ESTABLISHMENT OF THAILAND PRESSURE STANDARD FROM 1.5 kPa TO 500 MPa

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Abstract:

This paper describes the method used to characterize the zero-pressure effective area (A_0) and pressure distortion coefficient (λ) of 200MPa-CCPG oil piston-cylinder unit (PCU) in order to realize the national pressure scale from 1.5 kPa to 500 MPa. The A_0 was determined by cross-floating method from a set of primary gas pressure standard, while the H-W method was used for calculating λ. A set of three oil PCUs was maintained as a primary pressure standard and used for scaling up and down pressure to determine λ for the other PCUs. The relative standard uncertainty of 200MPa-CCPG pressure standard is 3.0×10^{-5}.

Keywords: Zero-effective area; pressure distortion coefficient; primary standard

1. INTRODUCTION

Nowadays, pressure balances are still widely used as the primary pressure standard in many National Metrology Institutes (NMIs) from a few kPa up to approximately 1 GPa. The pressure balance consists of a loaded piston inserted into a closed fitting cylinder. The effective area (A_e) of PCU is commonly defined as a function of the effective area at zero pressure (A_0), the applied pressure (p) and the pressure distortion coefficient (λ) as equation (1),

$$A_e = A_0(1 + \lambda \cdot p) . \tag{1}$$

To determine an A_e for the pressure from a few kPa to 50 MPa, the most important parameter is A_0 which decisively defines the accuracy of the pressure measurement. While the pressure more than 50 MPa, the main uncertainty contribution of the pressure measurement becomes to λ. Therefore, the controlled-clearance piston gauge (CCPG) is widely used as the primary standard in many NMIs [1,2,3] for high pressure scale in order to realize and optimize the uncertainty estimation of λ.

The pressure laboratory of National Institute of Metrology (Thailand), NIMT started to establish the gas primary pressure standards from 1.5 to 350 kPa since 2012 by using the dimensional properties to determine A_0 [4]. Then the pressure standard obtained from the dimensional measurement were initially used to determine the effective area at zero pressure (A_0) up to pressure 500 MPa by using the cross-floating method.

During 2008 to 2014, λ was characterized by using the Heydemann and Welch method (H-W) [5] on the controlled-clearance piston gauge (CCPG), pressure range from 20 to 200 MPa (Figure 1). Then pressure standard of CCPG is used for scaling up to 500 MPa and down to 1 MPa in order to calculate λ.

Figure 1: Experiment set-up for the Heydemann and Welch method

In this paper, the characterizing and maintaining of NIMT primary oil pressure standards are summarized. The method for applying the primary high pressure standard values in order to realize the national pressure scale from 1.5 kPa to 500 MPa is described.

2. DESCRIPTION OF THE WORK

The controlled-clearance piston-cylinder unit, 200 MPa-CCPG, No. 799 which manufactured by DH Instruments was used to characterize A_0 and λ, as the followings. Both piston and cylinder were made from tungsten carbide. The medium fluid used was Di-2-Ethyl-Hexyl-Sebacate (DEHS).

2.1. Effective area determination

The piston-cylinder units (PCUs) No. 409 with 50 mm, No. 693 and No. 1671 with 35 mm diameter were selected as the primary gas pressure standard set for calculating the effective area. The dimensional data of the piston and cylinder which are diameter, straightness and roundness were obtained from PTB.

The effective area at zero pressure A_0 of 200MPa-CCPG obtaining by cross-floating method was initially determined from the primary gas pressure standard (Figure 2) as mentioned above, over the pressure range from 17.5 kPa to 10 MPa.
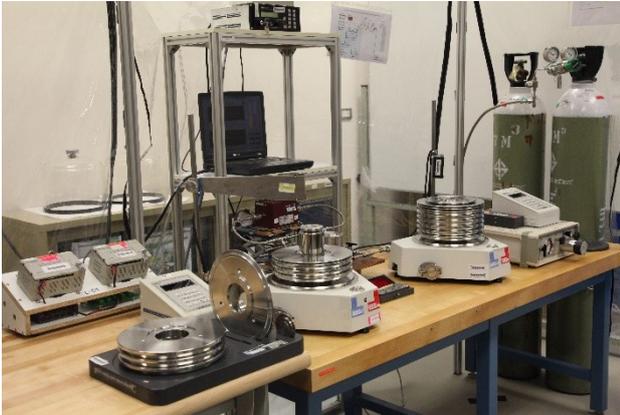

