Int. J. Metrol. Qual. Eng. **8**, 3 (2017)
© A.A. Eltawil and S.A. Gelany, published by EDP Sciences, 2017
DOI: 10.1051/ijmqe/2016031

International Journal of Metrology and Quality Engineering

Available online at:
www.metrology-journal.org

RESEARCH ARTICLE OPEN ACCESS

Validation of NIS 500 MPa hydraulic pressure measurement

Alaaeldin A. Eltawil* and Shaker A. Gelany

Mass, Density and Pressure Department, National Institute for Standards (NIS), Giza, Egypt

Received: 6 January 2016 / Accepted: 31 December 2016

Abstract. 500 MPa pressure is considered as the common maximum pressure in most of the National Metrology Institutes worldwide; however, validation of the uncertainty in that range required a lot of work. NIS when recognized on, 2008 guaranteed big uncertainty value above 200 MPa due to the absence of international comparison at that time. This paper summarizes the results of a validation of 500 MPa range of hydraulic gauge pressure measurements carried out at NIS. The study covers the calibration through direct comparison and through using of a pressure sensor. The paper summarized the technical work carried out at the results of measurements and the effect of these results on NIS Calibration Measurements Capability. The validation also includes the comparison between the obtained results and pervious calibration of the same piston-cylinder assembly that calibrated against the NIST primary standard.

Keywords: pressure sensor / calibration / pressure balance / uncertainty / primary / traceability

1 Introduction

One of the most important devices used to generate accurate pressures is known as pressure balance as shown in Figure 1. Using this instrument the pressure is generated by loading a known mass on a piston-cylinder assembly (PCA) of known effective area under specified conditions. The method used for calibration of pressure balance known as cross-floating [1–4]. Within this method, the unit under test (UUT) is cross-floated against a reference standard (RS) which is previously calibrated PCA with known effective area using two calibrated mass sets. For the above reason, the determination of the ratio of the effective areas of the two PCAs is a particularly important aspect of calibration, for which Figure 2 gives a generalized schematic diagram. The two assemblies, of effective areas RS and UUT, are shown mounted on a common pressure system, shown in Figure 3 and are 'in equilibrium', at the applied pressure P, calculated at an appropriate reference level for each assembly. In Figure 3, two constant volume valves are used to avoid volume change of the oil inside the tubing between the RS and the UUT. A special designed Data Acquisition (DAQ) is used to collect the data from the two PCAs, the pressure transducer and the environmental condition measurement system. The DAQ will feed the data to the specially designed software in order to calculate the results.

* Corresponding author: eltaweel38@yahoo.com

It will be recalled that a pressure balance forming part of a closed system acts, in its equilibrium state, as a barostat, fixing the applied pressure at the value defined by the applied load and the effective area.

The basis of the comparison is, therefore, the determination of the loads applied on the RS and loads applied on the UUT at which each balance would individually barostat the system at precisely the same pressure. The available methods, may conveniently be classified as 'falling rate' and 'sensor based' respectively, the distinction between them being based on the, different techniques by which the state of equilibrium is identified.

The effective area of the UUT at each cross floated pressure point is calculated as well as the elastic distortion function is obtained from the variation of the PCA effective area with pressure. The cross-float method requires that the masses of the used mass set, the piston and any load element to be well known, including any corrections to the mass values such as the forces due to variation of the local gravity acceleration, surface tension or fluid buoyancy. The method used in this study incorporates using a precise transducer with a specific procedure to overcome the time consuming and need for a well-trained operator to perform the cross floating experiment. The transducer is to be connected first to the standard and then to the UUT [5]. The method for estimating the fractional mass to be placed on the pressure balance in order to obtain the equivalent pressure of two pressure balances is also discussed.

