

# A NEW OIL OPERATED CONTROLLED CLEARANCE PISTON GAUGE FOR OPERATION TO 200 MPa

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## Abstract

An oil operated, controlled clearance piston gauge has been developed for the purpose of experimentally determining the pressure deformation coefficient of a piston-cylinder by varying an independent pressure around the cylinder. The gauge is obtained by designing a new mounting post for a commercially available piston gauge platform. The piston-cylinders, also commercially produced in diameters from 11.2 to 2.5 mm, are integrated into interchangeable modules which include dedicated mounting components. A standard 100 kg mass set gives ranges from 10 to 200 MPa. The piston-cylinders can be operated with a controlled clearance pressure or without, in which case they behave as in a conventional free deformation piston gauge. The piston gauge is well suited for intercomparisons as it is easily transportable and accepts masses that are already present in many metrology laboratories.

## 1. Introduction

In recent years, major efforts have been devoted to reducing the uncertainty in effective area of piston gauges used as primary pressure standards. The main focus of these efforts has been on the effective area of gas operated piston-cylinders in the relatively low range from a less than one to several atmospheres. In this range, the dominant uncertainties are those associated with knowledge of the exact physical dimensions of the piston and the cylinder and the behavior of gas in the gap between the two. Over the past 10 to 15 years, the application of improved dimensional measurement capabilities to large diameter piston-cylinders has allowed the estimated uncertainty in effective area for piston gauges used as primary standards to be reduced by nearly an order of magnitude. Direct comparisons with manometers, another technique that derives pressure directly from the base units of mass, length and time, has supported the reduced uncertainty estimates.

The situation for higher pressures is quite different. As the use of manometers above a few atmospheres is not practical, the piston gauge is the only primary standard available. Effective area values determined for large diameter, low pressure piston-cylinders can be transferred to smaller diameter higher pressure piston-cylinders with very little added uncertainty. However, as pressure increases, the uncertainty in effective area due to the uncertainty in change in effective area with pressure becomes significant. A typical tungsten carbide piston-cylinder in a simple, free deformation mounting system has a theoretical pressure deformation coefficient of  $7.9 \times 10^{-7} \text{ MPa}^{-1}$  [1].

This leads to a change in effective area of  $1.6 \times 10^{-4}$  at 200 MPa. If the uncertainty in the deformation coefficient is estimated to be  $+1 \times 10^{-1}$ , the resulting uncertainty in effective area at 200 MPa due to uncertainty in the deformation coefficient is  $+1.6 \times 10^{-5}$ , very large relative to the starting uncertainty of less than  $+1 \times 10^{-5}$  that is achievable for the piston-cylinder effective area at low pressure.

The uncertainty in effective area at high pressure due to uncertainty in the pressure deformation coefficient can be reduced by experimental determination of deformation with pressure. The techniques for determining deformation generally have in common the application of an independent pressure, often called controlled clearance pressure (ccp), to the outside surface of the cylinder. The force resulting from the ccp counteracts the deformation of the cylinder and adjusts the gap between the piston and the cylinder.

The elastic behavior of the piston-cylinder assembly in response to measured and controlled clearance pressure is evaluated experimentally in two ways. One is by crossfloat with a highly reproduceable "tare" piston gauge at various measured pressures. At each measured pressure, the ccp is changed while the measured pressure is held constant by the tare gauge. For each controlled clearance pressure, a new crossfloat equilibrium is precisely established by slight adjustment of the mass load on one of the gauges. The relative change in effective area with controlled clearance pressure, is equal to the relative change in mass load. Another means of evaluating the elastic behavior of the piston-cylinder is by measurement of oil flow through the piston-cylinder gap for different values of ccp. Several approaches for deriving the pressure deformation coefficient from these experimental methods have been developed and are well documented [2, 3, 4].

Piston gauges using a controlled clearance pressure have been produced commercially for many years. Though they are used to study piston-cylinder pressure deformation, their principle application and the focus of their design was to allow operation at very high pressure ( $> 500 \text{ MPa}$ ). In this case, the main function of the controlled clearance pressure was to limit the deformation of the cylinder in order to maintain acceptable piston drop rates and, with the introduction of tungsten carbide cylinders, to prevent breakage when the stresses induced by the measured pressure exceeded the tensile strength of the material. Most existing controlled clearance piston gauges have several shortcomings for use as primary standards.

