
EVALUATION ON THE CONSISTENCY OF CALIBRATION RESULTS BETWEEN REFERENCE STANDARDS OF PNEUMATIC PRESSURE BALANCE BASED ON NON-FULL RANGE CALIBRATION

Evaluasi Konsistensi Hasil Kalibrasi Antara Standar DWT Pnumatik Berdasarkan Kalibrasi Pada Sebagian Rentang

Adindra Vickar Ega dan R.Rudi Anggoro Samodro

Center for Research and Human Resource Development – National Standardization Agency of Indonesia,
Kompleks Puspiptek Gedung 420, Setu, South Tangerang, Indonesia 15314

e-mail: ega@bsn.go.id

Diterima: 1 April 2019, Direvisi: 4 Oktober 2019, Disetujui: 8 November 2019

Abstract

To provide calibration services for pressure measuring devices, SNSU-BSN has several piston-cylinder standard that may traceable to different National Metrology Institute (NMIs). Non-full range calibration of pressure balance has been performed to evaluate the consistency of calibration results between those standard, especially for establishing self-traceability in the future. In this research, a piston-cylinder unit S/N 1926 with medium pressure range of 1750 kPa, was calibrated with low pressure range S/N 978 of 350 kPa and high pressure range S/N 1054 of 7000 kPa. The calibration was performed with cross-float method to evaluate the effective area of piston-cylinder at null pressure and reference temperature of 20°C ($A_{0,20}$) and distortion coefficient (λ) as the 1926 main parameters. The obtained value, respectively are $(1.961\ 166 \times 10^{-4} \pm 4.4 \times 10^{-9})\ m^2$ and $(-1.67 \times 10^{-12} \pm 9.4 \times 10^{-13})\ Pa^{-1}$ from 978 and $(1.961166 \times 10^{-4} \pm 5.1 \times 10^{-9})\ m^2$ and $(-1.58 \times 10^{-12} \pm 8.4 \times 10^{-13})\ Pa^{-1}$ from 1054. The result of 1926 from both methods shows good conformity with Normalized Error (E_n) of 0.0007 and 0.069, respectively. Linearity of effective area changes to the pressure is very consistent in both low and high pressure range. Validation results by using PTB-Germany results, shows the relative different for A_0 and λ obtained are less than $0,1 \times 10^{-6}$ and 6%, respectively. Therefore, the pneumatic pressure balance of SNSU-BSN is traceable, consistent with each other and capable for disseminating the pressure unit along all primary pressure standard owned with high agreement compared to those of other advance NMIs.

Keywords : consistency between standard, non-full range calibration, pneumatic, pressure balance

Abstrak

Untuk layanan kalibrasi alat ukur tekanan, SNSU-BSN memiliki beberapa standar piston-silinder yang dapat tertelusur ke berbagai NMI. Kalibrasi pressure balance pada sebagian rentang telah dilakukan untuk mengetahui konsistensi hasil kalibrasi antara standar DWT pnumatik yang dimiliki dalam membangun ketertelusuran mandiri untuk semua standar primer tekanan di SNSU-BSN yang memiliki perbedaan rentang tekanan antara satu dengan yang lainnya. Pada penelitian ini, sebuah piston-silinder unit S/N 1926 dengan kapasitas medium hingga 1750 kPa, dikalibrasi dengan S/N 978 kapasitas tekanan rendah hingga 350 kPa dan S/N 1054 kapasitas tekanan tinggi hingga 7000 kPa. Kalibrasi dilakukan dengan menggunakan metode cross-float untuk mengevaluasi luasan efektif piston-silinder pada tekanan nol dan suhu acuan 20°C ($A_{0,20}$) dan koefisien distorsi (λ) sebagai parameter hasil kalibrasi piston-silinder 1926. $A_{0,20}$ dan λ yang didapat adalah $(1.961\ 166 \times 10^{-4} \pm 4.4 \times 10^{-9})\ m^2$ dan $(-1.67 \times 10^{-12} \pm 9.4 \times 10^{-13})\ Pa^{-1}$ dengan piston-silinder 978 dan $(1.961\ 166 \times 10^{-4} \pm 5.1 \times 10^{-9})\ m^2$ and $(-1.58 \times 10^{-12} \pm 8.4 \times 10^{-13})\ Pa^{-1}$ dengan piston-silinder 1054. Hasil kalibrasi piston-silinder 1926 dari kedua metode menunjukkan kesesuaian yang baik dengan error ternormalisasi (E_n), yaitu masing-masing 0,0007 dan 0,069. Linearitas perubahan luas efektif piston-silinder terhadap tekanan sangat konsisten baik pada rentang tekanan rendah maupun tinggi. Dari hasil validasi menggunakan nilai hasil kalibrasi dari PTB-Jerman, didapatkan bahwa perbedaan relatif untuk $A_{0,20}$ dan λ tersebut masing-masing adalah dibawah $0,1 \times 10^{-6}$ dan 6%. Dapat disimpulkan bahwa standar DWT pnumatik yang dimiliki oleh SNSU-BSN selain tertelusur juga memiliki hasil kalibrasi yang konsisten antara satu dengan lainnya dan dapat digunakan untuk diseminasi satuan tekanan dengan tingkat kesesuaian yang tinggi dibandingkan dengan NMI maju.

