A Review of Gas-operated Piston Gauges

C. Ehrlich

Abstract. While hydraulic piston gauge technology dates from the mid-1800s, the first practical gas-lubricated pneumatic piston gauges for metrological applications were not developed until almost one hundred years later. The major reason for this delay was the need for adequate materials and machining technology to fabricate pistons and cylinders with tight enough tolerances for acceptable instrument operation. As the need for reduced uncertainties increased for gas pressure measurements in the ranges covered by manometry and above, technological improvement in gas-operated piston gauges advanced rapidly. Requirements for the development of high-quality air bearings added stimulus to the push for improved piston and cylinder technology. Investigations into the possible use of pneumatic piston gauges as primary pressure standards competitive with manometry had begun by 1965. Although lack of a fundamental detailed model of the vertical momentum transfer from the moving gas to the flanks of the piston currently somewhat limits this application, improvements in understanding and technology are continually being made. The relatively recent discoveries of the sometimes significant dependence of the effective area of certain pneumatic piston gauges on the gas species used during operation, or on whether the gauge is operating in the gauge or absolute mode, underscore the need for continued research in this field.

1. Introduction

Over the last forty to fifty years the gas-operated piston gauge has developed into an important tool for making primary and secondary measurements of pneumatic hydrostatic pressure. Combined standard uncertainties (at the 1 σ level) of the effective areas of some of these instruments have been reported below the 5 ppm* level [1-3]. A variety of types and designs of modern gas-operated piston gauges is used to cover a wide range of pressure, from under 10 kPa to over 100 MPa, and for relatively small differential pressures with line pressures from below atmospheric to as high as 20 MPa.

Two books containing comprehensive discussions and reviews of gas-operated piston gauges, with numerous references, exist in the literature [4, 5]. It is not within the scope of this paper to attempt such a thorough review, but rather to complement these sources with a concise overview and update.

C. Ehrlich: Thermophysics Division, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA.

2. Historical Perspective

While published reports describing the use of liquid-operated, liquid-lubricated piston gauges date back to the mid- to late nineteenth century, one of the first literature references to a device resembling a modern gas-operated, gas-lubricated piston gauge was published by Brubach in 1947 [6]. The piston and cylinder were assembled as the elements of "an ordinary glass hypodermic syringe" in which the plunger was spun within the barrel using vanes, attached to the head of the plunger, that were driven by an air stream.

The work of Brubach influenced Hutton [7] in 1958 in his development of a tilting gas piston gauge for measuring low pressures, over the stated range of $3{,}4 \times 10^{-3}$ Pa to $1{,}7 \times 10^{3}$ Pa. The gauge utilized the same basic hypodermic syringe design, with resolution at the 1 ppm level.

By this time, however, the first commercial gas-lubricated piston gauge had already become available. The instrument had a steel piston and cylinder, and operated in both the gauge and absolute modes over the ap-

* 1 ppm ≡ 1 × 10^{-6}.

proximate pressure range of 2 kPa to 35 kPa. Development of this gauge was made possible by overcoming what was then a severe machining tolerance requirement, a uniform radial gap of less than 2,5 µm over a length of 36 mm. This requirement assured that the fall rate of the floating cylinder was about 1 mm per minute or less over the full operating pressure range. This instrument was developed primarily to provide portable, efficient calibration capability of electromanometer transducers used in the characterization of a large wind tunnel for aircraft and aircraft engine design and development [8]. Typical random scatter (at the 2 σ level) in the calibration of the effective area of these gauges ranged from 8 ppm to 16 ppm [9, 10].

In 1958, a gas-operated controlled clearance piston gauge was developed at the National Bureau of Standards (NBS). The gauge operated from about 2 kPa to 4 MPa with an uncertainty of 20 ppm (at the 2 σ level) in the measured pressure. The gas-operated controlled clearance piston gauge is commercially available, and continues to be used successfully at around the ± 25 ppm level (1 σ) at the National Physical Laboratory (NPL), India, where it has also been studied experimentally with different gases [11, 12].

By the mid-1960s the gas-operated piston gauge had become fully established as a legitimate metrological and industrial tool. The first commercial gas-operated tilting piston gauge was offered for sale in 1963. In 1964 Dadson and Greig presented a paper [13] devoted to the "air-operated pressure balance" which is still relevant today. Effects discussed include nonuniformities in piston and cylinder geometry, tilt of the piston axis with respect to the vertical, and flow properties of the gas in the region between the piston and cylinder for viscous (nominal pressures greater than about 1 MPa), transition (nominal pressures around 100 kPa) and molecular (nominal pressures less than about 10 kPa) flow. Interestingly, in this paper the authors predicted that the effective area for molecular flow conditions (absolute mode) should increase relative to that for transition or viscous flow conditions (gauge mode) by up to 20 % of the gap-to-radius ratio, but they later refuted their derivation [5]. Recent experiments have also yielded mixed results, usually showing an increase in effective area [14, 15] but sometimes a decrease [9, 16]. This effect may actually be instrument-dependent.