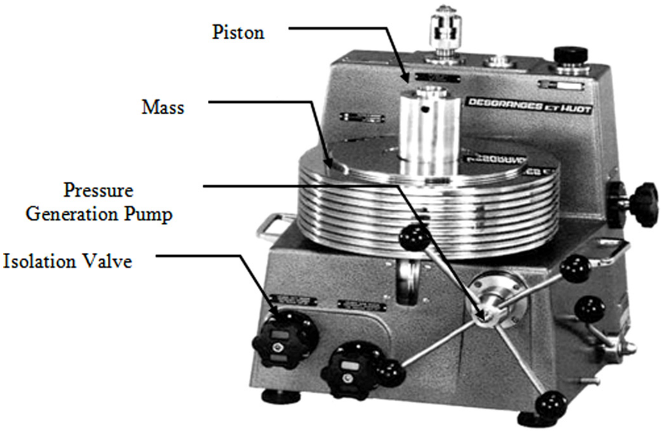

Fig. 1. UUT simple type pressure balance used as a unit under test.

2 Measurement procedures

The UUT was a simple type PCA of 2 mm^2 nominal effective areas. It is one part of a pressure balance equipped with a mass carrier; all parts are commercially available as shown in Figure 1. Measurements of the UUT effective area vs. pressure were made using cross-floating technique [3] against NIS Reference Standard (RS) piston gauge. System setup is shown in Figure 2 where the UUT was directly connected with the reference standard. NIS masses were used on the UUT. The characteristics (zero pressure effective area and distortion coefficient) of the RS were taken from calibration certificate [6]. The UUT was operated with the motor drive on. The motor was switched on at least 30 minutes prior to the first measurement of a calibration cycle.

The intensity of magnetization of the piston and cylinder was measured at the first of the 5 cycles using Tesla meter. The piston magnetization was found to be 0.4×10^{-4} Tesla and the cylinder magnetization was 0.4×10^{-4} Tesla with uncertainty of measurements 2% such measurements were carried out to confirm that there are no extra magnetic forces acting on the PCA. Ambient air pressure, relative humidity, and temperature were measured with commercially available measurement system for each parameter. The standard expanded uncertainties of the relative humidity, temperature and air pressure were 1% [7], 0.02 °C [7] and 15 Pa [8], respectively.

The UUT was measured in 5 cycles against the RS; each cycle consists of 20 observations carried out at 10 pressure points in the ascending direction and the same 10 pressures points in the descending direction. The 10 pressures points were (50, 100, 150, 200, 250, 300, 350, 400, 450 and 500) MPa. There were 100 measurements points in total. The nominal reference temperature for the RS was 20 °C, and the measured temperature was between 19.43 °C and 20.61 °C. The measured temperature for the UUT was between 19.35 °C and 20.62 °C, with the temperature increasing from the beginning to the end of a cycle. The ambient air temperature varied from 20.0 °C to 20.7 °C over the 5 cycles.

The used formula to calculate the generated pressure [3] at the reference level of the UUT that includes all the correction is

$$p' = \frac{\sum_i m'_i g\left(1 - \frac{\rho_a}{\rho'_i}\right) + \sigma' C'}{A_p(1 + (\alpha'_p + \alpha'_c)(t' - 20))}, \quad (1)$$

where p' is the pressure generated by the reference standard at the UUT reference level; m'_i are true masses of the piston, the weight carrier, and the mass pieces placed on the weight carrier of the UUT; ρ'_i are densities of the parts with masses m'_i; ρ_a is the air density; g is the local gravitational acceleration, which is $9.79299376\,\mathrm{m/s^2} \pm 3 \times 10^{-8}\,\mathrm{m/s^2}$; σ' is the surface tension of the UUT oil; C' is the nominal circumference of the UUT piston; A_p is the effective area at pressure p; α'_p and α'_c are thermal expansion coefficients of the piston and cylinder materials, respectively; t' is the temperature of the UUT

$$A_p = A_0(1 + \lambda p), \quad (2)$$

where A_0, effective area at zero pressure; λ, pressure distortion coefficient.