Kata kunci : kalibrasi sebagian rentang, konsistensi antar standar, pnumatik, DWT

1. INTRODUCTION

Pressure Balance is the primary standard in the field of pressure metrology, which has been used

by SNSU-BSN, as well as many other National Metrology Institute, to provide traceability of pressure measurement for calibration laboratories and industries in Indonesia (Ega &

Samodro, 2014). Those pressure balance itself are traceable to the SI unit, either by the SNSU-BSN or through other developed NMIs. As for example the mass of the pressure balance has been traceable to the mass standard owned by Mass Laboratory of SNSU-BSN. However, the effective area of several piston-cylinders are still depends on the primary pressure standard of the other developed NMIs, such as PTB-Germany, KRISS-Korea and NMIJ-Japan. Therefore, a five years period of Pressure Laboratory road map program has been proposed, one of them is to develop the capability in maintaining of primary pressure standard through the independent calibration chain, with means of calibrating its primary pressure standard by the lab itself (Samodro & Ega, 2016), (Samodro et al, 2012).

Typically, the calibration of pressure balance is performed with the full range calibration by using an appropriate or the best matches with the desired pressure range and accuracy of piston gauge standards (Olson, 2009). The full range calibration of pressure balance means that the direct comparison method between pressure balance to be calibrated (DUT) and the reference pressure balance (STD) is performed until the maximum pressure range of the DUT.

However, as the masses are fixed, the pressure generated by the pressure balance depends on the size of its piston-cylinder effective area, which resulting in the different pressure range and limitation of maximum pressure of each piston-cylinder pressure balance can be generated. Meanwhile, the traceability chain is necessary to be realized from low pressure until high pressure (Bair, 2011) (Owen, 2011). Therefore, a non-full range calibration method has been proposed to realize the independent calibration chain. The non-full range calibration of pressure balance means that the direct comparison method between pressure balance to be calibrated (DUT) and the reference pressure balance (STD) is performed until the maximum pressure range of the STD, due to the different pressure range between STD and DUT.

A preliminary study of non-full range calibration method in the calibration of pressure balance has been performed before (Samodro & Ega, 2016). The results was satisfactory proven by the deviation of the effective area $A_{(0,20)}$ less than 2 parts per million (ppm) from the last certificate calibration with full range calibration. Therefore, the research is continued with the purpose to ensure that the reference standards of pneumatic pressure balance owned by SNSU-BSN are traceable and consistent with each other, before conducting the development of self-traceability in pneumatic pressure of SNSU-BSN,

by means of self-disseminating of all primary pneumatic pressure standard in SNSU-BSN that has different pressure range with each other.