The maturing of the gas-lubricated journal bearing industry around this same time provided useful theoretical support, such as for calculating the nature of self-centering restoring forces on the piston. Further, the machining tolerance demands for self-acting bearings sometimes rivaled the requirements for piston gauges [17]. Also worth noting at this point is the 1965 landmark paper of Dadson et al. [18], in which the now well-known general expressions for the dependence of the effective area on the applied pressure, including geometrical distortions, were developed (equations (2.2) and (2.3) in [18]). It is important to keep in mind that these expressions were derived for the case where "the pressure transmitting fluid in the interspace flows in accordance with the normal laws of viscosity", a condition not always met in gas-operated piston gauges.

In 1972, Bass and Green [19] published one of the first papers to compare the effective area calculated in two different ways: (a) from dimensional measurements combined with the Dadson [18] model for pressure dependence; and (b) from measurements obtained via cross-float with a mercury manometer. In this paper, data is also presented which show a difference in measured pressure at 10^5 Pa between the piston gauge and the mercury manometer of 7,3 ppm in absolute mode and 9,4 ppm in gauge mode. The manometer had a column height of 0,760 m, and the piston gauge had a nominal diameter of 0,02 m with an uncertainty 0,05 µm, or 2,5 ppm. It is interesting to note that several more recent comparisons of this type [20-24], usually with gauges of larger diameter, resulted in levels of agreement and uncertainty not much improved over Bass's values. Bass later extended his work [25] to include effects caused by elastic distortion of the piston and cylinder.

3. More Recent Developments

By the mid- to late 1970s the pneumatic piston gauge had found its way into several more national standards laboratories, and had become the subject of more frequent and intense theoretical and experimental investigations. Heydemann and Welch [26] briefly mentioned gas-operated gauges in their 1975 review article, and a flurry of activity in 1977 included reports by Sutton [27] and Peggs [28] addressing, in considerable detail, the use of gas-operated piston gauges as primary standards. The concept of the neutral surface was extended to absolute mode operation of these instruments. Studies of the dependence of the generated pressures of gas-lubricated piston gauges on their speed of rotation [29, 30] revealed that, under certain gauge-mode operating conditions, differences corresponding to hundreds of ppm may be observed for high rotational rates. Around this same time, gas-operated, oil-lubricated piston gauges were being developed and sold for applications where particulate contamination in the annular space between the piston and cylinder is a potential problem [31].

International and bilateral intercomparisons of gas-operated piston gauges between standards laboratories began to appear in the late 1970s and early 1980s [32-34]. Reported differences between nominally identical pressures in the range from 40 kPa to 5 MPa were typically around 10 ppm or less, with uncertainties associated with the individual instruments usually at least twice this amount. By the mid-1980s, an international effort to compare the capabilitites of national standards laboratories to measure the gauge and absolute mode effective areas of a gas-operated, gas-lubricated piston gauge, over the pressure range from 10 kPa to about 110 kPa, was well under way. Preliminary results show that, above 40 kPa in the absolute mode, the mean value of effective area for almost all laboratories clusters in a band nominally 10 ppm wide [35]. A progress report by Stuart [36] on this study, which also includes gauge mode results from seven laboratories indicating "a significant difference between the results in the absolute and gauge modes", is included in these proceedings.

The generation and measurement of small, stable absolute pressures, and differential gas pressures over a wide range of line pressures, became a topic of increasing interest in the late 1970s and early to mid-1980s. While emphasis was placed on line pressures around atmospheric [37], an international comparison was also reported by Daborn [38] at line pressures up to 8 MPa for differential pressures between 30 kPa and 150 kPa, with uncertainties from ± 7 Pa to ± 38 Pa. The method of using twin piston gauges [39, 40] to measure small differential pressures at varying line pressures appears to have been the most popular. Several interesting techniques for measuring relatively low absolute pressures, such as using tilting piston gauges or using the bell-jar pressure as the calibration pressure, were also developed [40, 41].

4. Current Research

As commercial piston gauges continued to improve into the 1980s, uncertainties associated with their operation improved accordingly. By the mid-1980s serious attention was being paid to factors influencing the effective area of gas-operated piston gauges at the part per million level [42]. Such factors included the design of the interface between the piston and weight hanger, surface finish treatment of the masses, method of rotation, speed of rotation, magnetic and electrostatic forces, and absolute versus gauge mode operation. As an example, it was found that electrostatic charging effects caused by the wiping of a plastic cover with a cotton cloth could result in a 20 ppm change in the measured effective area of a gas-operated piston gauge [42]. In general, such effects depend on the detailed design and operation of a gauge.