Figure 2: Experiment set-up for cross-floating method of gas pressure standard

For the pressure from 1 MPa to 10 MPa, the air operated, oil lubricated piston-cylinder unit was used as the intermediate point between gas and oil.
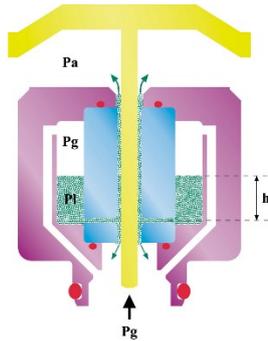

Figure 3: Schematic of air operate, oil lubricate piston-cylinder unit

The operation of the air operated, oil lubricated piston-cylinder unit is shown in Figure 3. The gauge pressure of nitrogen was applied at the bottom of piston and the top of the oil reservoir located around outside of the cylinder. After the pressure measurement using the nitrogen, then filled up the oil, in the DEHS reservoir as much as possible. After that installed the unit in the same instrument base, then use the oil DEHS instead of nitrogen.

The effective area, A_0 of 200 MPa-CCPG obtained from pressure between 10 MPa to 100 MPa and was checked by the pressure from 20 MPa to 200 MPa which is equal to 4.90202 mm^2 and its relative standard uncertainty 1.9×10^{-5} was obtained from Year 2013. The distribution of effective area, A_e in function of pressure was shown in Figure 4.
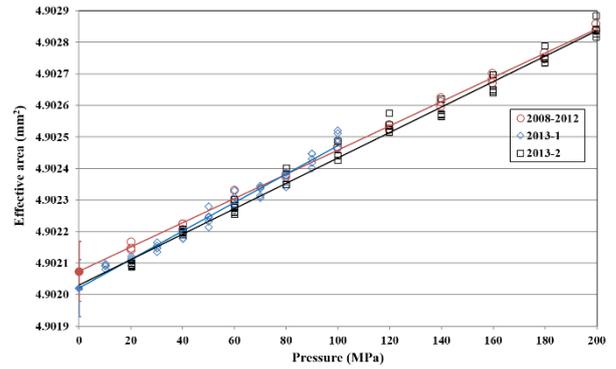

Figure 4: Distribution of an effective area in the function of pressure between Year 2008 to Year 2013

2.2. Pressure distortion coefficient determination

The Heydemann and Welch method was used to obtain λ through the effective area (A_e) as shown in equation (2),

$$A_e = A_{0,p}\left[(1 + b \cdot p)\left\{1 + (\alpha_p + \alpha_c)(t - t_r)\right\}\left\{1 + d(p_z - p_j)\right\}\right], \quad (2)$$

where $A_{0,p}$ is the zero-pressure area of piston, b and d, are the distortion coefficient of the piston and cylinder respectively. The coefficient b can be determined by equation (3) as below,

$$b = \frac{3 \cdot \mu - 1}{E}, \quad (3)$$

where μ is the Poisson's ratio, 0.218 and E is the modulus of elasticity, 560 GPa. Both values are provided by the manufacturer. Therefore, the distortion coefficient, b can be calculated as -6.18 × 10^{-4}/GPa with the standard uncertainty of 1.12 × 10^{-4}/GPa.

The coefficient, α_p and α_c are the thermal expansion coefficient of the piston and cylinder using as 4.5 × 10^{-6}/^{o}C with the standard uncertainty of 0.26 × 10^{-6}/^{o}C^{-1} for both of the piston and cylinder. The temperature t and t_r are the temperature of piston-cylinder and the temperature of reference (20 ^{o}C) respectively. The standard uncertainty of temperature t is 0.14 ^{o}C. The pressure p_z is the jacket-pressure at which the gap between piston and cylinder goes to zero and p_j is the jacket- pressure around the outside of cylinder.

