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**The Development of Novel Interchangeable Pistons for Pressure Performance
Optimisation in a Gas-Operated Dead Weight Pressure Balance**

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ABSTRACT

The texture of surfaces within a Piston Cylinder Assembly (PCA) can influence the pressure performance of gas-operated Dead Weight Pressure Balances (DWPB). In order to systematically study this response, it has been necessary to design, develop and manufacture uniquely interchangeable 35mm diameter PCAs for use in a novel hybrid gas-operated DWPB with high mechanical, thermal and pressure stability. This work reports the development of the PCAs and the validation of the DWPB design, allowing the performance characteristics of the interchangeable PCAs to be understood, in terms of variations of effective area calculations. This is achieved by investigating the pressure responses of the DWPBs by changing the speed and direction of rotation. The results demonstrate the stability of the gas-operated DWPB design when used in gauge mode, and importantly allow the verification of the performance of the interchangeable PCAs.

1.0 INTRODUCTION

Dead Weight Pressure Balances (DWPBs) are widely used around the world to generate pressures with high levels of accuracy, from several kPa to several hundred MPa [1-3]. Both, hydraulic and gas operated DWPBs provide one of two primary methods for deriving pressure from the base units of mass, length and time; the other being the liquid manometer [1-3]. One of the major differences between these two (the DWPB and the manometer) types of instrument is their measuring range, where the former can measure in a very wide range, whilst the latter is usually limited to near atmospheric pressure regions.

The DWPB's principle component consists of a Piston-Cylinder Assembly (PCA) with a known effective area (A_0), which is oriented vertically to the earth's gravitational force. A PCA consists of a finely lapped and polished piston, fitting into a geometrically and dimensionally matching cylinder of similar surface characteristics.

Weights of known mass can be loaded onto the piston, so that the upward vertical force (due to the pressure) acting on the piston (across the A_0) exactly balances the total downward gravitational force, so that at equilibrium the piston floats while falling at its natural fall rate. The piston and weights are rotated during operation in order to alleviate frictional components and to ensure concentricity, thus helping the piston to float freely [2,3]. It should be noted that in some DWPB designs, the cylinder may be rotating instead of the piston [4], but the physical principle remains the same.

The pressure is defined as the ratio of the total downward gravitational force to the A_0 , where A_0 is most commonly determined through a comparison against another DWPB or a

mercury manometer, although dimensional characterizations have also been used [5-9]. The fact that the force can be measured with greater accuracy than area is well known. To increase the accuracy of pressure measurement it is necessary to better understand the determination of A_0 , and hence the correct determination of the A_0 becomes the core issue related to further development of the DWPB as a primary standard.

Pressure (in gauge mode) is related to the effective area [1-3], via Equation 1,

$$p = \frac{\sum_i m_i (1 - \rho_a / \rho_m) g_L + \pi D T}{A_0 (1 + \lambda p) [1 + (\alpha_p + \alpha_c)(t - t_{ref})]} \pm (\rho_f - \rho_a) g_L h \quad \text{Eq.1}$$

where p is the calculated pressure at a reference level h from the base of the piston; m_i is the mass of the i th weight; ρ_a is the air density; ρ_m is the density of the weight; g_L is the local acceleration of gravity; D is the diameter of the piston; T is the surface tension of the pressure transmitting fluid used; A_0 is the effective area of the PCA at atmospheric pressure and reference temperature, t_{ref} ; λ is the pressure distortion coefficient of the PCA; α_p and α_c are the linear thermal expansion coefficients of the piston and cylinder respectively, t is the temperature of the PCA at the time pressure being measured; t_{ref} is the reference temperature of the PCA; ρ_f is the density of the pressure transmitting fluid; and h is the distance between the piston base and a selected reference level.

The current method for determining the effective area of a PCA relies on the neutral surface between the cylinder and piston walls, with A_0 currently being defined as [2, 5]:

$$A_0 = \pi r_0^2 \left[1 + \frac{h_0}{r_0} - \frac{1}{r_0(p_1 - p_2)} \int_0^l [(u + U) dp/dx] dx \right] \quad \text{Eq.2}$$

where r_0 is the radius of the piston at the lowest extent of the engagement length between piston and cylinder; h_0 is the radial separation between two surfaces of the piston and cylinder at the same level as r_0 ; p_1 is the pressure being applied at the lowest extent of the engagement length, p_2 is the pressure around the top end of the piston (atmospheric pressure in gauge mode operation, or reference vacuum for absolute mode operation); u and U are the radial deviations from the radii of the piston and cylinder respectively at the lowest extent of the engagement length. For a PCA with a perfect geometry ($u = U = 0$, i.e. constant radial clearance) the effective area, A_0 is exactly the arithmetic mean of the area of piston and cylinder [3].

