Progress in development of controlled-clearance pressure balance in NMIJ

H Kajikawa, K Ide and T Kobata
National Metrology Institute of Japan (NMIJ), AIST, Tsukuba, Ibaraki 305-8563, Japan
E-mail: kajikawa.hiroaki@aist.go.jp

Abstract. A new controlled-clearance pressure balance is under development with the aim of improving the hydraulic high-pressure standard up to 1 GPa. This pressure balance consists of three parts: (i) a pressure generation device up to 1 GPa, (ii) a weight-loading unit which can load/unload weights automatically and independently, (iii) a controlled-clearance piston-cylinder which is designed to allow the jacket pressure to be applied independently. Some adjustments were made for loading heavy weights on/off the piston safely, keeping them in balance, then generating the pressure stably. Stability of the generated pressure was checked for several piston-cylinders, and it was found that pressure fluctuation was less than a few parts per million. The jacket pressure coefficient of a 500 MPa controlled-clearance piston-cylinder was precisely evaluated as a function of both the system pressure and the jacket pressure.

1. Introduction
A pressure balance is one of the most stable apparatus for pressure generation and measurement. National Metrology Institute of Japan (NMIJ) has established the hydraulic pressure standard in the pressure range up to 1 GPa using several pressure balances and a precise pressure multiplier. The pressure generated by the pressure balance is calculated from the gravitational downward force due to the masses of the piston and weights divided by the effective area of the piston-cylinder assembly. The difficulty in precise determination of the pressure comes from the estimation of the effective area because it also depends on the pressure due to the pressure distortion of both the piston and cylinder. Among several types of the piston-cylinder, the controlled-clearance piston-cylinder becomes useful because the deformation of the piston and cylinder is partially controlled by the application of another pressure, jacket pressure, on the outer surface of the cylinder. Moreover, the pressure dependence of the effective area is able to be evaluated independently from the deformational characteristics in response to the applied jacket pressure.

A new pressure balance with a controlled-clearance piston-cylinder is originally developed with the aim of improving high pressure standard. In this paper, some achievements in the development are reported.

2. Features of controlled-clearance pressure balance
Figure 1 shows a schematic drawing of the newly-developed pressure balance. The pressure balance consists of three parts: a pressure generating unit, a weight-loading unit, and a controlled-clearance piston-cylinder (CCPC) [1, 2].
The pressure generating unit can generate and control two pressure lines, system pressure, $p_s$, and jacket pressure lines, $p_j$, separately. In the unit, an oil-operated compressor is used in common, and an intensifier with a nominal ratio of 1:50 is used for each line; the maximum pressure that can be achieved is 1 GPa. Variable volumes are also used for the fine control of the pressure. The system pressure line is connected to another pressure balance through valves and a pressure transducer for the characterization experiments of CCPC.

In the weight loading unit, the weights are suspended below the piston-cylinder assembly through a frame and a rod. The total mass of the weights is approximately 1100 kg. The weight set consists of disk weights of 95 kg and 19 kg, and cylindrical weights of 2.5 kg and 0.5 kg. Each weight is supported by pneumatic actuators and is lifted up/down independently. Stability of the mass of each weight has been confirmed by in situ mass calibrations [2].

The piston-cylinder assembly is made from tungsten carbide and is packed in a steel housing. At present, we have several CCPCs for different pressure ranges: for 100 MPa, 200 MPa, 500 MPa, and 1 GPa. During the operations, the piston is rotated by an electric motor through a pulley and a rubber belt. The jacket pressure is applied to the outer surface of the cylinder from the side inlet of the housing. The maximum value of $p_j$ is carefully determined depending on the characteristics of each CCPC to avoid excessive application of $p_j$, which may damage the piston and cylinder. In general, $p_j$ is applied up to 50 % of the system pressure.

3. Stability of generated pressure
Some adjustments were made for loading heavy weights on/off the top of the piston safely, keeping them in balance, then generating the pressure stably. For example, lifting speed of the actuators was precisely adjusted to make sure that the weight should be kept horizontal. To prevent the frame from wobbling widely and from rotating following the rotation of the piston, restraint mechanism was adopted. A wheel is used at the contact point, avoiding frictional force in the vertical direction. An appropriate range in use within the stroke of the piston was determined for each CCPC so that the piston fall-rate and the generated pressure have little or no dependence on the piston position. The rotational speed at which the fluctuation of the generated pressure becomes smallest was found to be approximately 15 revolutions per minute.