One of these is piston-cylinder mounting designs in which unintended stresses are caused by the measured pressure connection and/or in which pressure seals are located on the outside of the cylinder in a manner which results in unfavorable stress distribution. Another is that at the time the gauges were produced, the materials and machining techniques available did allow the quality of parts that can be produced today. In consequence, to operate properly, a larger starting gap was necessary. This resulted in a high gap to radius ratio and, in turn, high piston drop rate. High piston drop rate makes routine use awkward and hinders precise crossfloating and drop rate measurement. These problems are compounded by non-ideal geometry which causes effective area to change with piston position. Finally, existing controlled clearance gauges tend to be very large and non-transportable, making direct intercomparisons between laboratories impractical.

DH Instruments, Inc., a manufacturer of high performance piston gauges, has introduced a new oil operated, controlled clearance piston gauge. The new piston gauge is specifically intended as a tool for determining the pressure deformation coefficient of piston-cylinders in the pressure range from 0.1 to 200 MPa. It is designed to maximize repeatability for given measured pressure and controlled clearance pressure values.

## 2. Overview of the Controlled Clearance Piston Gauge

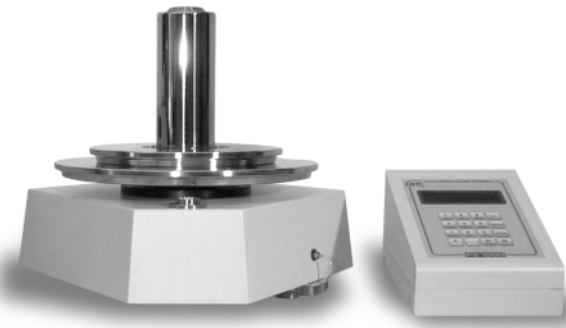


Figure 1 – Oil Operated, Controlled Clearance Piston Gauge (PG7307)

The new controlled clearance piston gauge [Figures 1] is derived from the commercially available PG7302 oil operated piston gauge. Existing piston-cylinder sizes are used in a new piston-cylinder module with provision for application of the controlled clearance pressure to the outside of the cylinder. The proven mechanical design and extensive features of the existing PG7000 piston gauges are exploited by installing a new mounting post on the existing PG7000 platform. These features include on-board monitoring of ambient conditions, piston temperature, piston position and rotation rate. These are accessible both remotely and from a local display. The PG7000 mass loading bell is used assuring compatibility with existing DH Instruments PG7000, as well as Desgranges et Huot Type 5000, mass sets.

## 3. The Piston-Cylinder Modules

As with other PG7000 piston gauges, the piston-cylinder is associated with its own dedicated critical mounting components in a module [Figure 2]. The module is handled as integrated assembly, installed or removed from the piston gauge platform by threading it on and off the mounting post in



Figure 2 – Oil Piston-Cylinder Module

a simple, repeatable process [Figure 3]. Thus, the piston-cylinder and all of the parts that influence its pressure deformation coefficient always remain together. By design, the seals between the module and the mounting post play no role in the pressure deformation of the piston-cylinder. The piston-cylinder modules accommodate existing piston-cylinder sizes (nominal diameter): 11.2, 7.9, 4.9, 3.5 and 2.5 mm. These give maximum

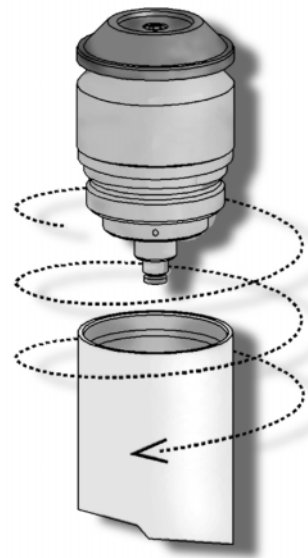


Figure 3 – Oil Piston-Cylinder Module Installation

pressure with a 100 kg mass load of 10, 20, 50, 100 and 200 MPa respectively. By using existing piston-cylinder sizes, the piston-cylinders benefit from the experience and size specific know how that come from producing them in significant quantities. All pistons and cylinders are made of tungsten carbide. Typical deviation from ideal cylindrical shape for the piston and the cylinder is equal to or better than  $\pm 0.2$  micrometer. The normal piston-cylinder gap size is from 0.6 to 1.2 micrometers. The specific size is determined by piston-cylinder diameter to optimize performance when operated with a controlled clearance pressure value that causes the deformation coefficient to be close to zero. However, the gap size can be adapted for other considerations, for example to allow the ccp to be as high as 100 % of the measured pressure.

