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A STUDY ON CHARACTERISTICS OF 1 GPA CONTTROLLED CLEARANCE PISTON GAUGE USING FINITE ELEMENT METHOD

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Abstract: Metrological characteristics of 1 GPa controlled clearance piston gauge (CCPG) were investigated using a finite element method (FEM). These are a piston/cylinder distortion coefficient in free deformation mode, distortion coefficient of jacket pressure and stall pressure in controlled clearance mode. The effective area of CCPG was constant according to different applied pressure when relative jacket pressure of 17.3 % was applied. Comparison experiments with KRISS 500 MPa standards were carried out to verify the FEM results.

Keywords: Finite Element Method, Controlled Clearance Piston Gauge, Effective Area, Distortion Coefficient

1. INTRODUCTION

As in line with the development of technology as well as increasingly sophisticated pressure technique, the improvement of accurate measurement and the establishment of standard are getting important [1].

A primary standard in the field of pressure is a piston gauge. A controlled clearance piston gauge (CCPG) is used in high pressure range, especially up to 1 GPa. It has an unique capability to reduce piston-cylinder (P/C) distortion by applying jacket pressure (p_j) to the outer cylinder surface.

A FEM is quite effective way to investigate many effects that influence the effective area change of the P/C according to pressure [2]. Indeed, a EURAMET project was conducted by several national metrology institutes (NMIs), including PTB (Germany), for the purpose of developing numerical procedures to calculate the pressure distortion coefficient of 1 GPa CCPG with reasonable uncertainties [3][4].

Assuming the proportionality of pressure distribution along the P/C gap and local P/C surface, the general method is based on the combination of separate analysis of fluid flow along the piston cylinder gap and the radial distortion due to its pressure distribution. From the two analyses results, a convergent solution of metrological characteristics of 1 GPa CCPG can be obtained. A reasonable uncertainty was evaluated from the sensitivity of FEM result with respect to the input parameters used in the model [3][4][5].

In this paper, it concludes that the effective area (A_e) of 1 GPa CCPG is constant according to the different applied pressure (p_s), when 17.3% of relative jacket pressure (p_j/p_s) is applied to the outer cylinder surface.

2. CHARACTERIZATION OF 1 GPA CCPG USING FEM

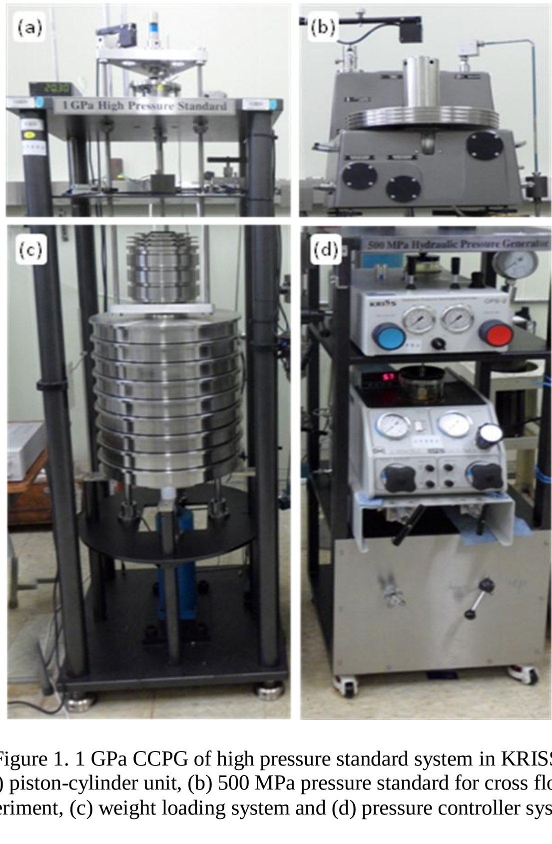

Figure 1. 1 GPa CCPG of high pressure standard system in KRISS
(a) piston-cylinder unit, (b) 500 MPa pressure standard for cross float experiment, (c) weight loading system and (d) pressure controller system.

