

REALISATION OF PRIMARY PRESSURE MEASUREMENT SYSTEM

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Abstract: NMC recently established the primary deadweight pressure standards in the range from 10 kPa to 1 MPa. The primary standard includes two piston-cylinder (PC) units, the diameters of which derive the pressure values. While two other of the PC units serve as the reference in the higher range of 24 kPa to 10 MPa are traceable to the primary PC units through cross-floating measurement method. Together with a primary laser manometer and a hydraulic deadweight pressure standard, NMC realises the pressure measurement system from 1 Pa to 400 MPa. This paper describes the method of realisation of the pressure unit at NMC.

Keywords: pressure; primary standards; uncertainty evaluation

1. INTRODUCTION

Pressure measurement is one of the key physical quantities monitored and measured in industrial processes in a wide range of industries, from aerospace, chemicals, petrochemicals, manufacturing to healthcare [1-2]. The measurements have to be sufficiently accurate and reliable to facilitate the implementation of sophisticated process-control. To meet the growing demands for higher precision, a pressure standard that realises the pressure unit in the pressure range of 1 Pa to 10 MPa with a measurement uncertainty of not more than 20 ppm is required, for example altitude meter of aeroplane. This in turn requires the pressure standard to be directly traceable to the SI units of length and mass for gas medium pressure in order to minimise uncertainty contributions from various sources.

2. THE PRIMARY PRESSURE STANDARD

Two types of primary pressure standards are commonly used to realise the SI unit for pressure, the *Pascal*: 1) mercury manometers for lower and barometric pressure; 2) deadweight piston gauge pressure standards for higher pressure ranges [3-6]. Both types of primary standards are capable of realising the *Pascal* with directly traceability to the SI. The two primary pressure standards established at NMC are described below.

2.1 Primary deadweight pressure standards

The primary deadweight pressure standards, manufactured by Fluke Corporation [7], are specially

designed to minimise measurement uncertainty. This was accomplished by reducing mechanical distortions of the piston-cylinder units under high pressure; better temperature control; higher sensitivities; and greater stability in the floating of the PC units. The system includes two pressure balance platforms, four PC units having nominal diameters of 50 mm, 35 mm, 25 mm and 11 mm and identified as serial number of 1595, 1618, 1601 and 1644, respectively. The measurement range is from 10 kPa to 10,000 kPa for both absolute and relative measurement modes.



Figure 1: Primary deadweight pressure standards established at NMC

2.1.1 Dimensional characterisation

The effective area, A_o , of PC units, which are used as primary pressure balances, is usually determined from dimensional characterisations. Currently, the smallest uncertainty achievable in the measurement of diameters for PC units is between 20 nm and 50 nm. To relatively minimise this uncertainty, it is advantageous for the size of PC units to be as large as possible. For this reason, two larger PC units having diameters of 50 mm and 35 mm were selected as the primary standards and whose dimensional parameters – diameters, roundness and straightness of outer surface of the pistons and inner surface of the cylinders – were precisely measured. Figure 2 shows the dimensional measurements done on the $\phi 35\text{mm}$ -piston.

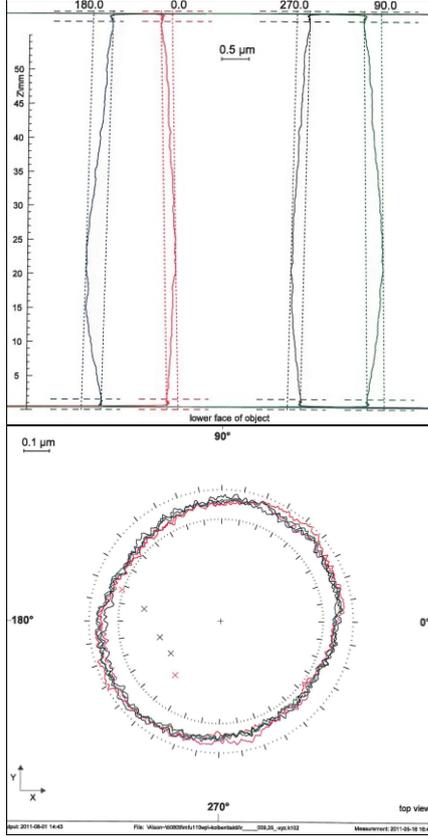


Figure 2: Dimensional characterisation of the $\phi 35$ -mm PC units.