Three main parameters in the equation (2), $A_{0,p}$, d and p_z were characterized by following.

2.2.1 Zero-pressure area of piston ($A_{0,p}$)

The piston area, $A_{0,p}$ of the CCPG was obtained by two experimental methods to calculate the effective area, A_0 and the gap between piston and cylinder at zero pressure (h_0) instead of direct dimensional measurement. The effective area A_0 was measured by cross-floating against 100 MPa piston-cylinder unit (Free deformation, FD) and checked by 200 MPa piston-cylinder, FD. The obtained value of

A_0 was shown in section 2.1. The gap h_0 at zero pressure was determined from the gap between piston and cylinder $h(p)$ at each system pressure p by measuring the piston fall rate (v_f) at low pressure as possible by using the Laser Displacement Sensor installing at the top of piston.

Assuming the fluid is incompressible, the mass flow (Q_m) through the gap between the piston and the cylinder is constant along the engagement length of piston and cylinder (Figure 5). There is no fluid accumulate in the gap. Therefore, the mass flow at the inlet of engagement length is the flow at the outlet by evaluating as equation (4),

$$Q_m = \int_s \rho_f \cdot v(r) \cdot ds , \qquad (4)$$

where ρ_f is the fluid density, $v(r)$ is the velocity of fluid in the function of the gap between piston and cylinder.
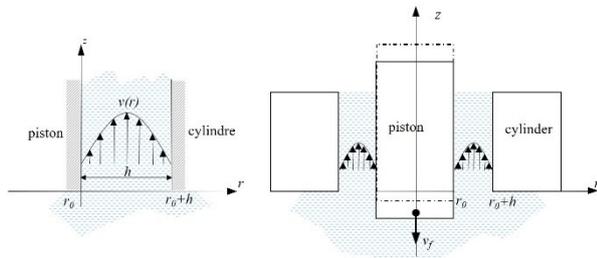

Figure 5: Schematic of fluid flow in the gap between piston and cylinder and piston fall rate

When the piston fall rate, v_f is proportional to the flow rate, Q_m therefore the mass flow rate can be determined as equation (5),

$$Q_m = \pi r_p^2 \cdot \rho_f \cdot v_f , \qquad (5)$$

where r_p is the nominal radius of piston taken from the manufacturer as 1.2491 mm.

Applying the flow velocity, $v(r)$ with a parallel planes model, the fluid is incompressible and Newtonian, the fluid flow is stationary, isothermal, laminar and one-dimensional, and the mass force is negligible, in the equation (4). Therefore, the gap between piston and cylinder $h(p)$ at each system pressure p can be determined as in equation (6),

$$h(p) = \sqrt[3]{6r_0 \cdot v_f \cdot \eta(p) \cdot \frac{l}{p}}, \qquad (6)$$

where $\eta(p)$ is the dynamic viscosity which is modified from the experiment data [6], [7], l is the engagement length of piston and cylinder.

From the piston fall rate measurements at low pressure, the mean gap width between the piston and cylinder (h_0) at zero pressure was found after extrapolating the mean gap width, $h(p)$ at the different pressure to zero pressure.

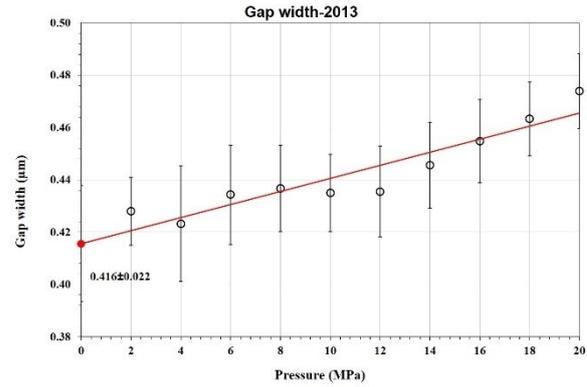The gap width $h(p)$ in the function of p obtained from Year 2013 is shown in Figure 6.

