Results of hydraulic pressure comparison in the range from 25 MPa to 200 MPa between NIS-Egypt and NIST-USA

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Abstract

The results of an informal pressure comparison between the National Institute of Standards and Technology (NIST), USA, and the National Institute of Standards (NIS), Egypt, are presented. The comparison was aimed to determine degree of equivalence between NIST and NIS in the pressure range from 25 MPa to 200 MPa at a reference temperature of 20 °C. The comparison used a transfer standard (TS) which was a piston-cylinder assembly (PCA) of 4.9 mm^2 nominal effective area. The results of the comparison show agreement between the laboratory results to within their claimed standard (k=1) uncertainties.

Introduction

Key comparisons APMP.M.P-K7 [1] and CCM.P-K7 [2], hydraulic gauge pressure from 10 MPa to 100 MPa, showed differences in the result between NIS and NIST. These differences were 70 ppm at 10 MPa, 15 ppm at 50 MPa and 9 ppm at 100 MPa; the difference at 10 MPa was larger than the combined expanded uncertainty of the difference. NIS and NIST initiated US-Egyptian project number (STM9-002-001), "Establishment of mutual coherence in the oil primary pressure standards used at NIST-US and NIS-Egypt" [3] to investigate these differences by directly comparing pressure standards. This report describes a bilateral comparison of hydraulic pressure standards that was carried out in from 2009 to 2010 to determine the degree of equivalence in the range 25 MPa to 200 MPa of gauge pressure.

The TS was cross-floated against the laboratory standards (LS) of NIS and NIST at nominal pressure points of (25, 50, 75, 100, 125, 150, 175, 200) MPa. The NIS laboratory standard was a pressure balance with a free deformation PCA of full range of 500 MPa, and a nominal effective area of 1.9 mm^2. The NIST laboratory standard was a reentrant pressure balance with a full range of 280 MPa and a nominal effective area of 8.40 mm^2. Measurements were conducted at NIST during March, 2009, and at NIS during February, 2010.Measurements at both institutes consisted of three complete and identical cycles of increasing and decreasing pressures at the nominal pressures noted above.

Transfer Standard

The TS used in the comparison was a piston-cylinder assembly Fig. 1 of free deformation type. The TS was acquired by NIS in 1997 from DH Budenberg [4]. The specifications and technical information of the TS are listed in Table 1.

Fig. 1.Free deformation PCA used as the TS.

Table 1. Specifications of the PCA used as the TS in the comparison. All uncertainties listed are standard (k=1).

Measurement range	2 MPa to 200 MPa
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Operation mode	Free-deformation
Nominal effective area	4.90 mm^2
Mass of piston	0.200004 kg $\pm$ 0.3 mg
Density of piston	7920 $kg/m^3 \pm$ 20 kg/m^3
Linear thermal expansion coefficient of piston (α_p)	(0.45 ± 0.05) $x10^{-5}$ $°C^{-1}$
Linear thermal expansion coefficient of cylinder (α_c)	(0.45 ± 0.05) $x10^{-5}$ $°C^{-1}$
Reference temperature (t_0)	20 °C

Each laboratory used their own pressure balance to mount the TS and their own mass set to apply force to the TS. Based on repeated calibrations of the TS at NIS over two years, the relative standard uncertainty in its effective area due to long term stability is estimated as 4 ppm.

NIST laboratory standard, PG21

PG21 is a working standard piston gauge that has been in service at NIST since 1978 [5]. The characterization and uncertainty of PG21 comes from comparison against two NIST controlled clearance primary pressure standards, designated as PG20 and PG67. The details of the metrological characteristics of PG21 are shown in Table 2. PG21 is used with Spinesstic oil.

NIS laboratory standard, PC- NIS13

The laboratory standard used at NIS is designated as PC-NIS13 [6]. PC-NIS13 is traceable to NIS primary standards. The characteristics of PC-NIS13 are also shown in Table 2. It is used with Sebacate oil.