Theoretical understanding and manufacturing improvements have allowed the gas-operated DWPB to develop over the last forty years, resulting in pressure determination from a few kPa to several hundred MPa. However in practice, besides the effects of gas leakage through the PCA clearance, other possible sources of uncertainty have been recognised, such as inconsistencies in PCA geometric form, inclination of the PCA, eccentricities of applied load etc [6], although not necessarily quantified. One aspect which has not been reported is the affect that piston (and/or cylinder) surface texture or structure, has on the fluid flow characteristics and hence the effective area determination. This is an element that is not modelled or taken into account within Eqs 1 and 2.

Investigating surface texture characteristics of PCAs on DWPB performance is challenging, with the following key issues identified in order to enable this research:

- Interchangeable PCAs are required to explore a range of surface textures (random and structured), with different pistons being used in common cylinders.
- Methods of pre-determined texturing of PCA surfaces (typically Tungsten Carbide) require investigation and implementation.
- DWPB units are required which allow integration and interchangeability of PCA units, with high thermal stability.
- Any new design of PCA (and DWPB) requires metrological assessment with respect to primary standards, before it can be used to investigate the impact of process variables, to ascertain the mechanical, thermal and pressure stability.

This paper describes the design, development and manufacture of uniquely interchangeable 35mm PCAs, along with the design and manufacture of a novel hybrid gas-operated DWPB. As part of the preliminary work and instrumentation proving process, detailed analysis of low rotational spin speed and spin direction pressure related characteristics have been completed, along with direct calibration to UK national standards.

2.0 DESCRIPTION OF INSTRUMENTS

The development of the DWPB detailed in this work, has been necessary to allow straight forward PCA interchangeability, resulting in a unique design [10,11] that recognises elements of other pressure balances [2,12,13]. The DWPB design has been optimised to specifically enable research to be completed on understanding dimensional tolerance and surface characteristic issues of the 35mm PCAs. However, this has necessitated the understanding of various potential error sources, and specifically in this case, issues of spin direction and spin speed and the effect on the generated pressures at low rotational speeds.

2.1 Piston cylinder assembly (PCA)

Pistons and cylinders were manufactured from Dymet Grade DF6 Tungsten Carbide (Table 1). Pistons were constructed from hollow Tungsten Carbide blanks (60mm height, 25mm inner diameter, 35mm outer diameter) bonded with a 316 Stainless Steel head (30mm height, 25mm outer diameter) with a hemispherical cup on the top surface to accommodate the interfacing 316 Stainless Steel ball-bearing. Cylinders were manufactured from hollow Dymet Grade DF6 Tungsten Carbide blanks (40mm in height, 35mm inner diameter, 52 mm in outer diameter). The pistons and cylinders are illustrated in the DWPB assembly drawing in Figure 1.

The majority of commercially available PCA combinations can be described as matched pairs, with gap clearances typically in the order of 0.5 μm to 1 μm for gas based DWPBs. This research programme has required the development of a large number of pistons, which uniquely have operational interchangeability with a number cylinders, with gap clearances of approximately 1 μm . Eight interchangeable pistons (labelled as P_1 to P_8

respectively) and four interchangeable cylinders (labelled as C_1 to C_4 respectively) have been produced using rotary lapping and polishing techniques.

2.2 The Dead Weight Pressure Balance (DWPB)

Two identical gas-operated DWPBs were designed and manufactured for measuring pressures with an uncertainty budget of approximately 10ppm ($k = 2$), as detailed in Figure 1. The base of each DWPB was triangular in shape (25mm thick HE15 aluminium alloy), supported with 3 adjustable leveling feet. The 316 Stainless Steel mounting post was 90 mm in diameter and 214 mm in height. A large overhang type weight loading bell (102 mm inner diameter) with associated ring weights was designed in order to accept very large PCAs (35 mm and 50 mm diameter). The maximum pressure specification for the DWPBs was 700 kPa with 35 mm diameter PCAs.

The PCA cylinder was seated vertically on top of an o-ring, located in a groove inside the mounting post, secured using a 316 Stainless Steel cylinder retainer for pressure sealing purposes, consequently forming a free-deformation type of assembly. The PCA piston was secured by a 316 Stainless Steel piston retainer, acting as a retainer when the pressure increased beyond the equilibrium point. A piston-retainer coupled with a 316 Stainless Steel upper-bearing washer acted as a supporting mechanism when pressure decreased below the lower equilibrium point. This mechanism enabled the piston and associated weights to rotate on the thrust bearing while the piston was fully seated.

