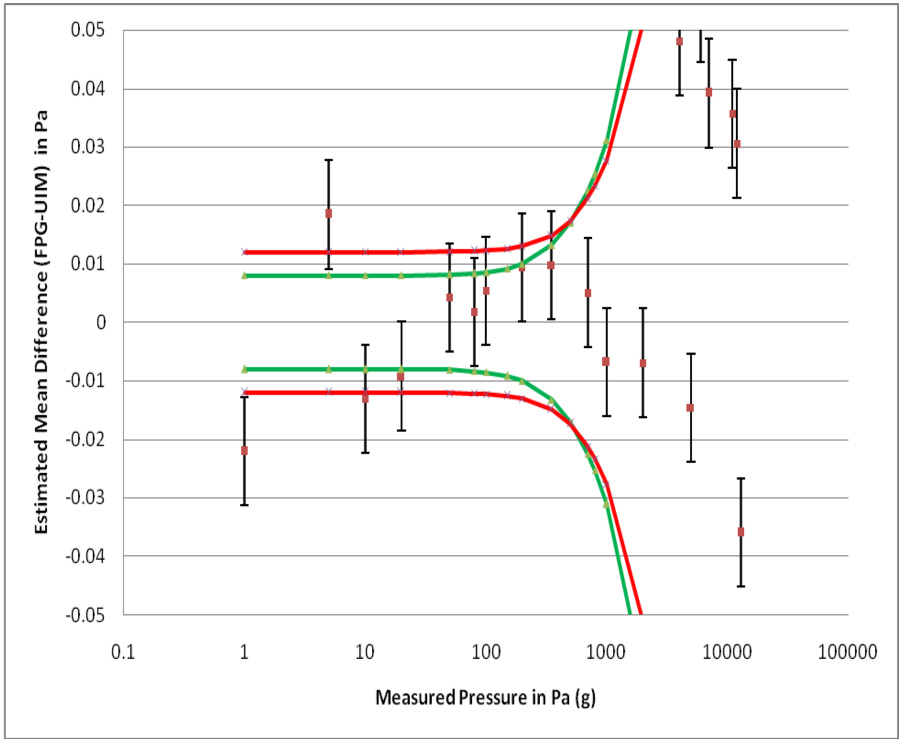


Estimated Mean Differences with in Uncertainty Bands

Absolute Mode

Gauge Mode





Conclusion

It is important that the FPG requires lubricating gas flow to center the piston in the gap and the gas is to be humidified to reduce static charge effects in the FPG load cell. Therefore, use of FPG against ultra high vacuum (UHV) systems should have a null-indicating CDG to isolate water vapor from entering the UHV system as in the case of our experimental setup.

At low pressures below 10 Pa, stability is hard to achieve, as reported by other NMIs and above 10 Pa, the deviations are well with in the evaluated expanded uncertainty. So below 10 Pa, caution is advised while using FPG for both absolute and gauge mode measurements.

Conclusion

While working in gauge mode measurements, it is advisable that the reference ports of both the FPG and the reference standard are to be in closed loop connection, otherwise vast difference is observed in the measured pressures.

While working in absolute mode measurements, especially against mercury manometers, mercury vapor pressure correction is required to be applied to manometer readings apart from zero pressure corrections to the FPG reading

Conclusion

The expanded uncertainty of piston cylinder assembly of FPG is 19.97 ppm at k=2.025 (calculated effective degrees of freedom is 74), which is less compared to the manufacturer’s reported value of 26.0 ppm at k=2. This may be attributed to the choice of reference standard, namely the UIM, instead of a simple air piston gauge.

The expanded uncertainty of FPG is evaluated using theoretical method is Q(0.0084 Pa, 24.2 ppm of reading) at k=2 for absolute mode measurements and Q(0.0076 Pa, 24.4 ppm of reading) at k=2 for gauge mode measurements.

Conclusion

The expanded uncertainty of FPG evaluated using comparison method is Q(0.0113 Pa, 24.8 ppm of reading)at k=2.15 (calculated effective degrees of freedom is 18) for absolute mode measurements and Q(0.013 Pa, 25.4 ppm of reading) at k=2.11 (calculated effective degrees of freedom is 24) for gauge mode measurements.

The expanded uncertainty evaluated through the budgets prepared using theoretical and comparison methods are found to be very much comparable for both absolute and gauge mode measurements, even when there is some difference observed in the estimated coverage factors. This proves the validity of the comparison method proposed by the author [5].

[5] Arun Vijayakumar D 2006 *MAPAN* 21(1) 23-36

Thank you