The Influence of Hydraulic Fluids on Pressure Balance Calibration Results

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Abstract. The effective area of a hydraulic pressure balance is typically characterised using the cross-floating technique, where the pressure balance is compared against a standard instrument. This method usually involves operating both instruments in the pressure transmitting fluid of the standard, even if the tested device is normally operated with a different fluid. We describe novel experiments to determine the influence of various commonly used oils on the measured effective area of the balances. Measurements were made using five different oils in the pressure range 28 MPa to 200 MPa. Our results show that in some cases the contribution to the effective area when using different oils was nearly 60 ppm. Although a difference in the effective area with respect to the liquid viscosity was intuitively expected, the results appear to show a greater dependency on the liquid density, which contradicts the current assumptions used to formulate the theory describing the pressure balance.

1. Introduction
One of the methods by which pressure can be measured is in terms of the force that acts on a surface of known area. The instrument using this approach is known as the pressure balance [1], in which the downward force, mainly due to known masses supported on the cylindrical piston, balances the pressure acting on the other end of the piston [2]. Pressure balances are widely used in the range 3.5 kPa to 500 MPa.

A formal theory of the pressure balance, based on the laws of fluid dynamics, was developed in the mid 1960s [3]. This theory has proven to be extremely successful, however, in recent years, with the introduction of modern manufacturing techniques and improved tolerances, a certain amount of anomalous behaviour has been observed [4],[5],[6],[7]. The most likely explanation is that the assumptions used to formulate the theoretical model for the pressure balance are no longer adequate.

Although the basic theory does not predict a change of the piston-cylinder’s effective area when using different liquids as pressure transmitting media, a difference related to the liquid viscosity, due to its contribution to the pressure distribution in the piston-cylinder gap, would be expected. As indicated by earlier work [1], if any such changes do occur, they will influence the effective area of the piston-cylinder at high pressures, thus having an effect on the ‘distortion coefficient’.

In general, working calibration laboratories use Sebacate oil (di-2-ethylhexylsebacate) in hydraulically operated devices, but laboratories also operate and calibrate instruments using other oils. The common approach however, is to calibrate the hydraulic pressure balance (HPB) piston-cylinder assembly (PCA) in the same fluid as is used for the standard instrument.
This paper describes some of the work performed within the scope of National Measurement System Directorate Engineering Measurement Programme, Project 2.19: *Improved Realisation of Conventional High Pressure Scale* which was initiated as a response to growing concerns about the use of different oils in pressure balances [8].

2. Experimental details

Following a survey to discover what types of lubricating liquids are used as pressure transmitting fluids by different laboratories, four oils were selected for evaluation.

The oils used in this work, together with some of the relevant characteristics (density and dynamic viscosity), are listed in Table 1.

| Fluid                          | Fluid density (kg m$^{-3}$) at 20 °C and 1 013.25 Pa | Viscosity (mPa s) |
|-------------------------------|-----------------------------------------------------|-------------------|
| DH-Budenberg - HP Fluid       | 989                                                 | 131               |
| Hydraulic Mineral Oil (Shell Tellus T15) - ISO VG15 | 862                                                 | 26                |
| Hydraulic Mineral Oil (Shell Tellus T37) - ISO VG37 | 870                                                 | 76                |
| Univis P12 (early NPL oil) (di-2-ethylhexylsebacate supplied by Esso) | 921                                                 | 22.5              |
| CP Hall Sebacate (current NPL oil) (di-2-ethylhexylsebacate supplied by CP Hall) | 915                                                 | 21.5              |

The experiment involved calibrating several test instruments using the oils detailed in Table 1 as the pressure-transmitting medium, against a standard instrument, which used CP Hall Sebacate.

The setup consists of two independent pressure systems and a High Pressure Sensor (HPS) with parts-per-million (ppm) resolution, linked together via two constant-volume valves (V1 and V2) as shown in Figure 1, in which the two valves kept the oils separated during tests.

Valves V3 and V4, the ram screw and oil reservoir at the left of valve V1 were used to create pressure in the ‘Test’ system isolated by valve V1. The valve V7 was used to drain the oil in the ‘Test’ system.

![Figure 1 Experimental setup (V1 to V7 are isolating valves)](image-url)
Valves V5 and V6, the ram screw and oil reservoir at the right of valve V2 were used to create pressure in the ‘Standard’ system. The HPS and the space between V1 and V2 were filled with CP Hall Sebacate and were initially pressurised with V2 open and V1 closed.

The experiment used nine PCAs (Ruska 2481) in three nominal sizes of effective area (84 mm$^2$, 16.8 mm$^2$, 8.4 mm$^2$), covering the hydraulic pressure range 2.8 MPa to 280 MPa.

