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A NEW METHOD FOR THE ABSOLUTE MEASUREMENT OF HIGH PRESSURES

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AS part of a programme of work in the field of high-pressure physics, the National Physical Laboratory is now working on a project for the establishment of standards for the measurement of high pressures.

In practice, most measurements of high pressures intended to be of the greatest precision are made with pressure balances, or dead-weight gauges, of the familiar type in which fluid pressure acting on a piston of known area is balanced by a load applied by means of calibrated weights. The accuracy of such balances has hitherto been limited principally by the fact that at high pressures the piston and the cylinder in which it moves are distorted to an extent which is not easily measurable. As a result of this, the 'effective area' of the assembly is subject to an uncertainty which is likely to increase as the pressure is raised.

The usual method adopted in the past for the determination of the effective areas of piston–cylinder assemblies[1] has relied on the use of high-pressure mercury columns, but the results of these investigations have not so far given any clear or consistent indication of the changes in effective area under the influence of elevated pressures. A new standard mercury column of this type capable of operating up to about 2,500 atmospheres has recently been described by Bett, Hayes and Newitt[2], who discuss in detail a number of factors affecting the accuracy likely to be achieved. So far, however, no results of measurements with this instrument on actual balances have been published. While it is clear that a well-designed high-pressure mercury column is capable of the establishment of high pressures with considerable accuracy, it nevertheless seems likely to be a somewhat difficult instrument to use, mainly on account of the long and laborious series of pressure transfers which need to be made to reach the high-pressure range.

The purpose of this communication is to give a preliminary description of a new method for establishing the calibrations of pressure balances which has recently been developed at the National Physical Laboratory. In measuring the change of effective area of a balance as the pressure is raised, the method makes use of a quite simple principle of similarity as applied to pressure balances of the same dimensions but constructed of different materials. If we consider two piston–cylinder assemblies of the same nominal dimensions but of materials the elastic constants of which differ in a known ratio, then in certain circumstances, considered in more detail below, the distortions, under applied pressure, of the two assemblies will remain proportional to one another throughout the range of pressure concerned. Under these conditions, and neglecting small quantities of the second order, we may represent the effective areas A and B of the two assemblies at a given pressure in the form

$$A = A_0\{1 + \alpha.\mathrm{f}(P)\}\ ;\ B = B_0\{1 + \beta.\mathrm{f}(P)\}.$$

In these expressions A_0 and B_0 are the (nominally equal) effective areas at zero pressure, α and β are constants inversely proportional to the elastic moduli of the two materials, and $\mathrm{f}(P)$ is an unknown function of the pressure, P. The ratio of the two effective areas will be given, to the same order, by the expression

$$A/B = A_0/B_0\{1 + (\alpha - \beta).\mathrm{f}(P)\}.$$

This ratio is easily determined by balancing the two assemblies directly against one another, and this procedure determines the quantity $(\alpha - \beta).\mathrm{f}(P)$. The quantity α/β may be obtained from direct measurements of the elastic constants of the two materials. These two procedures thus enable the absolute value of the change of effective area of each of the piston–cylinder assemblies to be determined.

For the theory outlined above to be valid, a number of conditions must be satisfied, both as regards the materials and the construction of the assemblies. Since two independent elastic moduli will be involved in a somewhat complicated manner in the distortion of each assembly, true proportionality can only be achieved if both moduli are in the same ratio—in other words, the values of Poisson's ratio for the two materials should be closely similar. As regards construction, the forms of the internal bores of the cylinders, and of the pistons, must be closely similar in contour, since otherwise the distributions of pressure in the gap between piston and cylinder will not be the same in the two assemblies. The similarity principle also requires that the gapwidths at zero pressure should be inversely proportional to the elastic moduli. If these conditions are adequately met, and the elastic properties of the materials are uniform throughout the range of stress involved, proportionality of the distortions will be assured. This will remain valid even if the viscosity of the transmitting fluid is dependent on pressure, as will almost certainly be the case. It is, however, worth noting that the effective area of a pressure balance may depend to some extent, at high pressures, on the viscous properties of the fluid used.