The results of the measurement are fitted as $r(\theta, z)$, defined as the calculated radius along the z -axis and its angles to x -axis, θ . Least-square fitting is to minimise the sum-of-square of the difference between calculated radius $d_{\theta z}$, the roundness of measurement $R_{\theta z}$, straightness $S_{\theta z}$ and measured diameter $D_{\theta z}$.

The measurement uncertainty of the fitting is calculated from the following equation:

$$u_r = \left\{ \sum_{\theta} \sum_z \left[\left(\frac{r_{\theta z} - R_{\theta z}}{u_R} \right)^2 + \left(\frac{r_{\theta z} - S_{\theta z}}{u_S} \right)^2 + \left(\frac{r_{\theta z} - D_{\theta z} / 2}{u_D} \right)^2 \right] \right\}^{1/2} \quad (1)$$

2.1.2 Calculation of the effective area A_o

Effective area, A_o , of an ideal PC units, which has constant clearance, h_o , between the piston and cylinder, can be calculated from $A_o = \pi r_o^2 \cdot (1 + h/r_o)$, where r_o is the radius of piston. For distorted PC units, the size differences from r_o by piston in u_o and by cylinder in U_o have to be considered in the calculation of A_o .

Two approaches were used to calculate A_o at zero pressure in relative measurement mode and absolute pressure mode.

The gauge mode pressure is calculated based on Dadson [8] theory under viscous flow condition:

$$A_o = \pi r_o^2 \left(1 + \frac{h_o}{r_o} + \frac{1}{r_o(p_1 - p_2)} \int_0^l P_z \frac{d(u+U)}{dz} dz \right) \quad (2)$$

p_1 and p_2 are the pressure across piston from bottom to top. l is engaged length of piston and cylinder assembly. P_z is the pressure distribution along the axis and was calculated from:

$$P_z = \left(p_1^2 + (p_2^2 - p_1^2) \int_0^z \frac{dz}{h^3} / \int_0^l \frac{dz}{h^3} \right)^{1/2} \quad (3)$$

Another model was used for absolute pressure measurement in considering the molecular flow regime. Effective area of the ideal PC units under absolute measurement mode is calculated as $A_o = \pi r_o^2 \cdot (1 + 8/3 \pi h/r_o)$. The effective area A_o for distorted units under the molecular flow condition can be developed as:

$$A_o = \pi r_o^2 \cdot f(z, h, r, r_o) \quad (4)$$

For comparison purpose, both $\phi 35$ -mm and $\phi 50$ -mm PC units were measured against the primary pressure standards maintained at Physikalisch-Technische Bundesanstalt (PTB) of Germany using cross-floating method. Table 1 shows A_o values determined from dimensional measurements and cross-floating measurement.

PC units	A_o determined by dimensional measurements, mm^2	A_o determined by cross floating measurement, mm^2	Relative Diff, ppm
$\phi 50$ -mm	1961.042 ± 0.0042	1961.038 ± 0.011	2.1
$\phi 35$ -mm	980.5011 ± 0.0045	980.5054 ± 0.0063	4.4

Table 1: Effective area, A_o , determined primary deadweight pressure standards PC units.

2.2 The primary laser interferometer mercury manometer

A laser interferometer mercury manometer was developed to realise the pressure unit at the lower pressure range from 1 Pa to 13,000 Pa. In order to achieve the lowest measurement uncertainty, the instrument uses a laser interferometer to measure the vertical separation between mercury menisci in two columns of the manometer. The two beams of the interferometer are focused and reflected directly on mercury menisci by means of optical devices – the “cat’s-eyes”. Temperature of mercury was directly measured by a PRT probe. The triple distilled mercury was placed in the manometer. Its density has measurement uncertainty of 3.6 ppm. This manometer is capable to perform absolute and relative pressure modes of measurement. Summary of measurement uncertainty are given in Table 2.

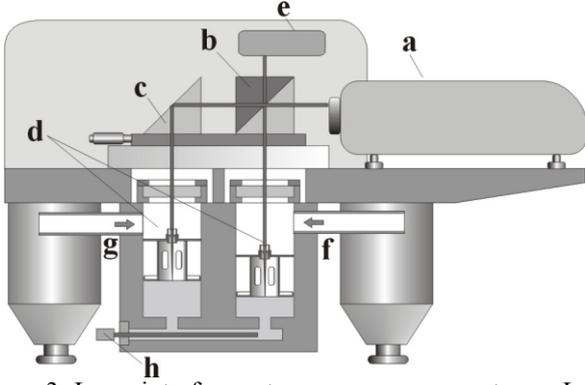


Figure 3: Laser interferometer-mercury manometer. *a*. Laser head; *b* Interferometer; *c* mirror; *d* cat's eyes floats; *e* signal receiver; *f* pressure connection pipe; *h* the PTR probe.