The method of obtaining the effective area used above could be named classical direct cross floating procedure, which suffers from experimental problems that could be summarized in the following points:

- It is a time consuming procedure where a pressure point usually takes from 30 min to 60 min in order to obtain the balancing condition. Sometimes it takes more time to get the balancing condition with good resolution.
- It needs a well-trained expert to carry out the measurements and to identify the balancing point.
- The long time that classical cross floating experiments takes for balancing point determination gives rise to the serious problem of the oil temperature variation in the clearance between piston and cylinder and consequently change its density and viscosity. This temperature deviation from the true value originates from the long operation time and continuous rotation of the piston.

Instead of the normal procedure of cross floating technique, a sensor-based method [3] is used to determine the balancing point, by connecting the two pressure balances through a pressure transducer of high accuracy. The use of high accuracy pressure transducers allows for a better resolution in determining the difference between the generated pressures from each pressure balance so no need for accurate determination of the balancing point in addition avoids the inherent uncertainty associated with the subjectivity of an operator in estimating the condition of balancing. The complete system configuration used to measure the effective area is shown in Figure 3.

The used transducer is a digital quartz sensor manometer commercially available shown in Figure 3 of range 280 MPa. Using suitable software advised by the manufacturer, the stated resolution was increased to become 0.01 ppm of full scale. Two constant volume air driven valves, CVV1 and CVV2, as shown in Figure 3, were

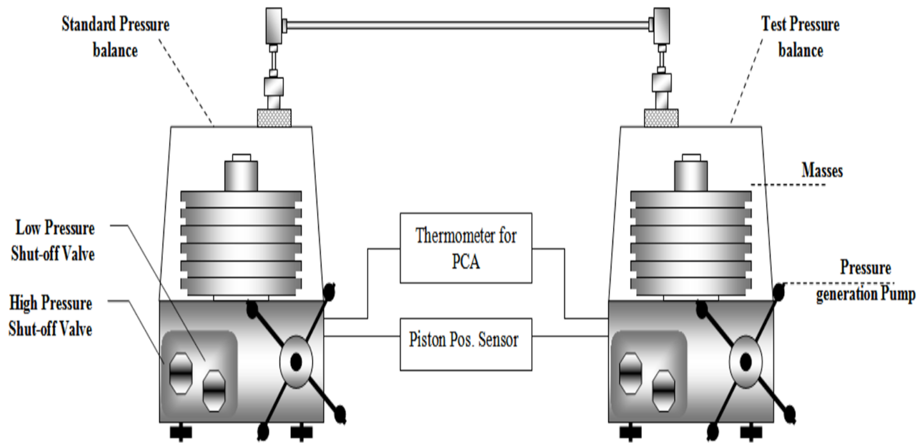

Fig. 2. Experimental set-up illustrating the method of cross-floating between a UUT vs. a RS.

