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By

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1. Introduction

Most investigations into the nature of flow in turbulent boundary layers involve a knowledge of the wall shearing stress, and in many flow problems frictional forces represent a major contribution to the drag or pressure drop. Because of this, the measurement of skin-friction is one of the basic problems of fluid mechanics and considerable effort has gone into devising suitable experimental techniques. In general, the simple methods of measurement are indirect and therefore call for calibration, and the direct method is difficult experimentally.

Calibration involves the use of the device in a situation where the skin-friction is known. The only flow configuration for which the skin-friction in turbulent flow is known with some confidence is the case of fully-developed flow in small diameter pipes of circular cross-section, where the skin-friction may be deduced from measurements of the pressure drop. However, although it is easy to calibrate a particular device by placing it in a circular pipe, doubts can arise as to whether or not the results obtained apply in other flow configurations, e.g. flows in which a boundary layer is developing or the surface curvature is different.

In principle, both of these effects could be investigated in flow down a pipe the cross-section of which is a circular annulus, for in this case the inner and outer surfaces of the annulus have different curvature and experiments could be carried out in the entry length as well as downstream where the flow is fully developed. The difficulty here, however, is that the skin-friction on the two surfaces is not known directly and although the sum of the skin-frictions is known from the pressure drop, an independent measurement is required to find their ratio. This independent measurement must be a direct one.

Direct measurements of skin-friction may be carried out by making part of the surface over which the fluid flows moveable, and then measuring the drag on this floating element of surface. This method also has its disadvantages. Apart from the experimental difficulty, which makes the method suitable only for the laboratory, the fact that the element must be free to move means that it must be surrounded by a gap. The effects of this gap are not understood and may be important, particularly in flows with pressure gradients. Since flow down an annular pipe involves an appreciable pressure gradient, then if a floating element is to be used to measure the skin-friction directly, provision must be made to investigate the effect of the gap.

The/

Replaces A.R.C. 25 661.

The authors are currently investigating the problem of the measurement of skin-friction and, following the argument above, have built an annular wind-tunnel. This paper describes the construction of the tunnel and a floating element drag balance designed to measure the skin-friction on the inner surface of the annulus. Experiments are reported in which an attempt is made to determine the effect of the gap around the element and thence to deduce the ratio of the skin-frictions on the two surfaces of the annulus.

2. Description of Apparatus

(a) The Annular Tunnel

The tunnel consists of a central core of 4 in. outside diameter aluminium tubing inside a brass tube of 6 in. inside diameter. For reasons of construction (and also to allow the tunnel to be shortened for work on growing boundary layers) each of these tubes is made in 3 ft lengths, the inner tube being joined with flush brass connectors, the outer tube by flanges soldered to the tube. The aluminium tube is supported at one end by a wall bracket upstream of the wooden bell-mouth entry, and at the other end by a core-support section immediately downstream of the working section. In between these two main supports, concentricity is maintained by adjustable spiders of fine piano wire placed at 3 ft intervals.

The settling length of the tunnel, which after the bell-mouth entry consists of six 3 ft lengths, is followed by a 12 in. long working section. This is a brass casting split along a horizontal centre-plane so that the top may be removed and the central core examined.

In the support section the central core is made of brass and is rigidly supported by four equally-spaced vanes soldered to the inner and outer tubes. Two of the vanes are hollow and allow pressure tubes and electrical leads to be brought out without disturbing the flow. The support section is mounted on a trolley running on rails so that the central core of the working section may be run back for inspection; when this is done the main length of central core upstream of the working section is supported temporarily by a wooden block.

Downstream of the support section the tunnel is joined to a centrifugal fan by a diffuser in which the inner core is tapered to a point and the outer tube expanded to match the fan entry. The fan, which is driven by an 8 H.P. induction motor, gives a maximum speed in the working section of 180 f.p.s.; speeds below this are obtained by throttling the fan entry.

Great care was taken in the assembly of the tunnel to avoid ridges at the joints of both inner and outer tubes and to position the core centrally.

(b) The Drag Balance

The balance is designed to measure the skin-friction on the inner, convex surface of the annulus. A null method is used in which the spring-mounted element, having been deflected by the drag force, is pushed back to its initial position. In this way the force is measured with the fore and aft gaps equal.