A ball bearing was used as a non-rigid point load interface mechanism between the piston and the overhang-type weight loading bell. 316 Stainless Steel ring weights were stacked at the lower end of the loading bell (lower centre of gravity relative to the PCA), hence

improving the stability of the rotating piston (note that all weights, loading bells, pistons and other load elements were UCAS traceably calibrated). Consequently loaded weights were free to pivot, while maintaining the center of gravity coincident with the piston's axis. This design eliminated non-vertical (side loading) forces which may occur due to slight misalignment of loaded components [13].

The window-type weight loading bell was designed and manufactured with four windows (each 210 mm long and 40 mm width); to avoid having escaping gases (e.g. nitrogen through the PCA clearance) from introducing any additional source of error in equilibrium, to ensure that system exposure to ambient room temperature was maximized, and to reduce the initial mass value hence reducing the starting pressure point. The piston and loaded weights were rotated manually during operation, which demonstrated better temperature control compared to thermal input from a motor-driven DWPB.

2.3 Thermal stability

The design of the DWPB (including the PCA) provided direct contact for a large volume of material exposed to the ambient temperature, maximizing passive temperature stabilization, reducing the rate of change of PCA temperature, and consequently error terms as a function of thermal expansion. The temperature of the PCA was measured using a dual-channel digital thermometer, with two calibrated k-type thermo-couples running from the bottom of the mounting post to points close to the cylinder.

The stability of the PCA temperature was shown to be excellent throughout operation, as identified during calibration at the UK National Physical Laboratory (NPL) directly against the Primary Pressure Standard. The NPL standards room temperature fluctuated randomly

between 20.02°C to 20.49°C for a period of 4.5 hours between 11.00am and 3.30pm (11.00 – 15.30), with a standard deviation of 0.13°C. Meanwhile the previously thermally soaked PCA temperature working with this DWPB design, gave readings that changed almost linearly between 20.03°C to 20.10°C with a standard deviation of 0.02°C, this being illustrated in Figure 2.

2.4 Existing Spin-Speed Research

A significant issue for all DWPB designs is to determine if spin direction and spin speed attribute any systematic error to the pressure balance results. This has received limited reporting in the past, with investigations of the effect of rotation on generated pressures in gas-operated DWPB conducted by Prowse and Hatt [14], and subsequently by Sutton [15]. Both sets of researchers conducted investigations using Type 6-201 gas-operated DWPBs, manufactured by Consolidated Electrodynamics Corp. (CEC, USA), using pistons of diameter 3.2mm, 10.2mm and 32.1 mm (8.1mm², 81 mm² and 810 mm²) respectively.

Prowse and Hatt found that at a rotational frequency of approximately 1000 rpm (at 40 kPa), the maximum difference in pressure readings with and without a bell-jar in situ was approximately 20 Pa (when loaded with larger weights). At rotational frequencies of 50 rpm and below (at 70 kPa and above), the pressure determined was independent of a bell-jar, but decreased as rotational frequency decreased further.

In comparison, Sutton identified that the generated pressure at rotational speeds between 180rpm to 600 rpm (3Hz -10Hz) increased with the square of the rotational frequency, where the calculated pressure was equal to the extrapolated pressure at zero frequency (zero aerodynamic forces). It was suggested that this change was due to the airflow set up

225 by the rotating load carrier and weights, potentially forming a spiral flow down thus
226 forming a downward force onto the top of the pressure balance. The results also suggested
227 that this force depended only upon rotational frequency and not load, at rotational speeds
228 between 180 rpm to 480 rpm.
229

3.0 MEASUREMENTS

Cross-floating (either via flow sensing or pressure sensing) is one of the principle methods to determine the effective area (A_0) of a PCA under test, where the reference and test DWPBs are interconnected to a common pressure line. Trim weights are added onto either piston until barostatic equilibrium is established, with both pistons rotating and floating at their reference level, simultaneously falling at their natural fall rate. Once an equilibrium condition is established, the effective area under test can be calculated based on the ratio between two masses i.e. on one piston versus the other.