For each nominal size (family), one PCA was selected as ‘Standard’ instrument and two assemblies as ‘Test’ instruments.

For each family of PCAs, one of the ‘Test’ assemblies was calibrated in re-entrant mode, and the other ‘Test’ assembly was calibrated in free-deformation mode. The ‘Standard’ assembly was operated in re-entrant mode. A detailed account of PCA selection is given in the NPL report [8].

All piston cylinder assemblies under test were calibrated initially in CP Hall Sebacate and subsequently in the oils introduced in Table 1. For reconfirmation, a final calibration was performed using CP Hall Sebacate. The initial calibration results using CP Hall Sebacate in both PCAs were used as reference values. Six calibrations were therefore performed for each PCA at the same four nominal pressures.

3. Results

The effective area of a ‘Test’ pressure balance is usually determined by cross-floating the balance against a similar ‘Standard’ pressure balance.

To avoid the cancelling-out effects of the traditional cross-floating technique, an alternative technique was used in which the measurements were made using two separate oils simultaneously [8].

Initially, the effective area of the ‘Test’ pressure balance was determined by comparing against a ‘Standard’ pressure balance using the same oil (CP Hall Sebacate). After the initial calibration, the oil used by the ‘Test’ pressure balance was changed and the new effective area was determined.

Thus the differences in effective area when using different oils, $\Delta A_T$, will be given by:

$$\Delta A_T = p_{St}^{-1} \times \Delta F_T$$  \hspace{1cm} (1)

where $p_{St}$ is the pressure generated by ‘Standard’ and $\Delta F_T$ is the difference in force applied on tested piston due to the difference in effective area of the ‘Test’ pressure balance when changing the oil.

Some results of the calibrations performed in different oils are plotted in the graphs presented in Figure 2 a) and Figure 2 b). The graphs show the change in effective area with respect to the initial CP Hall Sebacate calibration, together with the typical uncertainties [8] of the 8.4 mm$^2$ family, for the free-deformation and re-entrant assembly respectively.

Figure 2 a) Difference in 8.4 mm$^2$ free-deformation assembly effective area w.r.t. CP Hall Sebacate; b) Difference in 8.4 mm$^2$ re-entrant assembly effective area w.r.t. CP Hall Sebacate. Typical error bars shown at $k = 1$. 

\[ \text{Figure 2 a)} \]

\[ \text{Figure 2 b)} \]
These results show the largest change in effective area for both ISO VG15 and ISO VG37 oil. For the free-deformation assembly the change seems to be positive for oils with lower densities than CP Hall Sebacate and negative for oils with bigger densities than CP Hall Sebacate, therefore change ΔAT is anti-correlated with oil density. However, for the re-entrant assembly the effect is positively correlated. The effect is consistent over most of pressure range, and at highest pressures (138.6 MPa and 193.8 MPa) the differences are significant when compared with the uncertainties.

It is predicted, on the basis of the current results, that the calibration of an instrument similar to the 8.4 mm² re-entrant assembly, using CP Hall Sebacate when it is designed to use ISO VG37, will introduce a possible relative systematic error of 60 ppm in effective area at 200 MPa. In the work reported here the relative uncertainty would be ± 68 ppm (k = 2) of effective area. It follows that, as calibration providers, we should either calibrate instruments using the prescribed operating oil or take extra account of the different oil when evaluating the uncertainties.

4. Conclusions
Significant systematic errors are found in the effective area when using different fluids as pressure transmitting media in a pressure balance. The change in effective area relative to CP Hall Sebacate is dependent on the pressure, and therefore on gap size, although at this time we cannot make any quantitative predictions relating the size of the effect to the initial gap. Although a difference related to the liquid viscosity (due to its contribution to the pressure distribution in the piston-cylinder inner space) was intuitively expected [1], the experiment instead appeared to show an effective area dependency on the liquid density.

Existing theories do not provide a mechanism for a density dependent effect. Efforts to validate any new theoretical model (that attempts to describe the behaviour seen in this work) are likely to require a selection of oils having a wider range of density and viscosity. Additionally, the experimental work will need to be extended to assemblies having better metrological characteristics than those used here (e.g. better repeatability and higher pressures ranges) and a wider range of PCA gap sizes.

Using piston cylinder assemblies with smaller gaps reduces the magnitude of the effect. When cross-floating two pressure balances with the same fluid many of the systematic effects, such as a change in effective area, are largely cancelled out - it is possible that larger effects would be seen if different oils were used to calibrate high precision electronic instruments.

References
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