2. BASIC THEORY

Pressure Balance is the primary standard in the pressure measurement, which its pressure (P) is defined by weight set that generate force acting on the piston-cylinder (P/C) effective area according to the Equation (1) : (Ginanjari, Ega & Samodro, 2017)

$$P = \frac{m \cdot g}{A_{p,t}} \dots \dots \dots (1)$$

Where:

- m = Total loaded true mass on the piston-cylinder assembly, kg
- g = Local gravity acceleration, m/s²
- $A_{p,t}$ = Effective area of the piston-cylinder at certain pressure (p) and temperature (t)

Typically, the piston-cylinder effective area changes with respect to the pressure (A_p) has the characteristic as linear function of pressure, as shown in Equation (2) - (3) and Figure 1 (Ramnath, 2011) (Olson, Driver & Bowers, 2010):

$$A_p = A_0 \cdot (1 + \lambda \cdot p) \dots \dots \dots (2)$$

or :

$$A_p = A_0 + A_0 \lambda \cdot p \dots \dots \dots (3)$$

where :

- A_0 = Effective area of PC unit at null pressure and reference temperature (m²)
- λ = Distortion coefficient (Pa⁻¹)

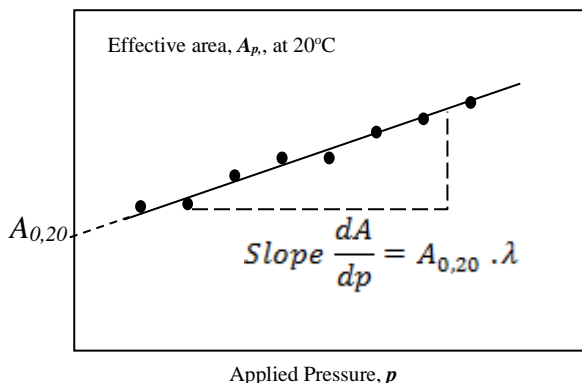


Figure 1 Linear dependency of effective area P/C at against to the applied pressure (RCM-LIPI, 2018).

The main parameters value of the pressure balance (A_0, λ) can be calculated by the following

Equation (4) until Equation(6) (Ega & Samodro, 2017):

$$A_0 = \frac{\sum p_j^2 \sum A_{pj} - \sum p_j \cdot \sum p_j \cdot A_{pj}}{N \cdot \sum p_j^2 - (\sum p_j)^2} \dots\dots (4)$$

$$\theta_1 = \frac{N \cdot \sum p_j \cdot A_{pj} - \sum p_j \cdot \sum A_{pj}}{N \cdot \sum p_j^2 - (\sum p_j)^2} \dots\dots (5)$$

$$\lambda = \frac{\theta_1}{A_0} \dots\dots\dots (6)$$

where :

- p_j = Generated pressure on each pressure calibration point (Pa)
- A_{pj} = Effective area of PC at each pressure calibration point (m²)
- θ_1 = Slope from the linear function curve

The type-A uncertainty of each A_0 dan λ that can be determined by calculating standard deviation of A_p , standard deviation of the intercept (A_0), standard deviation of the slope (θ_1) from number of n measurement data according to the Equation (7) until Equation (11) (Morrison, 2014).

$$s_{A_p} = \sqrt{\frac{\sum (A_{pj} - A_0 - A_0 \cdot \lambda p_j)^2}{n-2}} \dots\dots\dots (7)$$

$$s_{A_0} = s_{A_p} \sqrt{\frac{\sum p_j^2}{n \sum p_j^2 - (\sum p_j)^2}} \dots\dots\dots (8)$$

$$s_{\theta_1} = s_{A_p} \sqrt{\frac{n}{n \sum p_j^2 - (\sum p_j)^2}} \dots\dots\dots (9)$$

$$u_A(A_0) = s_{A_0} \cdot \sqrt{n} \dots\dots\dots (10)$$

$$u_A(\lambda) = \frac{s_{\theta_1}}{A_0} \dots\dots\dots (11)$$

The type-B uncertainty of A_0 comes from the effective area of P/C that has been corrected to the reference temperature of 20°C at applied pressure ($A_{p,20}$) equation, as described in Equation (12) – (14)

$$u_B(A_0) = \left[u(A_{p,20}) \left(\frac{\partial A_{0,20}}{\partial A_{p,20}} \right) \right] \dots\dots\dots (12)$$

$$A_{p,20} = \frac{[\sum (M_i + m) \cdot (1 - \frac{\rho_a}{\rho_{M_i}}) - V(\rho_f - \rho_a)] g}{P_s (1 + \alpha(t_p - 20))} \dots\dots (13)$$