Source of uncertainty:	Measurand Pressure	
	1000 Pa	10000Pa
	Uncertainty Contributions u(i)/mPa	
Density of mercury at known <i>t, p</i>	3.6	36
Average temperature of mercury	0.8	8.1
Temp. differences of mercury in the two limbs	20.7	8.2
Sampling of the interferometer signal	2.0	2.0
Zero drifts of the interferometer	23.9	23.9
Refractivity of gas	0.6	5.7
Aerostatic heads in the two limbs	9.5	10
Other sources	1.6	4.4
Combined Standard Uncertainty, <i>u</i> (<i>p</i>)/mPa	33.3	46.4

Table 2: Measurement uncertainty of laser interferometer-mercury manometer [3].

3. THE REFERENCE PRESSURE STANDARD

The smaller diameters PC units – $\phi 25$ -mm (S/N: 1601) and $\phi 11$ -mm (S/N:1644), are reference pressure standards sharing the same base as the $\phi 35$ -mm PC units. Both pistons have been calibrated against the primary pressure standards using cross-floating method to determine the effective area A_o . Pressure generated by the reference standards are calculated from:

$$p_e = \frac{g \left(\sum m_i \left(1 - \frac{\rho_{amb}}{\rho_i} \right) + V(\rho_l - \rho_{amb}) \right) + 2(\pi A_o)^{1/2} \sigma}{A_{p_{e,t}}} + gh(\rho_l - \rho_{amb}) \quad (5)$$

for pressure measurements in gauge mode, and

$$p_e = \frac{g(\sum m_i + V\rho_l) + 2(\pi A_o)^{1/2} \sigma}{A_{p_{abs,t}}} + p_{res} + gh\rho_l \quad (6)$$

for pressure measurements in absolute mode.

Where:

g is the local gravity acceleration;

m_i and ρ_i are respectively the masses and densities of loads;
 ρ_{amb} is the density of the ambient air at the reference level of the pressure balance;
 V is the piston's additional volume which requires a correction due to the buoyancy produced by the pressure-transmitting medium;
 ρ_l is the density of the pressure-transmitting medium;
 ρ is the surface tension of the pressure-transmitting medium if it is a liquid;
 P_{res} is the residual pressure of the gas above the piston;
 h is the height difference between the reference level of the pressure balance and the pressure measurement level.

There are also other three sets of PC units identified as TL881, C165 and 2578 covering the range from 1.4 kPa to 7 MPa, which serve as working standards for calibrations.

4. MEASUREMENT QUALITY SYSTEM

For the low pressures standards, a system to compare the standards and ensure measurement quality is shown in Figure 4.

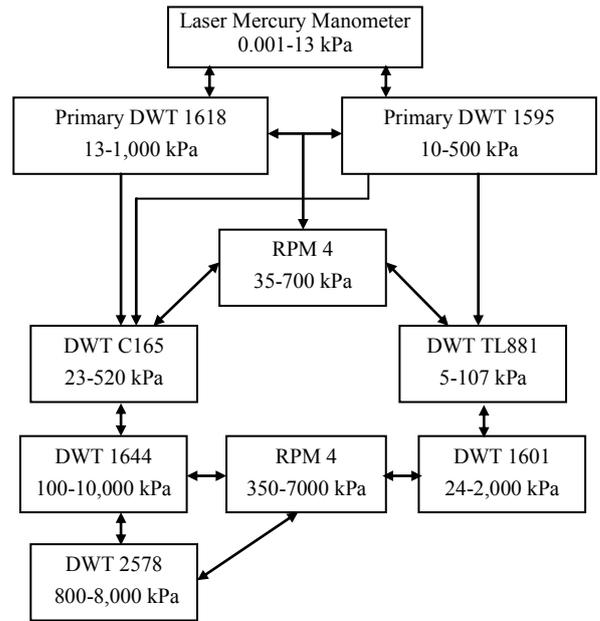


Figure 4: System for ensuring measurement quality of the low pressure standards.

Reference pressure value P_{ref} of the primary standards was determined from the dimensional measurement results with best agreement with cross-floating calibration results. The least-square values are formed from:

$$\chi = \sum_{v=1}^2 \sum_{j=1}^2 \sum_{k=1}^3 \frac{[p_{ref} - p(v, j, k)]^2}{u^2[p(v, j, k)]} \rightarrow \min \quad (7)$$

where: v is the pressure value derived from the dimensional measurement, j is the value obtained from cross floating calibration results and k is the primary standards.