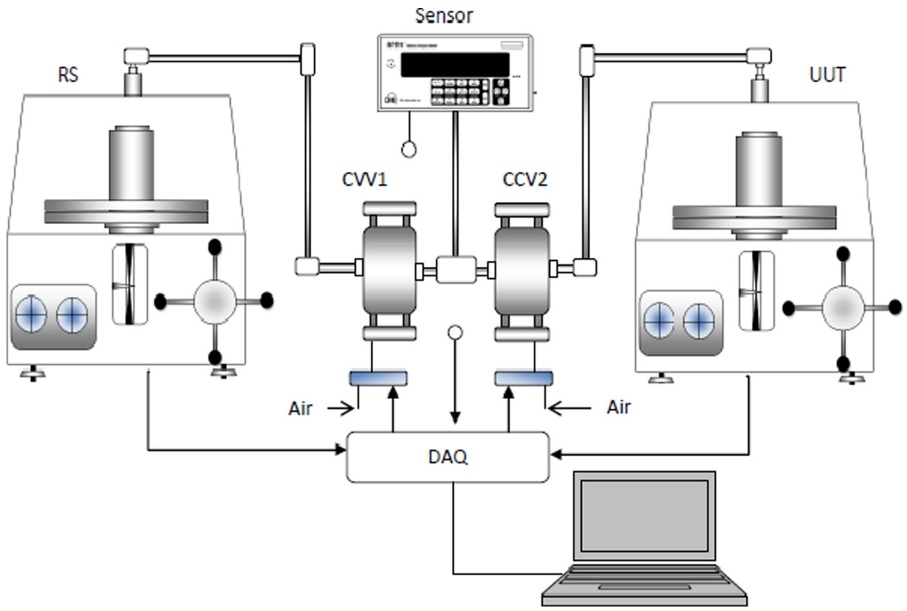

Fig. 3. Sensor base cross floating system.

used to connect and disconnect the RS and UUT respectively from the pressure transducer. The importance of using such valves is to keep the pressure stable where the normal isolation valve, when opening or closing, it's moving parts will change the volume inside the valve, which causes a change in the system pressure. Constant volume valve has a change of volume during its operation of less than 0.15 mm^3, which in fact generates immeasurable pressure [3].

Since there are many parameters to be measured and monitored at the same time such as the pistons positions, rotation speed and temperatures of both UUT and RS, environmental conditions and the pressure measured by the pressure transducer, a measuring software program was developed to record simultaneously these influence parameters, get the data from the pressure transducer and calculate the reference generated pressure then calculate the effective area of the UUT as a function of the generated pressure.

3 Results and discussion

3.1 Results of the falling rate

The falling rate has been studied in order to get information about the performance of the used piston cylinder assemblies, to compare this falling rate with the standard falling rate according to the international specification [9,10].

The fall rate was measured at 50 MPa, 250 and 500 MPa with both the low and high pressure shut-off valves of the UUT pressure balance closed as shown in Figure 2. Piston fall rates (v_f) measured by the NIS laboratory at temperatures around 20 °C. It should be waited minimum 10 min after generating the pressure in the UUT measurement system prior to starting the piston fall rate measurements in order to stabilize the UUT temperature. When measuring v_f, both the low and the high pressure shut off valves should be closed to avoid the effect of possible oil leak from the variable volume screw

Table 1. The fall rates (v_f) at different applied pressure.

Applied pressure (MPa)	Falling rate (mm/min)
50	0.05
250	0.14
500	0.22

press

$$v_f = \frac{S}{t}, \tag{3}$$

where S is the distance of the falling piston; t is the time of the falling piston.

The range of movement of the piston has been kept to be 1 mm to ensure that all measurements of the falling rate are at the same position of the piston. The falling rate measurements were carried out using an inductive probe, mounted in the pressure balance base and the piston position sensor is connected to a PC. The operating software was used to record the falling rate as a function of time.

The falling rates show a linear variation with the applied pressure as shown in Table 1. The fall rates were measured with an uncertainty of measurements 0.1%.

3.2 Results of the effective area

3.2.1 Direct cross floating

When the balancing point reached [11] the pressure generated from the UUT is equal to the pressure measured by the RS i.e. $P_{\text{UUT}} = P_{\text{RS}}$.

At ideal condition giving by equation (4):

$$\frac{\left\{\sum m_{\text{UUT}}\left(1-\frac{\rho_a}{\rho_{m,\text{UUT}}}\right)\right\}g+\sigma c_{\text{UUT}}}{A_{\text{TS}}} = \frac{\left\{\sum m_{\text{RS}}\left(1-\frac{\rho_a}{\rho_{m,\text{RS}}}\right)\right\}g+\sigma c_{\text{RS}}}{A_{\text{RS}}}. \tag{4}$$

The equilibrium condition of the comparison techniques ensures that at each reading, p_{UUT} and p_{RS} are identical, whence the following general expression for the ratio, R, of the effective areas of both PCAs, corresponding to the applied pressures at the reference level, and at the actual temperatures of the balances could be derived.