$$u(A_{p,20}) = \left[u(M_i) \left(\frac{\partial A_{p,20}}{\partial M_i} \right) + u(m) \left(\frac{\partial A_{p,20}}{\partial m} \right) + u(\rho_a) \left(\frac{\partial A_{p,20}}{\partial \rho_a} \right) + u(\rho_{M_i}) \left(\frac{\partial A_{p,20}}{\partial \rho_{M_i}} \right) + u(V) \left(\frac{\partial A_{p,20}}{\partial V} \right) + u(\rho_f) \left(\frac{\partial A_{p,20}}{\partial \rho_f} \right) + u(g) \left(\frac{\partial A_{p,20}}{\partial g} \right) + u(P_s) \left(\frac{\partial A_{p,20}}{\partial P_s} \right) + u(\alpha) \left(\frac{\partial A_{p,20}}{\partial \alpha} \right) + u(t_p) \left(\frac{\partial A_{p,20}}{\partial t_p} \right) \right] \dots\dots (14)$$

Where:

- M_i = Total loaded true mass on the piston-cylinder assembly, kg
- M = Additional trim mass, kg
- ρ_a = Air density, kg/m³
- ρ_{M_i} = Mass density, kg/m³
- V = Volume buoyancy of the piston-cylinder assembly, m³
- G = Local gravity acceleration, m/s²
- P_s = Applied pressure standard, Pa
- α = Thermal expansion coefficient of the piston-cylinder assembly, °C⁻¹
- t_p = Temperature of the piston-cylinder assembly, °C

The type-B uncertainty of λ comes from the slope of linear regression, as shown in Equation (15) – (17) :

$$Slope = (A_{0,20}) \cdot \lambda \dots\dots\dots (15)$$

$$\lambda = \frac{Slope}{(A_{0,20})} \dots\dots\dots (16)$$

$$u_B(\lambda) = \left[-\frac{Slope}{(A_{0,20})^2} u(A_{0,20}) \right] \dots\dots\dots (17)$$

Therefore, the combined uncertainty for the A_0 and λ are :

$$u(A_{0,20})^2 = [s_{A_0} \cdot \sqrt{n}]^2 + \left[u(A_{p,20}) \left(\frac{\partial A_{0,20}}{\partial A_{p,20}} \right) \right]^2 \dots\dots (18)$$

$$u(\lambda)^2 = \left[\frac{s_{\theta_1}}{A_0} \right]^2 + \left[-\frac{Slope}{(A_{0,20})^2} u(A_{0,20}) \right]^2 \dots\dots (19)$$

The conformity of the measurement results obtained from two different methods can be clarified by using the Normalized Error (E_n) equation, as shown in Equation (20) :

$$E_n = \frac{|X_A - X_B|}{\sqrt{U(X_A)^2 + U(X_B)^2}} \dots\dots (20)$$

Where:

- X_A = the measurement value from method A
- X_B = the measurement value from method B
- $U(X_A)$ = the expanded uncertainty from method A
- $U(X_B)$ = the expanded uncertainty from method B

Both methods results are said to be conformed with each other if the $|E_n| \leq 1$ (Ega & Samodro, 2014). This E_n can also be used to compare both calibration results, from method A and method B, with other value assumed as reference for the validation process.

3. METHOD

Figure 2 describes the non-full range pneumatic pressure balance calibration in SNSU-BSN. At the first step, the 1926 as the test Piston-Cylinder Assembly (PCA) with medium pressure range up to 1750 kPa is calibrated against low pressure range reference standard PCA 978 up to 350 kPa. The 978 is installed on the primary pressure balance with base number 169 with automatic mass handling (AMH), while the 1926 is installed on the secondary pressure balance with base number 1083 with manual mass load, as shown in Figure 3.