A detailed drawing of the balance is given in Fig.1. Here it will be seen that the main body of the balance is constructed in two pieces, one sliding inside the other and fixed relatively by the body adjusting plate at the forward end. Movement of the bolts in this plate alters the relative position of the two halves of the body and so changes the gap width. The floating element is fitted with three long bolts which pass through the main body and protrude into the cavities at each end. Here the bolts are secured to spiders which also clamp the suspension springs. The upper ends of the suspension springs are secured to the main body by a fixed clamp at the rear end and by a moveable clamp at the forward end, the moveable clamp being necessary to allow the element to be centralised in the gap in the main body.

Two support rods extend from a plate at the rear of the balance (not shown in Fig.1) and are tensioned against a plate covering the rear of the tunnel model support section. These rods carry the weight of the balance and also help to support the upstream end of the core of the tunnel. A sealing disc is provided at the forward end of the balance and this, together with the rear plate prevents internal flow in the main body. The rear cavity of the main body accommodates the three coils which are used as a force-displacement indicator.

(c) <u>The Force-Displacement Indicator</u>

The design and development of this device is described fully elsewhere [1]. It consists of three coils, two of which are attached to the main body the third to the floating element. In principle it is a combination of a Kelvin Current Balance and a differential transformer. An A.C. voltage supplied to the outer coils induces a voltage in the inner coil which depends on its position relative to the other two. One of the outer coils may be moved and by varying its position and choosing a suitable supply frequency the sensitivity can be adjusted such that the position of the centre coil (and therefore the floating element) may be determined to within ± 0.0001 in. In this way movements of the floating element under the action of drag forces are easily detected. To measure the drag force a constant D.C. current is supplied to the outer coils and a variable current to the inner is changed until the electromagnetic force developed is sufficient to push the floating element back to its original position.

The circuit diagram for the device is given in Fig. 2.

3. <u>Experimental Method</u>

The balance was set up by first assembling it so that the length of the main body was as short as possible and the screws securing the upper ends of the supporting springs were left loose. It was then placed across two vee blocks which supported both the main body and the floating element. In this way the load was held flush with the main body. The screws holding the springs were then tightened and the vee blocks separated so that the floating element was free to swing. By moving the floating element up to each half of the main body concentricity could now be checked by feeling all round for ridges and any corrections necessary could be made by slackening and retightening the upper screws on the spring supports, the holes in which had been made large enough to allow this. By this method ridges of at least 0.001 in. could be detected and corrected. The accuracy of this method of setting up was checked by dial gauge measurements and found to be quite satisfactory.

When/

When the adjustment of the floating element was completed, the rear coil of the force-displacement device was adjusted to give maximum displacement sensitivity and the balance then fitted into the support section of the tunnel.

The gap width and symmetry of the floating element was next adjusted by removing the forward sealing disc and using the appropriate screws. In all runs the gaps forward and aft of the floating element were made equal.

The balance being set up, the support section was closed up to the working section and the tunnel assembled except for the diffuser. This was left off to give access to a length of cotton connected to the rear spider of the element and threaded through a hole in the rear sealing plate ready to be used for calibration of the balance. To calibrate the balance, the cotton was passed over a small pulley and a light scale-pan attached to its end. Weights were then added to the scale pan and the current required in the centre coil to return the element to its equilibrium position determined. The calibration was carried out for currents of 0.2, 0.4, 0.6 amps in the outer coils; as explained in Reference 1, by using different values of current in the outer coils, the weighing sensitivity of the balance may be changed. Care was taken to check the null reading of the displacement before each weighing since this varied slowly due to heating effects in the coils.

After the calibration has been completed, the remainder of the tunnel was assembled and the experiment started. In each run the skin-friction was weighed for various values of velocity, the reference measurement being the pressure drop in the settling length over a distance of 72.5 in. just upstream from the working section.

4. Results of Experiments

As mentioned in the previous section, the balance was calibrated before each run. From this assembly of calibrations the force-sensitivity of the balance was found to be

$$F = 0.665\ Ii - 0.162 \qquad \dots (4.1)$$

Where F is in grams and the primary and secondary D.C. currents I and i are in amperes.

The results of the main experiments are given in Figs. 3(a) to (k), in each of which the product of the balance currents is plotted against the reference pressure drop. These graphs, taken together with equation (4.1) show that the force measured by the balance was a linear function of the pressure drop.