Figure 1 shows KRISS CCPG pressure standard that is used to provide the needs of traceability up to 1 GPa. It consists of piston-cylinder assembly (PCA), the weight loading system and pressure controller system. The controlled-clearance type of PCA consists of piston, inner-cylinder (cylinder) and outer-cylinder (sleeve). Jacket pressure, p_j is applied to the outer cylinder surface in order to reduce the radial distortion of cylinder.

A FEM is widely used by many NMIs to analyze their CCPG pressure standard. The most common method is the iterative combination of separate solutions of fluid flow analysis (FFA) and structural analysis (SA). In this method, it is assumed that the local radial distortion of P/C is proportional to the pressure distribution in its engagement length.

Pressure distribution (p_z) along the P/C engagement length (l) can be determined from FFA using following equation [5];

$$p_z = p - p\left(\frac{\int_0^z \frac{\eta_{(p_z)}}{\rho_{(p_z)}} \frac{1}{(h_z)^3} dz}{\int_0^l \frac{\eta_{(p_z)}}{\rho_{(p_z)}} \frac{1}{(h_z)^3} dz} \right) \tag{1}$$

where η and ρ are dynamic viscosity and density of fluid, respectively. h_z is PC gap width, z is the axial coordinate of P/C engagement length, with $z=0$ at the bottom and $z=l$ at the top of engagement.

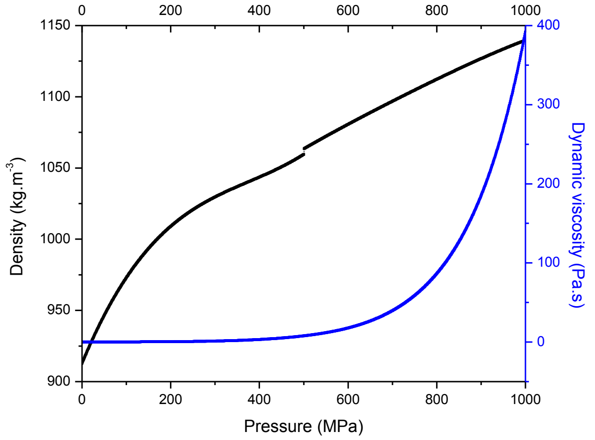

Figure 2. Pressure dependent of DHS fluid properties (η and ρ).

Di(2)-ethyl-hexyl-sebacate (DHS) is common pressure transmitting fluid used in piston gauges. Figure 2 shows the properties of DHS that are well-characterized experimentally as pressure dependent according to the derived equations in [3].

In SA, final p_z is used as the load along the P/C surface to obtain the deformation of piston (u_z) and cylinder (U_z), as well as its gap (h'_z). These parameters are required for the next FFA. In order to obtain a convergent result, FFA and SA need to be solved iteratively since they were correlated.

The equations to calculate effective area (A_p), distortion coefficient (λ) and piston fall rate (v), are given as follows [2];

$$A_P = \pi r_0^2 \left\{ 1 + \frac{h_0}{r_0} - \frac{1}{r_0 p} \int_0^l (u_z + U_z) \frac{dp_z}{dz} dz \right\} \tag{2}$$

$$\lambda = \left(\frac{A_p}{\left(\pi r_0^2 \left(1 + \frac{h_0}{r_0} \right) \right)} - 1 \right) \frac{1}{p} \tag{3}$$

$$v = \frac{p}{r_0 \rho(p) \left(6 \int_0^l \frac{\eta(p_z)}{\rho(p_z)} \frac{1}{h_z^3} dz \right)} \tag{4}$$

where h_0 and r_0 are undistorted gap and piston radii, respectively. The above equation of λ is suitable only for an "ideal gap profile" used in this study.