Table 2. Description of the laboratory standards used at NIST and NIS. Uncertainties listed are standard (k=1).

	NIS	**NIST**
Name of standards	PC-NIS13	PG21
Measurement range	5 MPa to 500 MPa	14 MPa to 280 MPa
Material of piston	Stainless steel	Tungsten carbide
Material of cylinder	Tungsten carbide	Tungsten carbide
Operation mode	Free-deformation	Re-entrant
Zero-pressure effective area (A_0) at reference temperature	1.96122 mm^2	8.402894 mm^2
Relative uncertainty of A_0	17.0 x 10^{-6}	16.0 x 10^{-6}
Pressure distortion coefficient (λ)	8.5x10^{-7} MPa^{-1}	-2.744x10^{-6} MPa^{-1}
Uncertainty of λ	8.5x10^{-8} MPa^{-1}	Combined with uncertainty of A_0
Relative uncertainty of mass pieces in 10^{-6}	0.55	2.89
Linear thermal expansion coefficient of piston (α_p)	1.05x10^{-5} °C^{-1}	4.11x10^{-6} °C^{-1}
Linear thermal expansion coefficient of cylinder (α_c)	4.5x10^{-6} °C^{-1}	4.11x10^{-6} °C^{-1}
Reference temperature (t_0)	20 °C	23 °C
Local gravity (g)	9.79299376m/s^2	9.801010 m/s^2
Relative uncertainty of g	0.1 x 10^{-6}	0.2 x 10^{-6}
Height difference between LS and TS (h)	0 mm	0 mm
Uncertainty of h	1 mm	1 mm
Operating fluid	Sebacate	Spinesstic

Calibration procedure

When the TS and LS are pressurized to the same constant arbitrarily chosen pressure, the ratio of their effective areas is equal to the ratio of the total downward forces acting on each piston gauge at equilibrium.

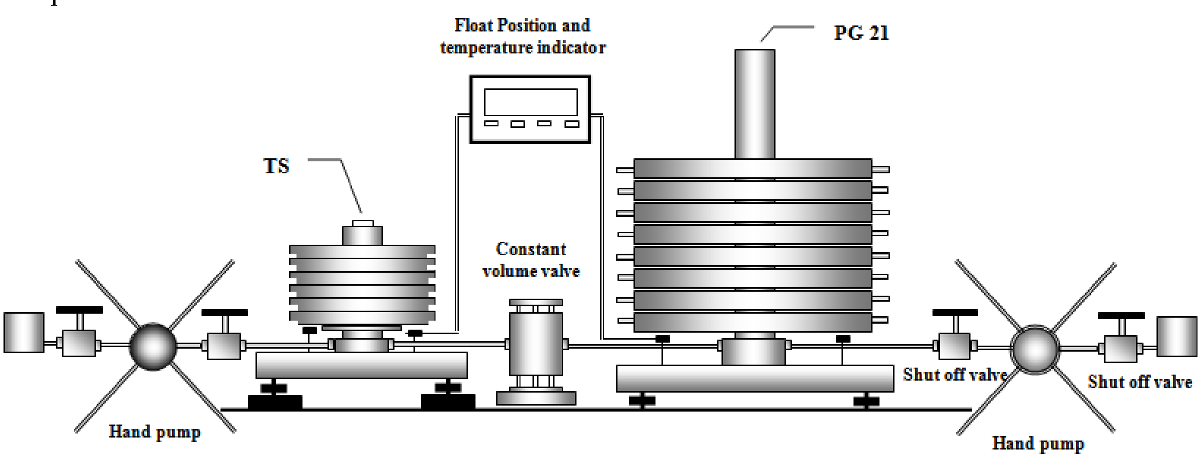

Fig.2.NIST experimental set-up showing the crossfloat system of TS versus LS.