Figure 6: Mean gap width between piston and cylinder, $h(p)$ in the function of pressure p

The gap h_0 and their uncertainties are shown in Table 1. In this paper, the results from Year 2013 was used to evaluate the piston radius r_0.

Table 1: Gaps between piston and cylinder, h_0 at zero pressure since Year 2008.

Year	$h_0 \pm u$	Pressure (MPa)
2008	0.416±0.031	20 - 200
2010	0.438±0.032	20 - 200
2011	0.432±0.032	20 - 200
2012	0.419±0.032	20 - 200
2013	0.416±0.022	2 - 20

The effective area at zero pressure (A_0) in case of an ideal gap profile can be calculated in the basic of equation (7) [8].

$$A_0 = \pi r_0^2 \left[1 + \frac{h_0}{r_0} \right]. \qquad (7)$$

After solving the second-degree polynomial on equation (7), the radius of piston (r_0) can be obtained, then $A_{0,p}$ was calculated by equation (8) and shown in Table 2,

$$A_{0,p} = \pi r_0^2 . \qquad (8)$$

Table 2: Piston radius (r_0) and piston area ($A_{0,p}$) and their uncertainties.

Parameters	Value ± u
r_0 (mm)	1.24894 ± 0.000015
$A_{0,p}$ (mm²)	4.90039 ± 0.00012

2.2.2 Distortion coefficient of cylinder (d)

The coefficient d was evaluated by observing the relative change of the system pressure ($\Delta p/p$) due to the change of jacket-pressure (Δp_j). Therefore, the other pressure balance with good sensitivity was used for monitoring (Δp) (Figure 7).

The pressure balance equipped with 200 MPa PCU (FD) manufactured by DH Instruments was used to observe the change of system pressure Δp.
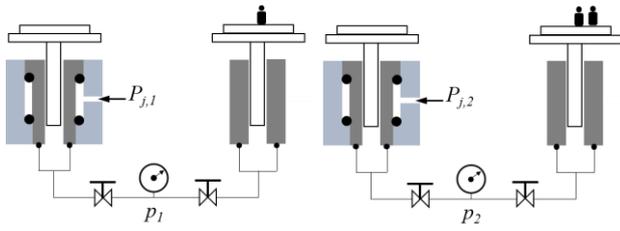

Figure 7: Schematic of experiment method for evaluating the coefficient d

The digital pressure manometer in the range up to 100 MPa with accuracy 0.013 % of the reading was used to measure the change of jacket-pressure (Δp_j). Two constant volume valves (CVV) were used to isolate the pressure line for each pressure balance.

The relationship between the changes of system pressure over the jacket-pressure can be shown in equation (9),

$$d = \frac{1}{p} \cdot \frac{\Delta p}{\Delta p_j} \cong \frac{1}{m} \cdot \frac{\Delta m}{\Delta p_j}, \tag{9}$$

where m and Δm are the total mass and the change of mass due to the change of Δp_j respectively. The coefficient d can be shown in Figure 8.
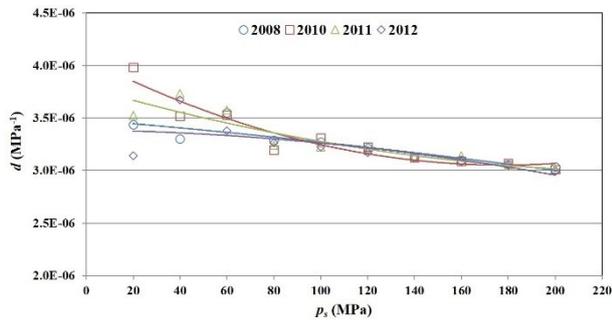

Figure 8: Distribution of the cylinder coefficient d in the function of system pressure (p) since Year 2008

Therefore, the results of coefficient d at each system pressure over Year 2008 to Year 2012 are then fitted to a polynomial in equation (10),

$$d = 3.6822 \cdot 10^{-6} - 5.0019 \cdot p + \\ 8.2302 \cdot 10^{-12} \cdot p^2. \tag{10}$$

A relative standard uncertainty of coefficient d varies from 0.023 to 0.17×10^{-6}/MPa.