Finite element analysis was fully written in ANSYS parametric design language (APDL) in this study. Since the CCPG was assumed perfectly straight and cylindrical or having "ideal gap profile", 2D axis-symmetry model can be created as shown in figure 3. Solid-rectangular element type of PLANE 183 with 8 nodes was used in this study. The model consists of around 7000 meshes. For the detail, 407 nodes were created along the engagement length of the P/C. Table 1 shows the dimensional and material properties of the model used in this investigation, as in [3].

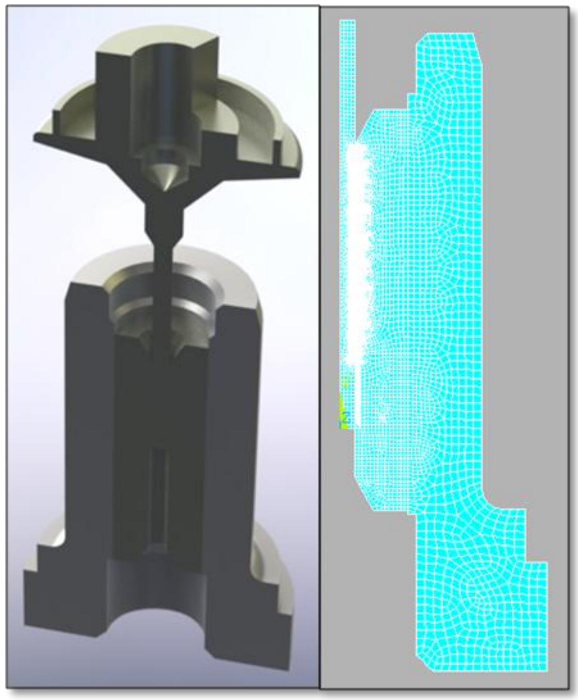

Figure 3. Transformation of CCPG physical structure to finite element model

Table 1. Dimensional and material properties of the model.

Property	Symbol	Value	Unit
# DIMENSIONAL			
Piston radius	r_o	1.248 99	mm
Cylinder radius	R_o	1.249 31	mm
Clearance	h_o	0.32	µm
Engagement length	l	19.3	mm
# MATERIAL			
Young modulus of piston	E_p	543 ± 7	GPa
Young modulus of cylinder	E_c	630 ± 15	GPa
Young modulus of sleeve	E_s	200 ± 7	GPa
Poisson's ratio of piston	μ_p	0.238 ± 0.002	-
Poisson's ratio of cylinder	μ_c	0.220 ± 0.006	-
Poisson's ratio of sleeve	μ_s	0.29 ± 0.02	-

3. EXPERIMENTAL VERIFICATION OF FEM

Effective area of 1 GPa CCPG against 500 MPa was obtained by cross-float between two piston gauges according to the configuration of figure 1. The experiment was performed by varying p_j/p_s from 2.5% up to 25%.

In order to determine the equilibrium pressure between these two pressure standards, the fall rate was measured accurately. This is based on the similarity between natural and cross fall rate when equilibrium pressure is achieved. An additional mass will be required to "added to" or "reduced from" the primary standard to eliminate an imbalance condition.

4. RESULTS AND DISCUSSIONS

As shown in figure 4, the effective area of CCPG was constant for different applied pressure (p_s) when the relative jacket pressure (p_j/p_s) of around 17 % was applied to the outer cylinder surface. This value was determined as 17.3%, in accordance with zero value of λ obtained from fitting equation of λ according to different jacket pressure p_j. It is different with conventional investigation result, since jacket pressure of 10% is commonly used when operating CCPG in CC mode. Therefore, it should be proceed into further investigation, considering λ is the main source of uncertainty in pressure measurement.

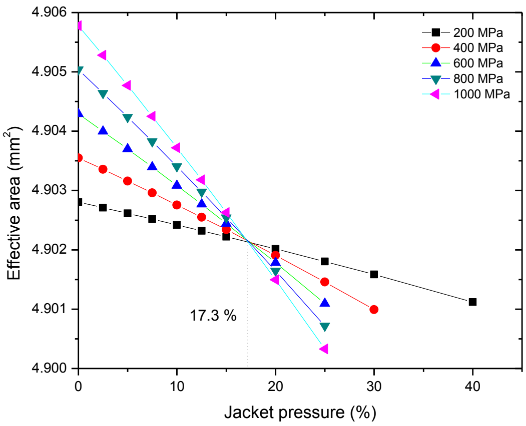

Figure 5. Effective area changes due to applied pressure and jacket pressure.