Fig. 2 shows the NIST calibration system. The TS was mounted on a custom-designed base (shown on the left in Fig. 2) in which a proximity sensor was placed below the lowest mass to monitor the fall rate of the piston. The reference level of the TS in the base was the same as the reference level of PG21. NIST used Spinesstic in both the TS and LS. Before opening the valve between the LS and TS, the natural falling rate of both pressure balances was measured. At pressure equilibrium with the connecting valve open, there is no net fluid flow through the common pressure line, and the fall rates for the LS and the TS will be the same as the natural fall rate. Equilibrium is obtained by adjusting fractional masses on the LS.

NIS used the same measurement procedure as NIST and the set-up is shown in Fig. 3. Here, two identical pressure balance bases were used for the LS and the TS. NIS used Sebacate as the operating fluid.

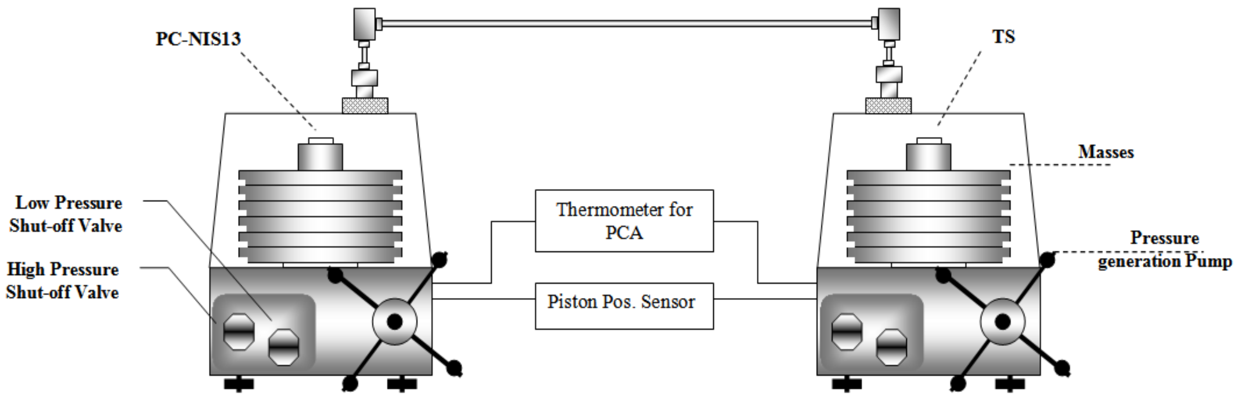

Fig. 3. NIS experimental set-up shows the crossfloat system of TS versus LS.

Results and discussion

The effective area of the TS at 20ºC, A'_p, for each pressure point of each cycle was determined from the following equation:

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

where:

m'_i true mass of element i of the masses applied on the piston;
ρ'_i density of the mass m'_i;
ρ_a air density;
g local acceleration of gravity;
σ' surface tension of the TS oil;
C' nominal circumference of the TS piston;
p' pressure generated by the laboratory standard at the TS reference level;
α'_p and α'_c thermal expansion coefficients of the piston and cylinder, respectively;
t' temperature of the TS.

The pressure at the level of the TS is calculated from:

$$p' = \frac{\sum_i m_i g\left(1-\frac{\rho_a}{\rho_i}\right)+\sigma C}{A_p\left(1+\left(\alpha_p+\alpha_c\right)\left(t-20\right)\right)} + \left(\rho_f-\rho_a\right)gh \quad . \tag{2}$$

Here, the first term on the RHS is the pressure generated by the LS, and the second term is the pressure due to the reference level differences between the LS and the TS. The parameters without the primes are the values at the LS, with the same definitions as above. The experimental data for the TS, A'_p as a function p', are measured at each nominal pressure for three cycles. Each cycle has a measurement in the ascending and descending direction, for a total of six measurements at each pressure. The averages of the six values are (p'_{av}, $A'_{p,av}$) and are listed in Table 3 for NIS and NIST.

Table 3. Average TS effective area and relative standard uncertainty at each pressure for NIS and NIST.