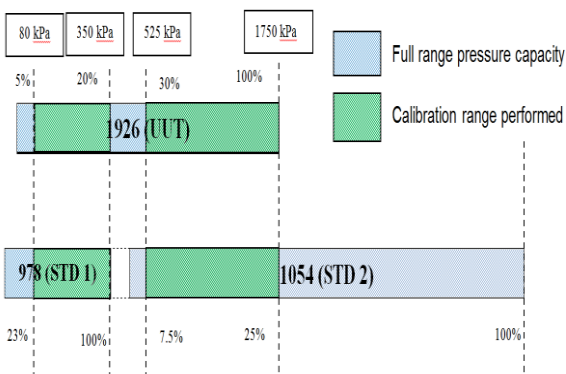


Figure 2 Non-full range calibration of the 1926 with two intersection range of standard.

The calibration was performed at 10 pressure intersection points (80 kPa, 110 kPa, 140 kPa, 170 kPa, 200 kPa, 230 kPa, 260 kPa, 290 kPa, 320 kPa, and 350 kPa) with three measurement series that consists of two increasing pressure measurement series and one decreasing pressure measurement series to evaluate the uncertainty from measurement repeatability.

In the second step, the 1926 PCA is calibrated against high pressure range reference

standard PCA 1054 up to 1750 kPa. The 1054 is installed on the primary pressure balance with base number 169 with AMH, while the 1926 is installed on the secondary pressure

balance with base number 1083 with manual mass load. The calibration is performed at 8 pressure intersection points (525 kPa, 700 kPa, 875 kPa, 1050 kPa, 1225 kPa, 1400 kPa, 1575 kPa, 1750 kPa) with three measurement series that consists of two increasing pressure measurement series and one decreasing pressure measurement series to evaluate the uncertainty from measurement repeatability.

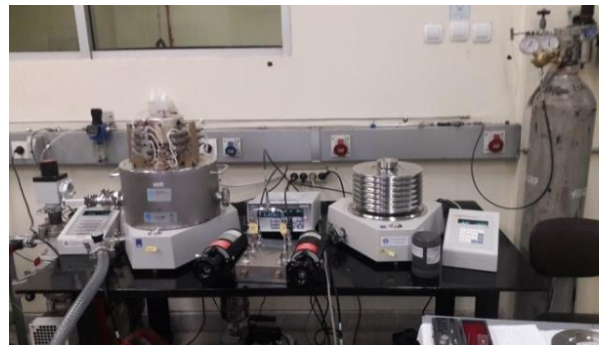


Figure 3 Pneumatic pressure balance calibration set up.

Both measurements conducted with two series of increasing pressure and one series decreasing pressure, according to the I.MM.3.03 SNSU-BSN procedure, which refers to the EURAMET cg-3 for pressure balance calibration (SNSU-BSN, 2019) (EURAMET, 2011).

The main parameters of the 1926 as the calibrated pressure balance ($A_{0,20}$ and λ) are calculated by using Equation (4) - (6), while for the uncertainties of both parameters are calculated by using Equation (7) - (19). The conformity of the calibration results between both measurements method are evaluated with E_n by using Equation (20). The linearity of the calibration has been investigated using all result from both reference standards along the coverage range. Validation of the non-full range calibration results in this research is performed by comparing the main parameters value, as well as its expanded uncertainty obtained between both methods with the value provided from the PTB calibration certificate, that used the full-range calibration method in their calibration method with direct comparison by means of the cross-float method (PTB, 2017).

4. RESULTS AND DISCUSSIONS

Figure 4 and Figure 5 represents the 1926 PCA effective area changes with respect to the pressure, when calibrated with the 978 and 1054 as the reference standard, respectively. From three series of measurement with two series of increasing pressure and one series of decreasing

pressure, it can be seen that the effective area of 1926 decreases linearly as the applied pressure increase. The effective area changes are fluctuates at each pressure point and measurement series, but resulting in linear function of pressure from the average of three measurement series.