3.1 Cross-floating and spin/speed experimentation

An arrangement for a traditional cross-floating experimentation is shown in Figure 3. Effective areas of 2 combinations of the PCAs were determined at 100 kPa using purified nitrogen (99.998% N_2). A combination of Piston 2 (P_2) and Cylinder 3 (C_3) was used as a reference (known as P_2C_3). Test PCAs were combinations of Piston 4 (P_4), Cylinder 2 and Cylinder 4, known as P_4C_2 and P_4C_4 respectively. In order to minimise the error of the total mass loaded on both pistons, the reference DWPB (P_2C_3) and the test DWPB (P_4C_2 and P_4C_4) weight sets were mutually exclusive. High accuracy trim weights (Mettler-Toledo class F1 weight, 1mg to 100g), were used for balancing purposes.

Investigation of the response of the novel interchangeable PCA units and the DWPB design, has been carried out by changing the speed of rotation between 30 rpm and 90 rpm (0.5 Hz and 1.5 Hz), and the direction of rotation either clockwise (cw) or counter-clockwise (ccw) on the reference and/or test DWPBs. This formed 4 different test conditions: i) cw – cw, ii) cw – ccw, iii) ccw – ccw and iv) ccw – cw which was noted as

being one completed experimental cycle of investigation. Each test PCA combination was experimentally verified over eight cycles, resulting in 32 calculated A_0 values per PCA.

3.2. Determination of equilibrium conditions

The natural fall rate of the reference DWPB (P_2C_3) was initially established using a non-contact Eddy Current displacement transducer (eddyNCDT 3300 - Micro-Epsilon Messtechnik GmbH) with a linear resolution of 1 μm . The reference level of the test DWPB (P_4C_2 or P_4C_4) was measured using a Mitutoyo height gauge (20 μm resolution). The fall rate value of the reference DWPB was established with P_2C_3 in a floating and rotating condition at its mid-float position, with ball valve V1 closed.

The equilibrium conditions were assessed using the differential pressure method, (acting as a null indicator), with a pressure transducer connected across an isolation ball valve (V3). The differential pressure sensor used was a high-accuracy capacitance diaphragm sensor (MKS Type 698A, 1 Torr range), set to 400 msec response time and 0.01 Pa resolution, corresponding to 0.1 ppm at 100 kPa. The smallest trim weight (sensitivity weight) that produced a detectable pressure change was a 2 mg weight (0.2 ppm at 100 kPa). The agreement of the results produced by the differential pressure transducer and the Eddy Current displacement sensor for indicating the equilibrium status were very good. Hence the displacement sensor was an ancillary instrument for judging equilibrium conditions.

A non-contact Compact Instruments CT6/LSR laser tachometer (1 rpm resolution) was used to measure speed of rotation of the piston. A RS 52 Dual Channel K Type digital thermometer (with K-type thermocouples of 0.1 $^{\circ}\text{C}$ resolution) was used to measure the temperature of both PCAs.

277

278 A full uncertainty analysis was completed (with respect to an analysis of the sensitivity
279 coefficients associated with effective area calculation) using the methods described in the
280 ISO Guide to the Expression of Uncertainty in Measurement [16], to provide a traceable
281 statement of uncertainty. The Type A component was based on the standard deviation of
282 the data sets. The Type B components (input parameters with rectangular probability
283 distributions) were estimated based on manufacturers reference data and instrumentation
284 error (weight density, air density, PCA coefficient of thermal expansion, PCA
285 temperature). The Standard Uncertainty of the test effective area at 100kPa and 20°C was
286 calculated as being 8.2ppm, with the Expanded Uncertainty (coverage factor of $k = 2$)
287 being 16.4ppm.

288

4.0 RESULTS

Cross-floating experiments directly against the UK's PG7601 Primary Pressure Standard (with a 35 mm diameter PCA, NPL Serial No. 602) were completed in order to define traceability of the reference and test PCAs. P_2C_3 (reference PCA) was cross-floated at 50 kPa, 75 kPa, 100 kPa, 200 kPa, 300 kPa and 400 kPa, in falling and rising mode, whilst P_4C_2 and P_4C_4 were cross-floated at 100 kPa only. The calibrated and traceable effective area values for the three PCAs identified in this work are detailed in Table 2.

Initially, two cross-float experiments were performed sequentially using P_4C_2 and P_4C_4 respectively, without any mechanical adjustment of the Test DWPB unit (apart from PCA change). Both DWPBs operated with a sensitivity-of-equilibrium of 0.2 ppm as defined by the differential pressure transducer over the entire cross-floating process. The spin times of the reference and test PCAs were approximately 45 and 35 minutes respectively (at 100 kPa, and 100 rpm initial speed of rotation) with drop rates of approximately 0.1 mm/min further demonstrating geometrical quality of the PCA units.