Laboratory Standard	p'_{av} (MPa)	$A'_{p,av}$ (mm^2)	$u_c(A'_{p,av})/A'_{p,av}$ x10^6
NIS	24.962444	4.903071	17
	49.925185	4.903030	18
	74.886860	4.903089	18
	99.847267	4.903185	19
	124.806496	4.903284	20
	149.764504	4.903390	21
	174.721416	4.903497	23
	199.677147	4.903604	24
NIST	24.982843	4.903000	17
	49.965103	4.903066	17
	74.946262	4.903142	17
	99.925993	4.903253	17
	124.904617	4.903364	17
	149.882200	4.903471	17
	174.858983	4.903572	17
	199.834767	4.903670	17

The uncertainty in the average effective area includes Type A and Type B components. The Type B components consist of the uncertainty from the LS and the calibration parameters ($u_B(A'_{p,av})$), along with the long-term stability of the TS ($u_{LTS}(A'_{p,av})$). The Type A ($u_A(A'_{p,av})$) uncertainty is taken as the standard deviation of the mean of the 6 observations that are averaged at each pressure. The Type B uncertainty is due mainly to the uncertainty in effective area of the LS, and also includes uncertainties in mass on both the LS and the TS, uncertainties in temperature of the LS and TS, uncertainties in the thermal expansion of the LS and TS, uncertainty in the head correction, and uncertainty in gravitational acceleration. The relative long-term stability uncertainty is estimated as 4 ppm. All components are listed at the standard level (k=1).

The uncertainty components are added in quadrature according to:

$$u_c\left(A'_{p,av}\right)=\left[u_A\left(A'_{p,av}\right)^2+u_B\left(A'_{p,av}\right)^2_{\text{NIS or NIST}}+u_{LTS}\left(A'_{p,av}\right)^2\right]^{1/2} \tag{3}$$

The combined standard uncertainty on a relative basis is listed in the fourth column of Table 3. Each laboratory fit the measured average effective area vs. pressure data to a linear distortion model using a least squares linear regression, given by:

$$A'_{p,fit}=A'_0\left(1+\lambda' p'\right) \tag{4}$$

Here, A'_0 and λ' are the fitted zero pressure effective area and distortion coefficient, respectively. Table 4 gives the values for NIST and NIS; the combined standard uncertainty, $u_c(A'_0)$, is given by the Type B uncertainty of eq. (3) along with the Type A uncertainty of the linear regression fit at $p' = 0$.

Table 4.Results of linear distortion model fit for A'_0 and λ for NIS and NIST.

Laboratory	A'_0 (mm^2)	$u_c(A'_0)/A'_0$ (ppm)	λ' (MPa^{-1})x10^{-7}
NIST	4.902872	17	8.1
NIS	4.902890	17	6.9

The relative difference in A'_0 between the two laboratories was 3.7 ppm, which is less than the relative standard uncertainty from either laboratory.

Calculation of lab to lab degree of equivalence

The lab to lab degree of equivalence is evaluated using the standard method for a CIPM bilateral comparison [7]. The difference in measured effective areas between NIST and NIS at each pressure is compared to the expanded uncertainty of the difference. If the difference is less than the expanded uncertainty, then there is equivalence between the laboratories at that pressure. Or,

$$d=A'_{p,av,NIST}-A'_{p,av,NIS} \tag{6}$$

and

$$u(d)=\left(u_c(A'_{p,av,NIST})^2+u_c(A'_{p,av,NIS})^2\right)^{1/2} \tag{7}$$

There is equivalence if the absolute value of d is less than $2u(d)$.

The results of the degree of equivalence are given in Table 5 and are plotted in Fig. 4. The difference and uncertainty are normalized to the average effective area of the TS from NIS and NIST, $A_{p,Ave}$. As can be seen, there is equivalence at all pressures at the k=1 level.

Table 5. Degree of equivalence between NIST and NIS expressed as a relative difference in effective area of the transfer standard, and the expanded uncertainty of the relative difference.