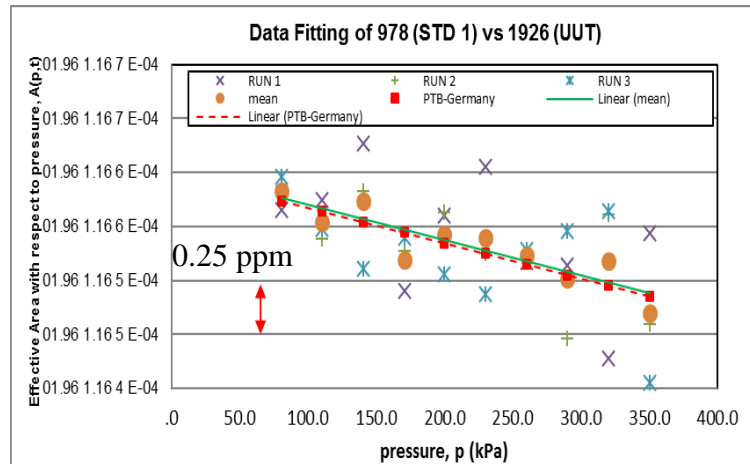


Figure 4 Calibration results of 1926 with the 978 as the reference standard.

As shown in Figure 4 and Figure 5, the standard deviation of the 1926 when calibrated with the 1054 are slightly larger compared to those when calibrated with the 978. The maximum relative standard deviation is $1,9 \times 10^{-6}$ from calibration with the 1054, while from

the 978 is $0,4 \times 10^{-6}$. It might due to practical reason that the sensitivity of cross-float is much higher using smaller diameter of PCA in relatively high pressure, while gas as the pressure medium is compressible.

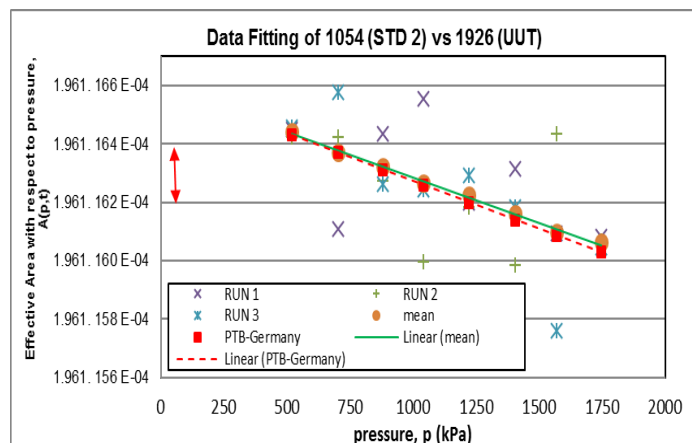


Figure 5 Calibration results of 1926 with 1054 as the reference standard..

Figure 6 shows the linearity of the effective area changes with respect to the pressure, A_p in the whole pressure range, combination of the calibration results of 1926 from the 978 at low pressure and 1054 at low pressure from the average of three measurement series. The linear curve of 1926 effective area during calibration against 978 up

to 350 kPa shows conformity with those of calibrated against 1054 up to 1750 kPa. Therefore, it can be said that the full range of the 1926 maximum capacity, which is 1750 kPa, has been calibrated from 80 kPa until 1750 kPa with high agreement through double calibration by using multiple piston gauge standards.

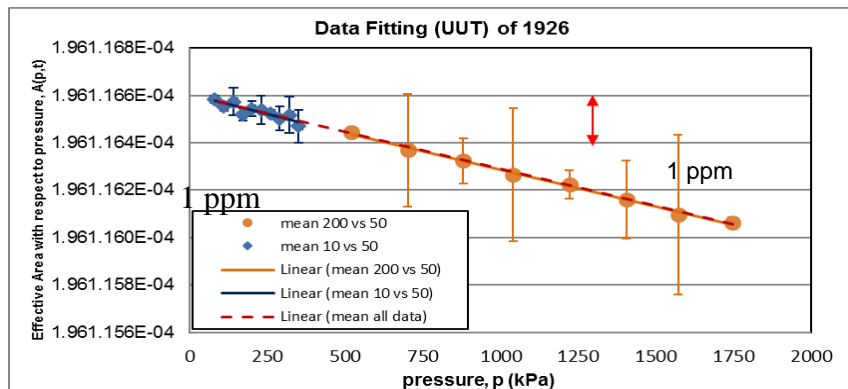


Figure 6 Calibration results of 1926 from both reference standards of 978 and 1054.