The cross float result can verify the FEM result as shown in figure 6. It shows the similar trend as obtained from FEM, although the values are slightly different. Effective areas are smaller as compared with those from FEM. It may be caused by the difference of real dimensional parameters of the P/C with the value used for the finite element model. The real P/C may have smaller radii of piston and gap width.

From the experiment, the change of A_e with respect to p_j is relatively smaller than those of FEM. Therefore, A_e is equal at larger p_j/p_s, which is about 21.4%, instead of 17.3% as in FEM result. It may occur if the material properties of real P/C are bigger than those of the model. It is also possible that the real gap profile of the PC is not ideal as assumed in this analysis. The effective area of "non-ideal gap profile", especially "divergent shapes" of P/C, was more sensitive to change of p_j [6].

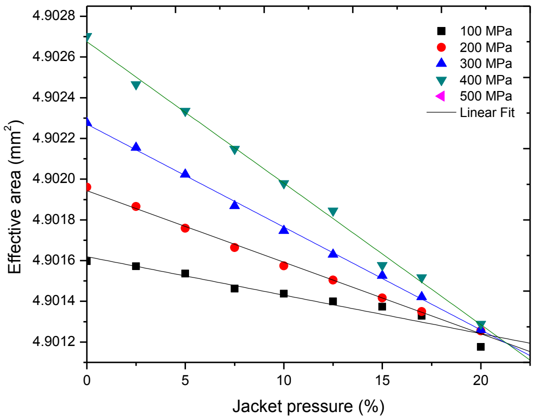

Figure 6. Cross float result of A_e change according to p_j.

5. CONCLUSIONS

FEM is quite useful in determining the metrological characteristics of 1 GPa CCPG for high pressure standard. However, it needs to verify the analysis results with the experimental results. As obtained from this study, λ is equal to almost zero when applying 17.3% of p_j to the outer cylinder, in other words, A_p will be constant at different p_s if CCPG are operated with this relative jacket pressure ratio.

In future works, the dimensional measurement of the P/C should be carried out to obtain more accurate distortion coefficient.

5. REFERENCES

[1] R.S. Dadson, S.L. Lewis and G.N Peggs, “The pressure balance theory and practice”, National Physical Laboratory, HMSO, 1982.

[2] S Y Woo, Y J Lee, I M Choi, B S Kim and H H Shin, “Effects of the O-ring used for sealing in high pressure balance on measurements of pressure”, Journal of Meas. Sci. Technol. vol. 13, pp. 1353-1358, 2002.

[3] W Sabuga, G Molinar, G Buonanno, T Eswald, J C Legras and L Yagmur, “Finite element method used for calculation of the distortion coefficient and associated uncertainty of a PTB 1 GPa pressure balance – EUROMET project 463”, Journal of Metrology, vol. 43, no. 8, pp. 311-325, June 2006.

[4] G Molinar, W Sabuga, G Robinson and J C Legras, “Comparison of methods for calculating distortion in pressure balance up to 400 MPa – EUROMET project #256 ”, Journal of Metrology, vol. 35, pp. 739, 1998.

[5] W. Sabuga, T. Priruenrom, G. Molinar M. B., G. Giovinco, T. Rabault, P. Wongthep, D. Prazak, “FEM calculation pressure distortion coefficients of gas-operated pressure balances - EURAMET project 1039”, Measurement, 2011.

[6] R. Rudi Anggoro S., "Characterization of 1 GPa Controlled Clearance Piston Gauge for High Pressure Standard using Finite Element Method", Master Degree Thesis, University of Science and Technology (UST), 2012.