The controlled clearance piston-cylinder module parts are designed to operate with controlled clearance pressure up to 100 % of the measured pressure to a maximum of 100 MPa, assuming the piston-cylinder gap is sized to allow it. For the different piston-cylinder sizes, the cylinder dimensions and mounting system are such that a ccp of 20 to 25 % of the measured pressure results in a pressure deformation coefficient close to zero. The modules can also be operated in simple free deformation, i.e. with zero controlled clearance pressure. In free deformation, the theoretical pressure deformation coefficient of the 200 MPa (2.5 mm nominal diameter) piston-cylinder with a 100 kg load is  $7.1 \times 10^{-7}$  MPa<sup>-1</sup>, about 10 % less than the same piston-cylinder in a conventional free deformation module.

#### 4. Design Comments and Considerations

Though the controlled clearance gauge uses the same nominal piston-cylinder diameters as those used in commercial free deformation piston gauges, in the controlled clearance application it was considered desirable to modify the design of the cylinder in order to further reduce end loading effects by minimizing constraints associated with boundaries between the cylinder and the mounting components [Figure 4] (all numerical references in this section refer to Figure 4). The length of the cylinder (4) is increased so that the measured pressure sealing O-ring (15) can be installed on an internal diameter that is slightly larger than the effective area diameter. This configuration almost completely eliminates any vertical force from the measured pressure on the cylinder.

The controlled clearance pressure is sealed near the peripheries of the top and bottom surfaces of the cylinder by two identical and symmetrically mounted o-rings (16, 17). The forces on the top and bottom of the cylinder resulting from the controlled clearance pressure cancel each other out resulting in a null vertical force value on the cylinder, regardless of the value of the controlled clearance pressure. This allows the upper portion of the cylinder to deform freely in the radial direction proportionally to the measured and controlled clearance pressures.

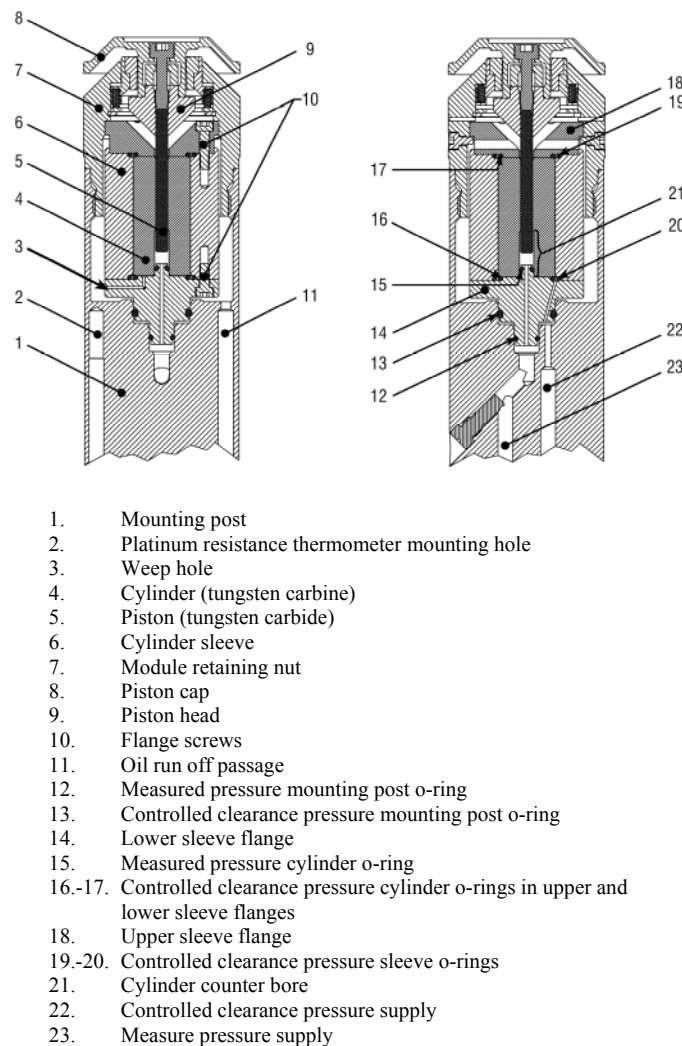


Figure 4 - Mounting Post with Piston-Cylinder Module Cutaways

#### 5. References

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