Single sets of calibrated weights loaded on both DWPBs during cross-floating experiments significantly reduced any systematic error inherited by each weight. Systematic errors incurred by the calibrated class F1 trim weights were deemed to be negligible. The standard deviation of effective area determined by both cross-floating experiments was calculated as being less than 1 ppm (due to the random effects).

Spin speed and spin direction experiments were completed as identified in Section 3. The DWPBs were manually spun, thereby reducing parasitic thermal input. Equilibrium

between DWPBs was typically achieved during a ten minute time frame, with negligible reduction of spin speed of either PCA during this time. The results of the two series of experiments are shown graphically in Figures 4 and 5 respectively, with summary data provided in Table 3. Each figure shows four discrete groupings of data points which are grey scale coded to identify the calculated effective area value.

The average values for P_4C_2 and P_4C_4 were 981.6387mm^2 (sample Standard Deviation (SD) 0.00087mm^2 or 0.87ppm) and 981.6293mm^2 (sample SD 0.00075mm^2 or 0.75ppm) respectively. There is only minor random variation of effective Area values for each spin condition (as demonstrated by the SD values) for each PCA combination, with no systematic difference or adverse trends between conditions. The random scatter with respect to the X and Y axes in both Figures 4 and 5 is a function of manually spinning the DWPBs to the approximate desired rotational speed.

Air temperature, atmospheric pressure and relative humidity were monitored throughout the experimentation showing minor changes of air pressure, allowing buoyancy calculations to be completed and applied. DWPB (Test and Reference) temperatures were also monitored, but found to be stable.

5. CONCLUSIONS AND FUTURE WORK

This research has been initiated with the eventual aim of providing detailed understanding of the influence of PCA surface texture (both random and structured), on the pressure and performance characteristics of gas-operated Dead Weight Pressure Balances at low rotational speeds. The current results have demonstrated confidence in two key elements of the initial research.

Firstly, the results have identified that 35mm Tungsten Carbide Piston Cylinder Assemblies can be efficiently manufactured to appropriate pressure related tolerances, and specifically allow different pistons to be used in common cylinders, with very limited variability of pressure performance. Hence PCA interchangeability has been achieved. This is a significant step forward in the pressure metrology optimisation research. Through careful manufacture, this will allow a large set of pistons to be developed which will be interchangeable, providing a range of piston surfaces that may be modified with respect to surface texture.

Secondly a simplified, novel, hybrid gas-operated DWPB design has been produced and operated in gauge mode, which exhibits high mechanical, thermal and pressure stability. This provides a stable platform for subsequent interchangeable PCA evaluation at low rotational speeds. It has been demonstrated that no significant differences in effective area determination will occur as a function of rotational speed and rotational direction specifically in the range 30 – 90 rpm (0.5 – 1.5 Hz). At present, these systems have not been systematically tested at speeds higher than 90 rpm.

356 With these two elements proven and demonstrated, experimentation concerning the effect
357 of surface texture on pressure performance can be investigated, with confidence that
358 significant variations may be attributed to piston surface form rather than other sources of
359 uncertainty. Clearly, any variations of effective area would need to recognise the
360 relevance of the Standard and Expanded Uncertainty statements.
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425

Dymet Grade No.	Average Grain Size / μm	ISO Code	Composition by weight (%)				Trans. Rupture / MPa	Hardness / HV50	Density / Kgm^{-3}
			WC	TaC	Cr_3C_2	Co			
DF6	1.0	K10	92.7	1.0	0.3	6.0	1800	1750	14900

426

427 Table 1: Basic composition of Dymet Grade DF6 tungsten

428 carbide and its physical properties

429

429

PCA Combination (PxCy)	Effective Area (A_o)	
	Value / mm^2	Uncertainty / (k=2)
P ₂ C ₃	981.605	0.014 (14.3 ppm)
P ₄ C ₂	981.635	0.014 (14.3 ppm)
P ₄ C ₄	981.625	0.014 (14.3 ppm)

430

431 Table 2: Calibrated and traceable PCA effective area values

432

432

	P₄C₂	P₄C₄
Minimum Effective Area / mm²	981.6372	981.6273
Maximum Effective Area / mm²	981.6399	981.6304
Mean Effective Area / mm²	981.6387	981.6293
Standard Deviation / ppm	0.75	0.87

433

Table 3: Summary of results of effective area determination for P₄C₂ and P₄C₄.

434

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