2.2.3 Jacket pressure at zero gap (p_z)

Assuming the relationship between the gap width and pressure p_j is a linear. The flow rate of fluid in the gap is proportional to the piston fall rate (v_f) as mentioned in section 2.2.1. The piston fall rate at jacket-pressure (p_j) between 1/10 to 1/2 of applying pressure (p) were observed to determine the pressure p_z. From the experiment, a linear relationship of cubic root of piston fall rate and p_j was found by equation (11).

$$p_j = p_z - \frac{1}{k} \cdot v_f^{\frac{1}{3}}. \tag{11}$$

Then p_z was obtained by extrapolation to the zero fall rates at each p_j as shown in Figure 9, which is the example for the results of Year 2012.
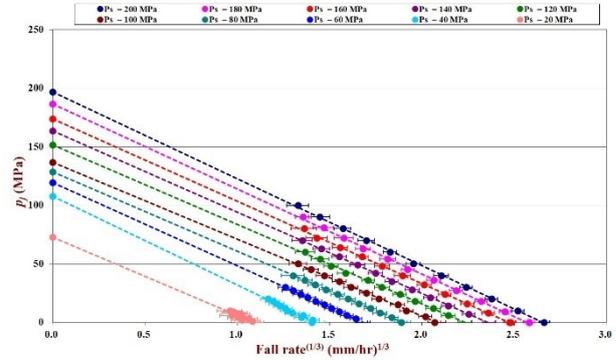

Figure 9: Experiment data of cubic root of piston fall rate ($v^{(1/3)}$) and jacket-pressure (p_j) in Year 2012

Therefore, p_z in the function of system pressure (p) over the results from Year 2008 to 2012, shown in Figure 10, was obtained as in equation (12),

$$p_z = 78.5578 + 0.60119 \cdot p. \tag{12}$$

The relative standard uncertainty of the jacket pressure p_z varies from 0.67 to 1.79 MPa.
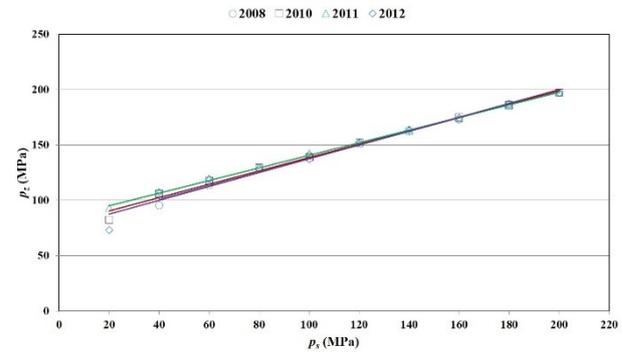

Figure 10: Jacket-pressure at zero gap (p_z) in the function of system pressure (p)

After characterising the three main parameters described above, the effective area at the reference temperature ($A_{e,20^oC}$) obtaining from equation (2) was used to determine λ at pressure p_j, which was approximately 1/4 of applied pressure as in equation (13),

$$A_{e,20^oC} = A(1 + \lambda \cdot p). \tag{13}$$

Considering only the slope of equation (13), λ equal to 1.6×10^{-7}/MPa with its relative standard uncertainty, 0.13×10^{-6}/MPa was obtained.

2.3. Realization of pressure standard

After characterizing the three main parameters, the piston area $A_{0,p}$, the cylinder coefficient d and the

jacket pressure, p_z of 200 MPa-CCPG piston-cylinder unit, the relative standard uncertainty of measured pressure is better than 3.0×10^{-5}.