The adoption of the different condition will lead to the general form for the conventional effective area for PCA [1–4] will reduce the general equation to equation (5):

$$R = \frac{A^*_{\text{UUT}}}{A^*_{\text{RS}}} = \left\{\frac{\sum m_{\text{UUT}}(1-\rho_a/\rho_{m,\text{UUT}}) + H'_{\text{UUT}}(\rho_f-\rho_a)S^*_{\text{UUT}}}{\{\sum m_{\text{RS}}(1-\rho_a/\rho_{m,\text{RS}})\}}\right\} \times \left\{\frac{1+\beta_{\text{RS}}(t_{\text{RS}}-20)}{1+\beta_{\text{UUR}}(t_{\text{UUT}}-20)}\right\}, \tag{5}$$

where H' is now the height difference between the two reference levels at which the conventional effective areas, A^*_{UUT} and A^*_{RS}, are defined, and β_{UUT} and β_{RS} are the effective linear thermal expansion coefficient of the materials of the PCA obtained through a summation of the respective piston and cylinder linear thermal expansion coefficients. The effective area of the UUT at 20 °C, A'_p, for each pressure point of each cycle was determined from the following equation (using notation from the protocol):

$$A'_p = \frac{\sum_i m'_i g\left(1-\frac{\rho_a}{\rho'_i}\right)+\sigma' C'}{p'(1+(\alpha'_p+\alpha'_c)(t'-20))}. \tag{6}$$

The results of the 5 cycles are averaged and the 100 data points of the 5 cycles were fitted as shown in Figure 4 using a linear regression model to the equation:

$$A'_{p,\text{fit}} = A'_0(1+\lambda' p'). \tag{7}$$

The residuals in effective area of UUT from a linear fit (A_e) for 5 cycles are shown in Figure 5. Table 2 gives the results of calibration the UUT using the direct cross floating procedure.

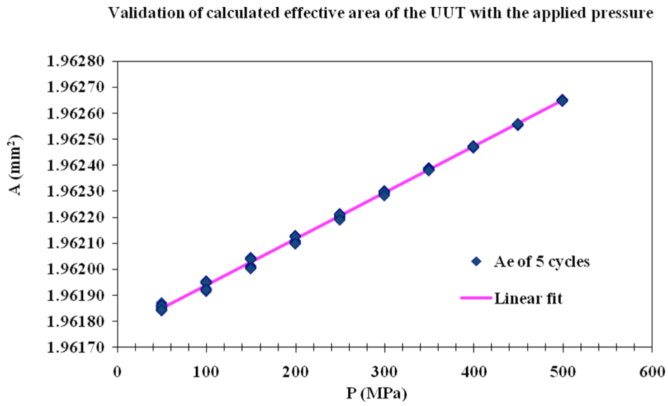

Fig. 4. Ae vs. P for UUT calibration against NIS pressure scale for 5 cycles, and linear fit in range from 50 to 500 MPa.

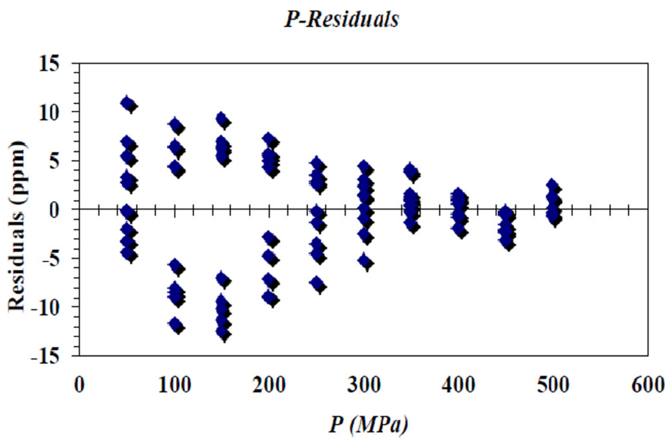

Fig. 5. Residuals in effective area of UUT from Linear fit (AeL.F) and direct comparison to NIS pressure scale (Ae) for 5 cycles.