Another important event in the mid-1980s was the development of gas-operated piston gauges with significantly larger diameters and better geometries than had been produced previously [1]. These gauges, with nominal diameters of 35 mm and with radial gaps of order 1 μm, were designed for use as primary standards up to 1 MPa with uncertainties that would be truly competitive with those achievable via manometry. This required piston and cylinder roundness within 0,1 μm, straightness within 0,15 μm, and the ability to make dimensional measurements of these quantities, as well as diameter measurements, with uncertainties of ± 0,05 μm or better. Comparisons between these and other large-diameter gauges and manometers have now been performed [21, 23, 24], with differences for individual comparisons ranging from 3 ppm to 30 ppm.

A direct result of more detailed studies of gas-operated piston gauges was the observation in the late 1980s and early 1990s that the effective areas of some gas-operated piston gauges depend on the type of gas being used as the operating fluid [3, 11, 12, 14, 15, 43, 44] as well as on the mode of operation [14, 15]. An example of the magnitude of such an effect on one gauge, as presented by Welch et al. [14], is shown in Figure 1. In this example the test gauge, with a diameter of 10 mm and a radial gap of about 2 μm, is cross-floated against a standard piston gauge, with a diameter of 20 mm and a gap of about 1,5 μm, for six different gases as indicated. The large relative differences in effective area under the conditions studied indicate a breakdown of the classical

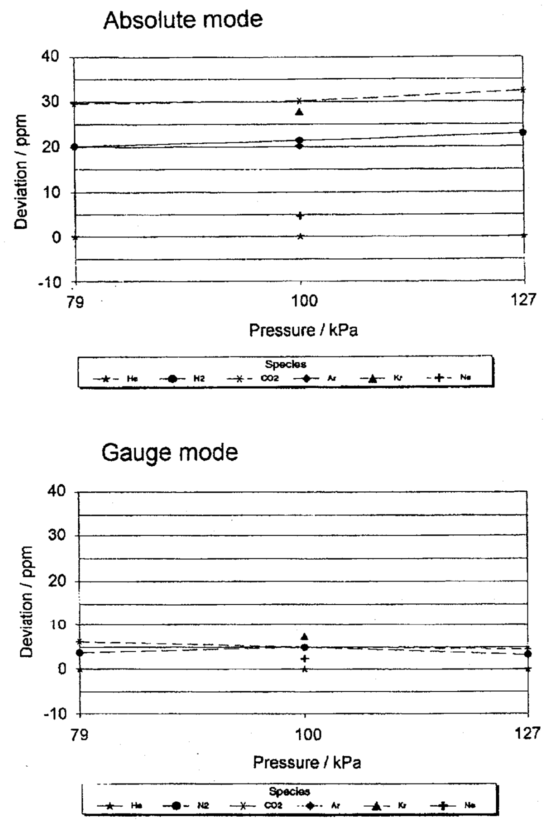

Figure 1. Measured deviation of the effective area of a gas-operated, gas-lubricated piston gauge, denoted PG30, as a function of pressure, mode of operation and gas species. Measurements are based on cross-float with another gas-operated, gas-lubricated piston gauge of different manufacture, assumed to exhibit no mode-of-operation and gas species dependencies.

theory of piston gauges [18], which assumes that laminar viscous flow exists throughout the annular region between the piston and cylinder with the result that the effective area should be independent of the operating fluid.

A physical model extending the classical theory to account for gas species and mode-of-operation effects has been reported by Schmidt et al. [45]. This model assumes from the start that viscous flow conditions in the annular region between the piston and cylinder do not always exist. The model is based on a derived expression for the mean-free-path of the gas molecules in the annular region that depends on both molecule-molecule and molecule-wall collision rates. The momentum transferred from the gas to the walls of the piston is explicitly calculated; the net forces on the piston and the molecular flow rate of gas through the annular region are found to depend on both the type of gas and the operating mode of the piston gauge.

5. Future

The reduction of uncertainties in the effective area of standards-quality gas-lubricated, gas-operated piston gauges appears to have reached a plateau at the 5 ppm to 10 ppm level. Below this level a number of competing, sometimes intertwined, effects become significant and further progress will be limited until the effects are better understood, brought under systematic control and/or eliminated.