5. Interpretation of Results

It is to be expected that the reading of the balance will depend in some way upon the width of the gaps at the two ends of the floating element. Examination of the data has so far revealed no way in which this dependence can be represented simply. As a result a purely empirical approach has been adopted.

Presumably/

Presumably the balance would give a correct reading of the skin-friction if the width of the gap were zero, for then there would be no interference with the flow and no leakage of air through the space under the floating element. Since the area of flow underneath the floating element was deliberately made large, for very small gap widths the pressure in this space will be uniform and therefore errors due to pressure forces negligible. Further it seems reasonable to assume that modification of the flow over the outer surface of the floating element is slight if the gap width is small. Thus it appears likely that for very small gap widths the balance gives results which are nearly correct and that the true value of skin-friction may be found by extrapolating the results of Fig. 3 to zero gap width.

To do this straight lines were fitted to each of the sets of data in Fig. 3 by the least squares method. The slopes and intercepts of these best straight lines are shown as functions of gap width in Fig. 4. From this diagram it seems clear that, although the dependence on gap width is complicated, the value of the intercept for zero gap width is almost certainly zero. Turning next to the data for the slopes of the lines, a linear regression analysis was carried out. The two lines are shown in Fig. 4 and it is found that the probable value of the slope of a graph similar to those of Fig. 3 for zero gap width will lie between 8.508 and 8.790.

Thus, after referring to equation (4.1) it is found that with no gap the force measured by the balance in grams should be directly proportional to the reference pressure drop in inches of water, the constant of proportionality lying between 5.658 and 5.845.

Now if the pressure drop in the tunnel over a length L is denoted by Δp, a diameter of the tunnel by d, the wall shearing stress by τ and suffices i and o are used to signify inner and outer surfaces, a balance of forces gives

$$\frac{\pi}{4}\left(d_o^2 - d_i^2\right) . \ \Delta p = \pi L\left(\tau_i . d_i + \tau_o d_o\right)$$

After rearranging this expression and inserting the appropriate figures, the force on the element in grams may be expressed in terms of the reference pressure drop in inches of water. The result is

$$F_i = 14.177 \left\{1 + \frac{\tau_o}{\tau_i} . \frac{d_o}{d_i}\right\}^{-1} . \ \Delta p$$

and on using the results of Fig. 4 it is easily shown that the ratio of the skin-frictions on the inner and outer surfaces of the annulus probably lies in the range

$$1.00 < \frac{\tau_i}{\tau_o} < 1.06$$

6. Conclusions

The investigation reported above had two main objects. The first was to examine the effect of gap width and pressure gradient on the readings obtained from a floating element drag balance. The results show that provided the gap width is kept small, (in this case less than 0.003" for an element length of 4.000"), neither of these effects is serious and the readings of the balance may be accepted with some confidence.

The second object was to determine the ratio of the skin-frictions on the two surfaces of an annular pipe when the flow in the pipe is turbulent. Here the result obtained was that the ratio is

$$\frac{\tau_1}{\tau_0} = 1.03 \pm 0.03$$

It might be thought that this ratio would be the same for turbulent flow as for laminar flow, and indeed this has been suggested by Rothfus et. al[2]. However, for an annulus with the diameter ratio used in the present work, the ratio of the skin-frictions in laminar flow is 1.147 and this is very different from the value found. The authors hope soon to present further measurements to confirm their view that the ratio in turbulent flow is different from that in laminar flow.

7. Acknowledgements

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No.	Author(s)	Title, etc.
1	R. E. Franklin	A force-displacement indicator for a drag balance. O.U.E.L. Report No. 137. A.R.C. C.P. 546. July, 1960.
2	R. R. Rothfus, C. C. Monrad and V. E. Senecal	Velocity distribution and fluid friction in smooth concentric annuli. Ind. Engg. Chem. 42. 1950.