The measurement uncertainty of the reference pressure values is calculated as:

$$u(p_{ref}) = \left[\sum_{v=1}^2 \sum_{j=1}^2 \sum_{k=1}^3 \frac{u^2[p(v,j,k)]}{p^2(v,j,k)} + [u(p_{head})/p(v,j,k)]^2 \right]^{1/2} \quad (8)$$

where: P_{head} is the correction value due to difference in height of PC units.

The reference pressure is disseminated by directly cross floating against other PC units by use of following formula.

$$A_{pt} = (p_{ref} + \rho_p \cdot (h - h_{ref}) \cdot g) / W_{pt} \quad (9)$$

where: A_{pt} is the unknown PC units effective area; ρ_p is the gas density; h is PC UNITS's vertical position; W_{pt} is the total loading weights on the unknown PC units.

The primary pressure deadweight standards are able to perform the automatic calibration. Two sets dual primer sensor RPM4 are characterised by the automatic calibrations for transferring pressure values between the standards. Both RPM4s have 1 ppm sensitivity. A total 5 cycles running tests was designed for characterising the pressure sensors before each of comparison. The typical repeatability of transfer standard are within 5 to 8 ppm as shown in Figure 5.

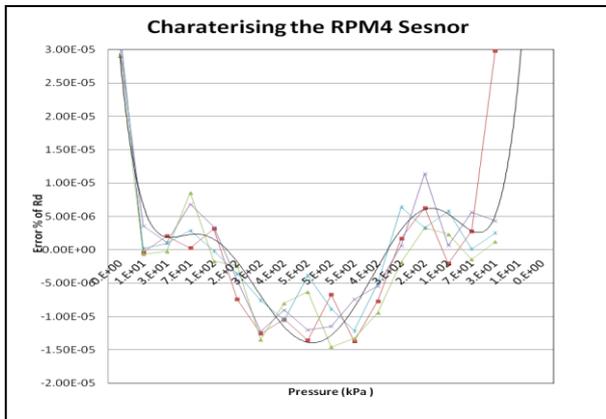


Figure 5: Characterising RPM4 sensor using primary pressure standards.

Since pressure sensors are affected by ambient temperature at about 30 Pa/°C. The coefficient β for compensation of temperature fluctuation has been predetermined at 20 °C (t_0) and 23 °C (t'). β is obtained from multiple measurements and calculated as:

$$\beta_{k,s,h,x} = \sum_k^2 \sum_s^3 \sum_h^n \sum_x^n \frac{P'_{kshg} - P_{o_{kshx}}}{t'_{kshg} - t_{o_{kshx}}} \quad (10)$$

where s is the number of test runs, h and x are the readings taken at ascending and descending pressure.

Each RPM4 has two sensors of the same type. By comparing the readings at the same pressure, the drifts during the measurements can be identified as $q_r/q_s \leq 1$.

The measurement uncertainty due to random errors and drift is given by:

$$q_r = \sqrt{\frac{1}{m-1} \sum_{w=1}^m \frac{(X_w - Y_w)^2}{2}} \quad (11)$$

where: X_w and Y_w are the reading taken by sensor 1 and sensor 2; m is number of the pressure points being compared

The measurement uncertainty due to pressure non-uniformity at different ports is given by:

$$q_s = \sqrt{\frac{1}{m-1} \sum_{w=1}^m \frac{(X_w + Y_w)^2}{2}} \quad (12)$$

The maintenance of pressure standards by using pressure sensors are calculated as:

$$A_{pt} = \{f_{fit}(p_{ref}) + \beta \cdot (t - t_0)p\} + \rho_p \cdot (h - h_{rpm}) \cdot g / W_{pt} \quad (13)$$

This maintenance system is able to monitor the long term stability for all pressure standards used in the laboratory and enables pressure values to be consisted within 20 ppm.

5. CONCLUSION

Primary standards for the realisation of the *Pascal* with direct traceability to the SI were established using large areas PC units and mercury manometer. Pressure values derived from dimensional measurements and modelling of the PC units agreed with cross-floating measurements to within 5 ppm. A measurement quality system was also developed to ensure the consistency and traceability of the pressure unit realised throughout the pressure range of 1 Pa to 10 MPa.

6. REFERENCES

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