The present series of experiments at the National Physical Laboratory is intended to cover the range up to 3,000 atmospheres. The two materials so far used are a hard tool steel and a special type of bronze of high tensile strength. The strains of the materials loaded in tension, compression and shear have been measured over the range of stresses imposed in the pressure experiments. Within the limits of accuracy of these measurements, the stress–strain relationships were linear and conformed to a fixed ratio of the elastic moduli of 1·44 : 1. Measurements in three directions at right angles which were made by the ultrasonic-wave velocity method, using longitudinal and shear waves, indicated the materials to be satisfactorily isotropic. The accuracy of construction of the assemblies is largely limited by the accuracy with which the cylinder bore can be made and measured. Owing to recent improvements which have been made in the Metrology Division of the Laboratory in the measurement of the form and diameters of cylinder bores[3], it has proved possible to construct piston–cylinder assemblies to the requisite precision, and with the required degree of similarity.

The results of the present series of measurements show that the method is capable of a very satisfactory degree of accuracy and consistency, and permits the measurement of the variation in effective area over a wide range of pressure to within a few parts in 10^6 of the total area. In fact, over small ranges of pressure, variations in effective area of only a few parts in 10^6 of the total area can be determined. An example of the results obtained is shown in Fig. 1, where it will be seen that a particular steel piston–cylinder assembly of nominal area 0·02 sq. in. may change in effective area by an amount of the order 1 part in 2,000 per 1,000 bars of applied pressure. In this instance the change proved to be a linear function of pressure to the order $\pm$ 1 part in 10^5 of the total area.

While the present series of tests is intended to cover the range up to 3,000 atmospheres, plans are being made to extend this range to higher pressures

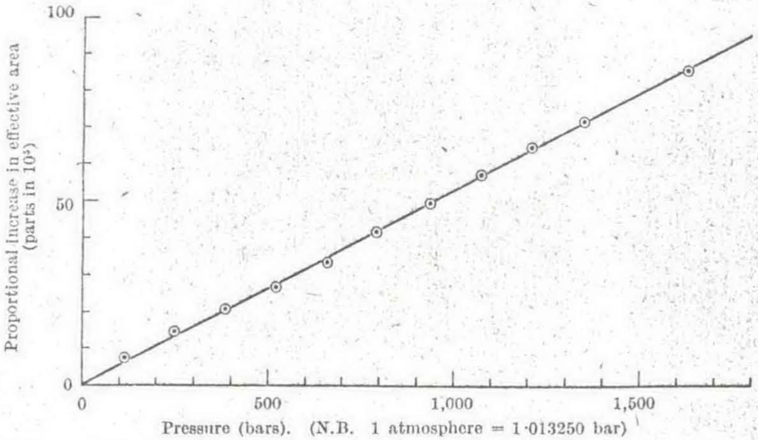

Fig. 1. Dependence of effective area on pressure for steel piston–cylinder assembly of nominal area 0·02 sq. in.

so far as may be practicable, and some further interesting possibilities of the similarity method are under investigation. Full details of this work will be published in a further paper. From the nature of the method it seems that it should be applicable over virtually any range over which pressure balances can be used, and in which two materials having the necessary properties are available. The main difficulty in the method resides in the construction of the highly accurate pistons and cylinders which are required. Once these are available, the experimental work in determining the variation of effective area is simple, quick and convenient.

We have so far dealt only with the variation in effective area with pressure, but at some point of the scale the effective area must be measured in absolute terms. This link is most easily made at a low pressure where distortion is known to be negligible. The present procedure at the National Physical Laboratory is to use two independent methods to obtain this measurement: (*a*) direct measurement by balancing at a low pressure against a mercury manometer; (*b*) by computing the effective area from the measured dimensions of the piston and cylinder.

These two methods of measurement have given agreement to within 2 parts in 10^5; but it is thought that this accuracy can be somewhat improved.

I acknowledge the helpful co-operation of the Metrology Division of the Laboratory, which undertook the measurement and construction of the special

piston–cylinder assemblies required, and of the Engineering Section of the Physics Division, which determined the elastic constants of the materials.

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