From the linear regression analysis according to the Equation (2) until Equation (15), the main parameter of the 1926 PCA, which are A_0 and λ obtained from both reference standards, are presented in Table 1, with the uncertainty component described in Table 2. The standard or combined uncertainty of the 1926 effective area at null pressure (A_0) with 1054 as the reference standard is larger than those of effective area with 978 as the reference standard, where the expanded uncertainty of A_0 with the 1054 is 26×10^{-6} while

with the 978 is 22×10^{-6} . The main contribution for the uncertainty comes from the Type-B uncertainty of those reference standards 978 and 1054 itself with standard uncertainty of 11×10^{-6} and 13×10^{-6} , respectively. While the Type-A uncertainty are small with value of 0.6×10^{-6} and 2.5×10^{-6} , for 978 and 1054 respectively as presented in Table 2. It shows that the A_0 can be determined accurately with better uncertainty in low pressure, than those of in the higher pressure.

Table1 Calibration results of 1926 (50 kPa/kg) from both reference standards.

Parameter	1926 against 978 as STD PCA		1926 against 1054 as STD PCA	
	Value	U (k=2)	Value	U (k=2)
A_0 (m ²)	$1.961\ 166 \times 10^{-4}$	4.4×10^{-9}	$1.961\ 166 \times 10^{-4}$	5.1×10^{-9}
λ (Pa ⁻¹)	-1.67×10^{-12}	9.4×10^{-13}	-1.58×10^{-12}	8.4×10^{-13}

In the other hand, the standard uncertainty of the 1926 distortion coefficient (λ) from both reference are similar and big as presented in Table 3. This due to the some measurement point has poor repeatability due to cross float sensitivity which is illustrated with

wide error bar in Figure 6. This could be improved by using another reliable calibration method that could overcome cross float sensitivity method is transducer assisted cross-float (TAC) method (Ega & Samodro, 2017).

Table 2 Uncertainty component for the A_0 value calibration results for the 1926.

Uncertainty component	1926 against 978 as STD PCA	1926 against 1054 as STD PCA
	($\times 10^{-6}$)	($\times 10^{-6}$)
$u_A(A_0)$ type-A	0.6	2.5
$u_B(A_0)$ type-B	11	13
Combined uncertainty $u_c(A_0)$ at k = 1	11	13
Expanded uncertainty $U(A_0)$ at k = 2, in ppm	22	26
Expanded uncertainty $U(A_0)$ at k = 2, in m ²	4.4×10^{-9}	5.1×10^{-9}

The conformity of calibration results of the 1926 from both methods with 978 and 1054 as reference standard shows very good conformity based on the calculation with the

Normalized Error (En) of 0.0007 and 0.069, respectively as presented in Table 4. It shows that both reference standards are consistent with each other.

Table 3 Uncertainty component for the λ value calibration results for the 1926.

Uncertainty component	1926 against 978 as STD PCA	1926 against 1054 as STD PCA
	(%)	(%)
$u_A(\lambda)$ type-A	28	27
$u_B(\lambda)$ type-B	0.1	<0.1
Combined uncertainty $u_c(\lambda)$ at $k = 1$	28	27
Expanded uncertainty $U(\lambda)$ at $k = 2$, in%	56	53
Expanded uncertainty $U(\lambda)$ at $k = 2$, in Pa^{-1}	9.4×10^{-13}	8.4×10^{-13}

Table 4 Normalized Error (En) of the 1926 parameter value from both calibration results

Parameter	Normalized Error (En)
A_0 (mm^2)	0.0007
λ (Pa^{-1})	0.069

Finally, for the validation, the main parameters of the 1926 values obtained are approximately the same when compared with the value from the calibration certificate provided by the PTB-Germany for the validation, with the value of A_0 and λ respectively are $(1.961\ 166 \times 10^{-4} \pm 1.6 \times 10^{-9}) \text{ m}^2$ and $(-1.67 \times 10^{-12} \pm 1.7 \times 10^{-13}) \text{ Pa}^{-1}$. The relative differences between the obtained A_0 and λ value from both methods with the PTB-Germany results are less than 0.1×10^{-6} and 6%, respectively, with En less than 0.07.

The calibration results of the 1926 from the SNSU-BSN shows very good conformity with PTB-Germany calibration results. Therefore, it can be concluded that the reference standard of pneumatic pressure balance which owned by SNSU-BSN are consistent with each other, according from the calibration results.