3.2.2 Sensor based cross floating

In this procedure the pressure generated from the RS is measured using the sensor while the line of the UUT is closed, then the constant volume valve (CVV1) is used to

Table 2. Results of the direct cross floating procedure.

A_0	1.96176032	mm^2
$U(A_0)$	5.89E−05	mm^2
λ	9.07E−7	MPa^{-1}
$U(\lambda)$	1.15E−7	MPa^{-1}

Table 3. Results of sensor cross floating calibration.

A_0	1.961749588	mm^2
$U(A_0)$	6.79E−05	mm^2
λ	9.55898E−07	MPa^{-1}
$U(\lambda)$	1.36E−7	MPa^{-1}

close the pressure line for the RS and the second CVV2 is used to open the line of the UUT then the pressure generated by the UUT is measured. The differential pressure could be determined accurately using the sensor-based method proposed. By the use of this procedure a quick calibration of pressure balance has been carried out. This procedure was carried out using a sequence of RS1–UUT1–UUT2–RS2. So the difference in the pressures generated by RS and UUT could be calculated in the following way:
– A1 = RS1 − UUT1.
– A2 = UUT2 − RS2.
– The difference between the RS and UUT = (A1 + A2)/2.

This sequence of data recording will eliminate any drift, if any, and it gives a lower standard deviation than the sequences “RS1–UUT1–RS2” or “RS–UUT”. These steps give the difference in one pressure point for one time.

Applying the above listed procedure for the range up to 280 MPa (the upper limit of the used pressure transducer) the obtained results are used to calculate the effective and pressure distortion coefficient at each pressure point as tabulated in Table 3.

In order to test the validity and coherency of the results of both methods as obtained from Tables 2 and 3, the normalized error was calculated (E_n ratio) was calculated using a standard statistical technique, derived from the following expression, for comparing values:

$$E_n(A) = \frac{|A_{0(\text{direct})} - A_{0(\text{sensor})}|}{\sqrt{(U_{A_{(\text{direct})}})^2 + (U_{A_{(\text{senor})}})^2}},$$

where $A_{0(\text{direct})}$ and $A_{0(\text{sensor})}$ are the measured effective areas of a PCA using direct comparison and using a pressure sensor respectively. The procedure described in Eltawil et al. [12] was used. $E_n(A)$ was found to be 0.12 which is much lower than the criteria proposed by [12] so that the measurements are consistence and validation is achieved.

$$E_n(\lambda) = \frac{|\lambda_{(\text{direct})} - \lambda_{(\text{sensor})}|}{\sqrt{(U_{\lambda_{(\text{direct})}})^2 + (U_{\lambda_{(\text{senor})}})^2}},$$

where $\lambda_{0(\text{direct})}$ and $\lambda_{0(\text{sensor})}$ are the measured effective areas of a PCA using direct comparison and using a pressure sensor respectively. The obtained E_n (λ) was found to be 0.27 which comply with the requirement of $E_n \leq 0.3$ adopted by [12].

Those two results of E_n (A) and E_n (λ) confirm that the measurements using direct cross floating and through sensor are consistence and validation is achieved.

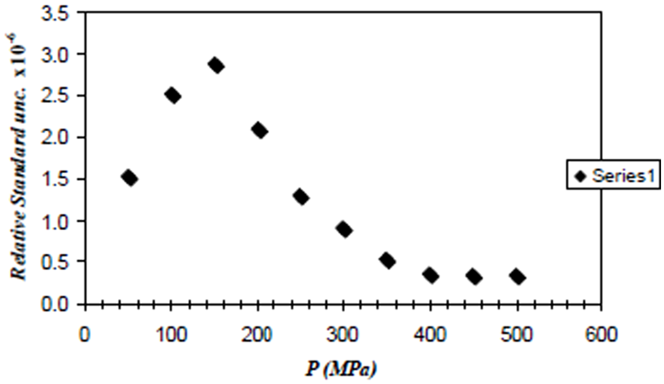

Fig. 6. Results of relative standard uncertainty type A with $k = 2$ from the reference values.