A 200 MPa-CCPG piston cylinder is initially used to determine the pressure distortion coefficient, λ of PCUs for high to low pressure by cross-floating method as shown in Figure 11. Therefore, the relative standard uncertainty of the pressure standard up to 500 MPa is better than 4.5×10^{-5} but not smaller than 0.1 Pa.

A set of three oil piston-cylinder units (PCUs), Figure 11 was maintained to be a set of primary oil pressure standard from 20 to 200 MPa.
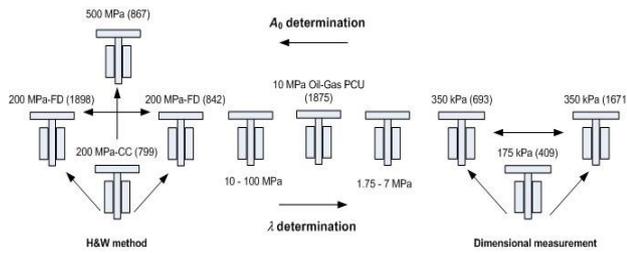

Figure 11: Thailand pressure standard scale from 1.5 kPa to 500 MPa

The effective area ratios from cross-floating measurements of each pair were determined the deviation in order to maintain the primary pressure standard. Each five years, the deviation should not be over the standard uncertainty of the effective area at zero pressure of 200 MPa-CCPG piston-cylinder unit.

The effective area ratio of each pair PCUs can be determined as shown in equation (14) ,

$$\frac{A_{01}}{A_{02}} = \frac{\sum m_2(1 - \rho_a / \rho_m)}{\sum m_1(1 - \rho_a / \rho_m)} \times \frac{(1 + \lambda_2 p)\left[1 + (\alpha_p + \alpha_c)(t - 20)\right]_2}{(1 + \lambda_1 p)\left[1 + (\alpha_p + \alpha_c)(t - 20)\right]_1}, \quad (14)$$

where m_i is the loaded mass and ρ_a and ρ_m are the air and mass density respectively.

3. VALIDATION OF THE 200MPA-CCPG PRESSURE STANDARD

A pressure balance equipped with 500 MPa PCU (FD) has been used as the artifice for participating of supplementary comparison of NIMT and LNE pressure standards in the range 50 MPa to 500 MPa of hydraulic gauge pressure, APMP.M.P-S7 in order to improve the result of NIMT's characterization by using the H-W method. The results show that the deviation between NIMT and LNE agrees with each other within the standard uncertainties claimed by each laboratory. The maximum deviation agrees within 13.3×10^{-6} for the pressure up to 200 MPa and 34.2×10^{-6} from 200 MPa to 500 MPa. From the characterization on H-W method, the high-pressure scale up to 200 MPa of controlled-clearance piston-cylinder unit is reliable and confirmed.

4. SUMMARY AND PERSPECTIVE

The national pressure standard scale of NIMT from 1.5 kPa to 500 MPa and its standard uncertainty has been carried out by using the two set of primary pressure standards gas and oil. The effective area, A_0 from low to high pressure scale was initially determined by a set of gas primary standard which their effective area, A_0 evaluated from the dimensional properties. While the pressure distortion coefficient, λ from high to low pressure scale was initially determined by H-W method. The relative standard uncertainty of measured pressure for 200 MPa-CCPG is better than 3.0×10^{-5}. After characterizing the primary standards (gas and oil), the relative standard uncertainty of the pressure standard range 1.5 kPa to 500 MPa varies from 1.9×10^{-6} to 4.5×10^{-5} but not smaller than 0.1 Pa.

However, the zero-pressure effective area and pressure distortion coefficient have to be improved by in-house dimensional measurement and numerical method (FEM) respectively in the next project.

Nevertheless, the development of the Thailand's industrial such as petroleum industries, food processing and military industries require the high pressure up to 1 GPa. Therefore, the pressure standard up to 1 GPa will be developed in the next future.

5. ACKNOWLEDGMENTS

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