5. CONCLUSION

Experiments and evaluation of the non-full range calibration of pneumatic pressure balance in SNSU-BSN were successfully performed. The calibration results of the 1926 shows good agreement when calibrated against 978 and 1054 with En far less than 1,

respectively. This proves that those reference standards are consistent with each other, regardless the differences of the pressure range between them.

Moreover, this has been validated by comparing the obtained values of $A_{0,20}$ and λ with the calibration certificate given by PTB-Germany in which is known as the advance NMI. The relative different between them were less than 0.1×10^{-6} and 6%, respectively, considering the typical uncertainty for this test PCA is 5×10^{-6} and 10%.

In addition, the establishment of self-traceability chain, from low pressure range of primary pneumatic PCA standard to high pressure range PCA standard in SNSU-BSN is potentially to be performed by using the proposed non-full range calibration method.

ACKNOWLEDGMENT

The author wishes to express his thanks to the Management of SNSU-BSN for the realization of the new medium pressure range piston-cylinder assembly DHI PG7601 S/N 1926, as well as for the calibration to the PTB-Germany.

REFERENCES

- Bair, M.(2011). A method for verifying traceability in effective area for high pressure oil piston-cylinder. 2011 NCSL International Workshop & Symposium.
- Ega, A. V.& Samodro, R. R. A.(2017). Penentuan parameter hasil kalibrasi Dead Weight Tester (DWT) berdasarkan analisa curve fitting. *PPI-KIM*, 43, 126–138.
- Ega, A. V.& Samodro, R. R. A.(2017).TAC

- method to overcome the practical difficulty in the calibration of DWT with insensitive piston. Presented on the 1st International Conference on Metrology (ICONMET) October 25-26 2017 in Jakarta, Indonesia.
- Ega, A. V., & Samodro, R. R. A. (2017). Analysis of MSL TG-13 pressure gauge calibration method. *Instrumentasi*, 38(2), 33-42.
- Ega, A. V., & Samodro, R. R. A. (2014). Pengecekan-antara pressure balance standar sebagai implementasi jaminan mutu laboratorium tekanan puslit metrologi lipi sesuai dengan sni iso/iec 17025: 2008. *Prosiding PPI Standardisasi*, 43-54.
- EURAMET. (2011). Calibration of pressure balance.
- Ginanjari, G., Ega, A. V. & Samodro, R. A. (2017). The characterization of automatic additional-mass handling for pressure balance interval checks. *12th Annual Meeting on Testing and Quality*, 28-31.
- Morrison, F. A. (2014). Obtaining uncertainty measures on slope and intercept of a least squares fit with Excel's LINEST.
- Olson, D. A. (2009). NIST calibration services for pressure using piston gauge standards. *NIST Special Publication*, 250, 39.
- Olson, D. A., Driver, R. G., & Bowers, W. J. (2010). A gas pressure scale based on primary standard piston gauges. *Journal of research of the National Institute of Standards and Technology*, 115(6), 393-412.
- Owen, N. (2011). Linking Hydraulic and Pneumatic Pressure Scales Using a Common Piston Gauge. In "5th CCM international conference on pressure and vacuum metrology" and the "4th international conference IMEKO TC16 (Vol. 121, No. 3, p. 281).
- PTB. (2017). Calibration certificate of pressure balance PG-7601 : PTB 30099/17. Germany.
- Ramnath, V. (2011). Determination of pressure balance distortion coefficient and zero-pressure effective area uncertainties. *International Journal of Metrology and Quality Engineering*, 2(2), 101-119.
- RCM-LIPI. (2018). *I.MM.3.03 Procedure of the pneumatic pressure balance calibration*. South Tangerang
- Samodro, R. A. & Ega, A. V. (2016). Kalibrasi pressure balance pada sebagian rentang dan analisa efektivitasnya dalam membangun sumber ketertelusuran pada lingkup tekanan. *PPI-KIM Ke-42*, 333-342.
- Samodro, R. A. et al. (2012). *Roadmap laboratorium tekanan (5 tahun)*, Slide Presentasi, Jakarta : Puslit Metrologi LIPI