These measures contributed the stability improvement of the generated pressure. The fluctuation of the pressure generated by a 200 MPa and a 500 MPa CCPC is exemplified in Figures 2(a1) and 2(b1), respectively, and is compared with the pressure generated by simple pressure balances used as standard devices. The pressure is measured by the same pressure transducer in series by switching the connection of the pressure line to the transducer [4]. The
Figure 2. Stability of the pressure generated by the developed CCPC, compared with that by the simple pressure balances. In (a1) and (b1), a series of six data labeled as $R_i (i = 1, 2, 3)$ denotes the pressure generated by simple pressure balance, while a series of six data labeled as $T_j (j = 1, 2)$ denotes the pressure by CCPC. In (a2) and (b2), the relative standard deviations of the groups, $R_1 (\bigcirc), R_2 (\triangle), R_3 (\square), T_1 (\bullet)$, and $T_2 (\blacksquare)$, are plotted against applied $p_j$.

pressure is averaged over four seconds and the data is obtained in every ten seconds. A group of six data referred to as $R_i (i = 1, 2, 3)$ is the data generated by the simple pressure balance, and that referred to as $T_j ( j = 1, 2)$ is the data by CCPC. The length of the arrow in the figure shows $2 \times 10^{-6}$ of the nominal value of the generated pressure: 200 MPa for (a1), and 500 MPa for (b1). In Figure 2(a1), at $p_s = 200$ MPa, the stability of $T_j$ is as well as that of $R_i$, and in Figure 2(b1), at $p_s = 500$ MPa, the stability of $T_j$ is better than that of $R_i$.

The stability of the generated pressure is checked similarly at other $p_j$, which is applied up to 50 % of $p_s$ in steps of 5 % of $p_s$. The standard deviation of a group of six data is calculated in every condition, then plotted in Figures 2(a2) and 2(b2). The relative standard deviation is within $4 \times 10^{-6}$ in all cases, and it does not depend on the applied $p_j$. Thus, it is found that the pressure generated by CCPC is kept stable as well as or better than that by our simple pressure balance despite of its complicated structure.

4. Precise determination of jacket pressure coefficient

The effective area of CCPC is able to be evaluated by the characterization experiments based on the Heydemann-Welch model [3]. One of the important parameters in the model is the jacket pressure coefficient, $d$. It is estimated from the relative change in the system pressure, $\Delta p_s/p_s$, in response to the change in the applied jacket pressure, $\Delta p_j$, as

$$d = \frac{1}{\Delta p_j} \cdot \left( \frac{\Delta p_s}{p_s} \right).$$

(1)

The change in $p_s$ is determined by the cross-float measurements against simple pressure balance.

The cross-float measurements for a 500 MPa CCPC were performed at $p_s$ from 50 MPa to 500 MPa in steps of 50 MPa. At each $p_s$, $p_j$ is changed from 0 % to 50 % in steps of 5 %. In each condition of $p_s$ and $p_j$, $p_s$ generated by CCPC is equilibrated with that by simple pressure balance [4]. Then, the relative change in $p_s$ due to $\Delta p_j$ is deduced by the relative change in
the mass loaded on the simple pressure balance. Thanks to the high stability of the pressure generated by CCPC, the change in $p_s$ due to $p_j$ was precisely traced. The results of $d$ at several system pressures, from 100 MPa to 500 MPa in steps of 100 MPa, are shown in Figure 3. For the 500 MPa CCPC, $d$ obviously depends on both $p_s$ and $p_j$, contrary to the conventional interpretation that $d$ depends only on $p_s$. To see the general shape of $d$ in the condition of both $p_s$ and $p_j$, the smoothed value of $d$ is plotted on the cubic graph in Figure 4. It is expected that the deformational characteristics of the CCPC will be revealed more clearly from the map of $d(p_s, p_j)$ and that the accuracy in the estimation of the effective area will be improved.

5. Summary

A new controlled-clearance pressure balance is under development with the aim of improving the hydraulic high-pressure standard up to 1 GPa. The pressure balance consists of three parts: a pressure generating unit, a weight-loading unit, and a controlled-clearance piston-cylinder. After some modifications in the loading and balancing mechanism of the pressure balance, stability of the generated pressure was checked for several controlled-clearance piston-cylinders. Then, it was found that the pressure fluctuation was less than a few parts per million independent of the applied $p_j$. The jacket pressure coefficient of the 500 MPa controlled-clearance piston-cylinder was precisely evaluated as a function of both the system pressure and the jacket pressure.

References

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