As an example of such correlated effects, Dadson et al. [5] estimate that the fractional change in effective area due to tilt and rotation may be as large as 50 % and 15 %, respectively, of the gap-to-radius ratio, and in opposite directions. While the calculations are performed independently for tilt and rotation, the degree of tilt will most likely depend on rotational parameters (e.g. angular frequency, moment of inertia). Note also that these calculations are performed assuming full laminar viscous flow conditions in the gap, which frequently do not exist *even in gauge mode operation!*

Better understanding of such effects requires better physical and mathematical models of the piston gauge system. New models for using gas-lubricated piston gauges as primary standards should not start with expressions for the effective area already derived on the assumption of laminar viscous flow, but rather should start with the most fundamental definition of the effective area, i.e. the full air-buoyancy-corrected weight of the piston and masses, divided by the gauge pressure at the specified reference level under balance conditions. The transfer of momentum from the gas in the annulus to the moving piston should be explicitly accounted for at the microscopic level [45, 46]. Another model from the microscopic level, utilizing the neutral surface concept, is presented in these seminar proceedings by Sutton [47]. In this model the effective area of the piston gauge depends on the gas species and mode-of-operation only if the geometry of the piston and cylinder is not ideal.

While knowledge of the pressure profile in the gap is very important for calculating the forces exerted by the gas on the flanks of the piston, when the ratio of the mean free path of the gas molecules to the width of the gap (the Knudsen number K_n) is roughly between 0,01 and 1 the flow is in the transition region between molecular and viscous flow, and *no good first-principles analytical or numerical methods are yet available* in the vacuum-science literature for calculating the pressure and flow distributions under these conditions. As an example of the ubiquitous nature of the problem concerning piston gauges, note that even for gauge mode operation at room temperature for a piston gauge having a radial gap of 2 μm, K_n is 0,035 for nitrogen, indicating that gas flow over some of the upper portion of the annular region between the piston and cylinder is probably in transition flow.

Before using a gas-operated piston gauge as a primary standard by calculating the effective area from geometrical measurements alone ("classical" theory), experiments should be performed to determine the flow regimes that exist in the annular region between the piston and cylinder for given operating parameters. First, measurements of the gas flow rate can be made by piston fall rate measurements or by measuring the gas flow rate required to keep the piston at its stationary operating height, for different operating pressures of the gauge. The flow regime(s) can then be determined by plotting the molar conductance C_m, defined as the ratio of the molar flow rate through the annulus to the pressure differential across the ends of the annulus, as a function of the pressure differential for pressure differentials spanning the operating range of the gauge. If C_m increases in proportion to the pressure differential with increasing pressure differential, the flow regime is viscous. However, if C_m is flat or has a mild increase (or decrease) with pressure, the flow is molecular or in transition from molecular to viscous. If the piston gauge is to be used as a primary standard over a range of pressure differentials where the flow is found not to be viscous, then an appropriate model other than the classical viscous flow model should be used. As more refined analytical and numerical methods are developed to model gas-operated piston gauges, they should be tested by comparing calculated molar conductances with the type of measurements described here.

Identification, let alone systematic control, of all of the parameters influencing piston gauge performance has proved to be difficult. Obvious factors such as proper temperature measurement or stable, repeatable mass loading have sometimes met with technical difficulties. The major manufacturers have indicated that slight geometrical imperfections, such as local taper, in piston or cylinder geometries may have a marked effect on the effective area. Some of the less obvious factors include the possible role of surface finish of the piston [9], the related influence of cleaning techniques [9, 10], and the potential influence of the plumbing beneath the cylinder on the rotational decay of an undriven piston [48].

Most of the effects influencing the performance and usefulness of gas-operated, gas-lubricated piston gauges as primary standards may be brought under control with proper design in a single instrument, but the need for a good model of the annular forces in the gap will persist. However, following the same logic as for the theory of the neutral surface, the effective area will almost certainly correspond to a radial dimension in the gap between the piston and cylinder, and so minimizing the ratio of the width of the gap to the radius of the piston will minimize the uncertainty in the contribution of the gap forces to the overall effective area. As one move in this direction, the Pressure and Dimensional Metrology Groups at the NIST have entered into a Cooperative Research and Development Agreement with a piston gauge manufacturer to characterize a piston gauge with a nominal 50 mm diameter and a variable gap, adjusted via a pressure on the inner wall of the piston, which is the nonrotating element. The piston and cylinder are both made of a ceramic material, allowing the weight of the cylinder, cap and bell to be such that the unit will perform down to 2,5 kPa in both gauge and absolute modes of operation. Evaluation tests on such a gauge are currently taking place.

Absolute dimensional uncertainties of piston and cylinder diameter at the $\pm 0{,}05$ μm level for a gauge of 50 mm diameter corresponds to an uncertainty in the effective area of about ± 2 ppm. Effects due to lack of roundness and/or straightness must also be included in the uncertainty analysis, and for comparative purposes it is desirable to develop an internationally-agreed method of assessing the uncertainty of the area of a cylindrical object.

Several improved calculation techniques for handling the effects due to distortion have been developed [49, 50] for oil-operated piston gauges. As progress is made in gas-operated gauges where distortions are also significant, these techniques should be applied and developed further with models for determination of the pressure profile in the gap for various operating conditions.

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