Nominal P (MPa)	$d / A_{p,Ave}$ (x10^6)	$2u(d) / A_{p,Ave}$ (x10^6)	$d / (2u(d))$
25.0	-14.3	48.6	-0.29
49.9	7.3	49.3	0.15
74.9	10.9	49.9	0.22
99.8	14.0	51.1	0.27
124.8	16.4	52.6	0.31
149.8	16.4	54.4	0.30
174.7	15.3	56.5	0.27
199.7	13.4	58.9	0.23

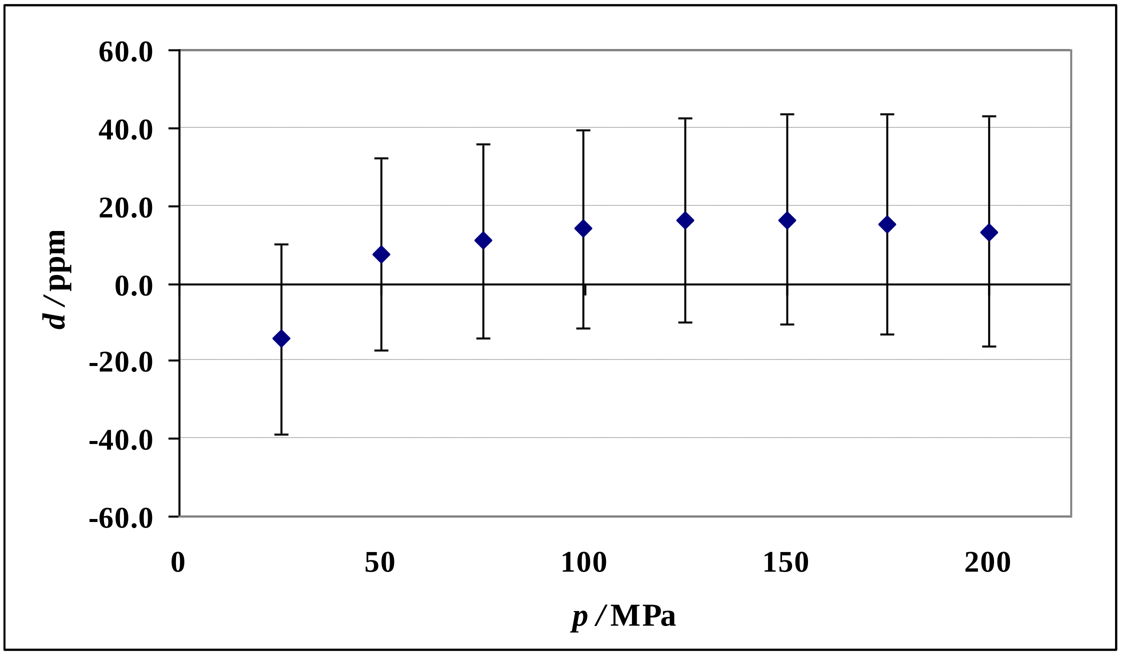

Fig. 4. Degree of equivalence between NIST and NIS plotted as the relative difference in effective area vs. pressure. Error bars are the standard uncertainty of the difference.

Conclusions

The effective area values determined by NIS, Egypt, and NIST, USA at eight nominal pressures from 25 MPa to 200 MPa in steps of 25 MPa were in a good agreement with each other; the difference in effective area was less than the standard uncertainty of the difference. The relative difference in effective area at 25 MPa in this work was 14.3 ppm, compared with the difference of 70 ppm at 10 MPa from APMP.M.P-K7 when linked to CCM.P-K7 [1, 2]. This improved coherency between the laboratories could be the result of the redefinition of the pressure scale at NIS [6].

The difference between the fitted values of pressure distortion coefficient as given in Table 4 is 15%, which can be attributed to the increased effective area measured by NIS at 25 MPa. If data were fit from 50 MPa to 200 MPa, the distortion coefficients of NIS and NIST would agree to within 5 %.

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4- Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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