Metrological Characterization of Non-Rotating Low-Pressure Piston-Cylinder Unit System

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Abstract. A Low-pressure non-rotating new piston gauge covers the range of gauge and absolute pressure from less than 1 Pa to 15 kPa in gas media [1]. The instrument operates on the piston gauge principle. However, the force resulting from pressure on the piston is measured by a force balanced load cell rather than a balanced system against masses subjected to the acceleration due to gravity. For this reason, the measuring portion is designated a force balanced piston gauge (FPG) [1]. While pressure measurement range of a conventional pressure balance can start from around 5 kPa, as the FPG can measure pressure starting from a few pascal. Calibration or determination of the effective area of FPG system can be done using a conventional pressure balance reference instrument gauge in gauge and absolute modes. This paper describes the metrological characterization of a low-pressure non-rotating piston-cylinder unit both in absolute and gauges pressure modes, in the range of 1 Pa to 15 kPa by direct comparison method.

1. Introduction
Force Balanced Piston Gauge (FPG) system is the reference calibration system for very low-pressure values. Working pressure of the system starts from a few Pascal to 15 kPa in gauge, negative gauge and absolute pressure modes. The main purpose of this instrument is to do measurements for low-pressure scales where the classical pressure balances cannot be reached. While the classical pressure balance systems work based on rotating piston inside the cylinder for centralizing and to overcome friction forces as the FPG system uses a non-rotating piston-cylinder unit. FPG pressure is defined by using a high precision load cell to measure the force exerted on the effective area of a piston-cylinder. Instead of rotating the piston like other piston gauges, the FPG provides sensitivity between the piston and cylinder by maintaining a constant flow through the annular gap. This flow generates a centring force that prevents the piston from touching the cylinder during normal operation. Noise normally associated with rotation is therefore not present [2].

2. Operating principle of the FPG system
Piston gauges are well-known standard instruments in the field of pressure metrology [3]. Conventional piston gauge mainly consist of the mass set and the piston-cylinder unit (PCU). Masses are loaded onto the piston-cylinder are subjected to gravitational force. Pressure is obtained as total force over the area of PCU. Conventional piston gauge (PG) and PCU are given in Figure 1 and Figure 2 respectively.
When the conventional piston-cylinder unit is configured with a dynamometer it is converted to a new fundamental pressure standard as FPG system as seen in Figure 3. It is intended to cover the range of relative and absolute pressure from less than 1 Pa to 15 kPa. The operation is fully automated and the complete system can be installed on a typical calibration laboratory bench.

The pressure in the FPG is defined by means of the force measured using a high precision load cell and the effective area of the piston-cylinder assembly [4]. The FPG standard includes two major components. The pressure measuring portion (up) and the pressure controlling portion (down) as seen in Figure 3. There are two independent, symmetrical chambers at either end of the piston-cylinder. The lower chamber is held in atmosphere or vacuum while the pressure to be measured is applied to the upper chamber. The net force resulting from the difference in pressure between the two chambers is transmitted to the load cell through the coupling. The overall system is interfaced with and controlled by a dedicated personal computer running specialized software. The pressure measuring portion operates on the piston gauge principle. However, the force resulting from pressure on the piston is measured by a force balanced load cell rather than balanced against masses subjected to the acceleration due to gravity as given in Figure 4. For this reason, the measuring portion is designated a
force balanced piston gauge (FPG) [1]. The piston-cylinder is suspended below the load cell. Rather than rotating the piston in the cylinder, the piston-cylinder gap is conical and gas flow through the gap is used to centre the piston and avoid dry static friction [1]. The force across the piston is transmitted to the load cell through a coupling system that holds the piston at its centre of gravity.

3. Calibration of FPG

Metrological traceability is the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty [5, 6]. In order to establish the metrological traceability of FPG system, it should be calibrated against a traceable reference standard. For the calibration purpose, the basic calculation of the pressure Δp measured by the FPG follows the standard equation of a conventional piston gauge as given in equation (1) [2].

\[
\Delta p = \frac{F}{A_e}
\]  

(1)

F refers to the force measured by the load cell. \(A_e\) is the effective area of piston-cylinder unit of FPG corrected by \((\alpha + \beta)\) thermal expansion coefficient and temperature of PCU of FPG. Calibration of the FPG consists of determining the effective area of the PCU. For such purpose a calibration setup was established as seen in Figure 5 and in Figure 6. In this setup, FPG system is connected to a conventional piston gauge system. Both systems are pressurised to the selected calibration points. Those nominal pressure points were, \((2, 4, 6, 8, 10, 12.5, 15)\) kPa. For each point, reference pressure, \(p_{\text{reference}}\) is applied from conventional piston gauge system to FPG as three cycles at these 7 nominal pressure points. Using the given equation (2) [2], \(A_e\) of the FPG was calculated for each calibration point. Later, the fitted effective area is calculated from the slope of the graph of areas versus applied pressure values.

\[
A_e = \frac{F}{(p_{\text{Reference}}) \cdot [1 + (\alpha + \beta) \cdot (T - 20)]}
\]  

(2)

Before floating the piston gauge at each pressure, a procedure is used to eliminate the effect of the lubrication gas flow into the FPG upper chamber which is seen in Figure 5, on the natural drop rate of the piston gauge. The pressure value of the comparison point is applied to the FPG upper chamber and a bypass valve on the tube connecting to the piston gauge is closed. With the FPG upper chamber so isolated, a needle valve as seen in Figure 5 is used to adjust a leak from the FPG upper chamber to atmosphere such that the FPG pressure reading is stable. The screen display is given in Figure 7 where pressure change inside the upper chamber of FPG is fluctuates around zero line.
Figure 7. Pressure change in upper chamber in FPG system

Figure 8. Experimental Calibration Setup of FPG in absolute pressure mode

The calibration setup in absolute mode is given in Figure 8. Absolute mode calibration method has similar setup to gauge one. But in this mode, reference piston gauge and FPG work in absolute mode. Lower chamber of FPG connects to a vacuum pump to set it to absolute zero. Residual gas is read from vacuum gauge which is seen in Figure 3.

4. Conclusion
Calibration or determination of the effective area of FPG system has been done by using a conventional pressure balance reference instrument both in gauge and in absolute pressure modes as given in the measurement setups in Figure 5 and Figure 6 up to 15 kPa by direct comparison method. The effective area of FPG was calculated both in gauge and absolute modes. While the calculated area values in the absolute mode experiment are repeatable and show a consistency among each other as the determined effective area values in gauge mode have bigger standard deviation value comparing the those of an absolute mode. It is observed that the difference between the effective area values in these two pressure modes reached up to hundreds of ppm range. It is concluded that the fluctuating in the atmospheric pressure was quite effective in gauge mode measurements. The traceability of effective area of FPG is achieved based on the area values determined in absolute mode experiment.

5. References
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