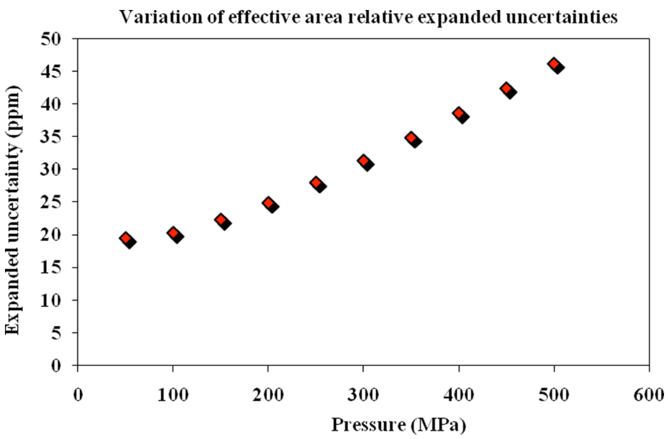

Fig. 7. Relative expanded uncertainty of the obtained effective area as a function of pressure.

4 Conclusions

The pressure measurement and effective area calculation up to 500 MPa was validated at NIS. The repeatability of the effective area values determined by the reference standard at ten nominal pressures from 50 MPa to 500 MPa in steps of 50 MPa were in a good agreement.

The relative standard uncertainty of measurements were varied from 1.5 to 3 ppm as shown in Figure 6 also the measurements shows that the relative expanded uncertainties were varied from 28 ppm to 90 ppm as shown in Figure 7 (expanded relative uncertainties). As the pressure distortion is the dominating source of uncertainty in this range, the claimed uncertainties were high at 500 MPa.

Successful application of the sensor based method for measurements of the effective area of PCA with the relative difference between its results and direct cross floating of 5.5 ppm for the effective area calculation which lie perfectly within the uncertainty of measurements of the effective area for both methods. Also the relative difference between the obtained pressure distortion coefficient is 5.4%, which also less than the uncertainties of the measurements in both methods.

References

1. A.K. Bandyopadhyay, A.C. Gupta, Realization of a national practical pressure scale for pressures up to 500 MPa, Metrologia **36**, 681–688 (1999)
2. P.L.M. Heydemann, W.E. Welch, Piston gauges, in *Experimental thermodynamics*, edited by B. Leneindre and B. Voder (Butterworths, London, 1975), Vol. II, pp. 147–201
3. A. Eltawil, Investigation of a primary system for measurement and calibration of pressure, Ph.D. thesis, Ain Shams University, Cairo, 2003
4. R.S. Dadson, S.L. Lewis, G.N. Peggs, *The pressure balance – theory and practice* (HMSO, London, 1982)
5. T. Kobata, D.A. Olson, Accurate determination of differential pressure between two pressure balances using a pressure transducer, in *SICE, Japan* (2003), pp. 2125–2130
6. NIS Calibration certificate No. NIS-13/2013
7. NIS Calibration certificate of Thermo-hygrometer No. 27/32-1/2015
8. NIS Calibration certificate of Digital Pressure Indicator No. Yokogawa-Abs/2015
9. Organization International De Metrologie Legale, OIML R110-1994 (E)
10. V.E. Bean, "*NIST Pressure Calibration Service*", NIST Special Publication 250-39 (U.S. Department of Commerce Technology Administration, National Institute of Standards and Technology, U.S.A., 1994)
11. European cooperation for Accreditation of Laboratories Publication Reference EAL-G26, Edition, 1 July 1997
12. A. Eltawil, S. Gelany, A. Magrabi, Traceability of NIS Piston-Cylinder Assemblies up to 500 MPa, PTB-Mitteilungen **12**, 289–292 (2011)

Cite this article as: Alaaeldin A. Eltawil, Shaker A. Gelany, Validation of NIS 500 MPa hydraulic pressure measurement, Int. J. Metrol. Qual. Eng. **8**, 3 (2017)