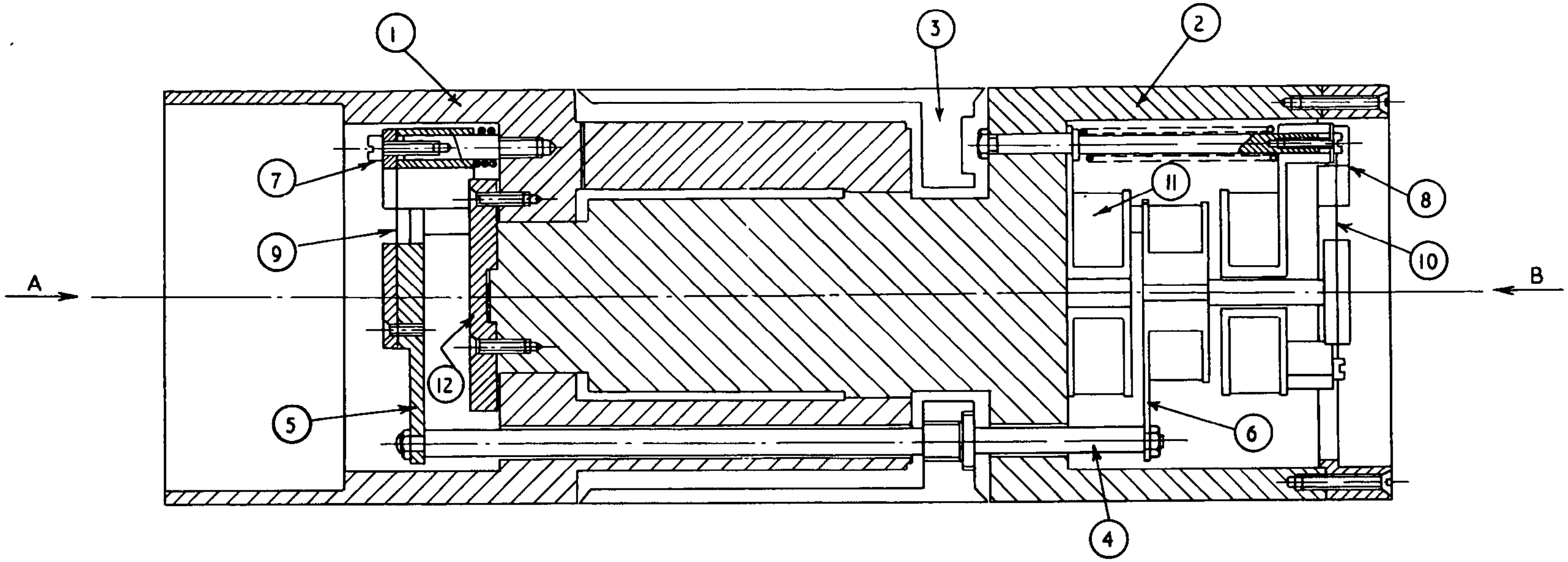
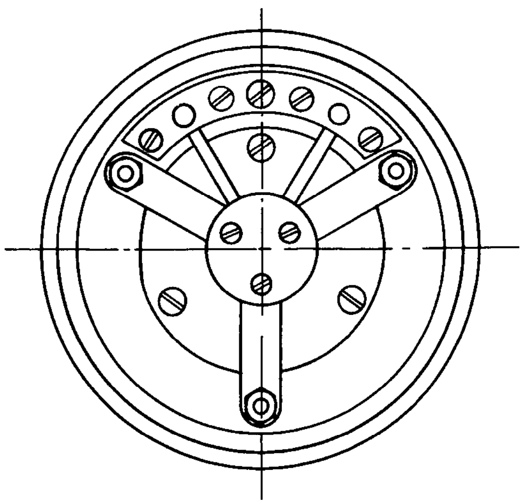


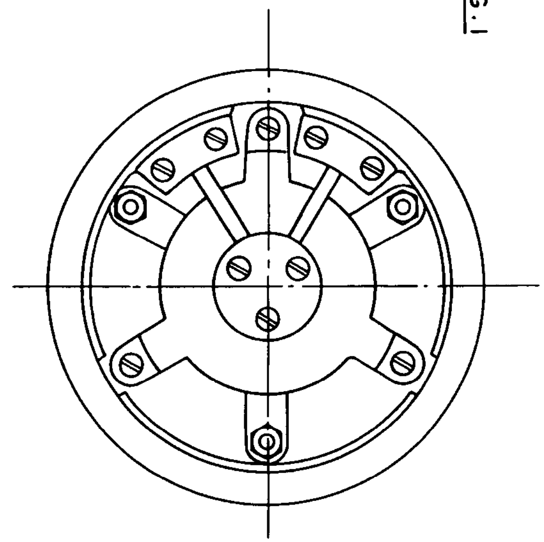
FIG. 1



View A

Key

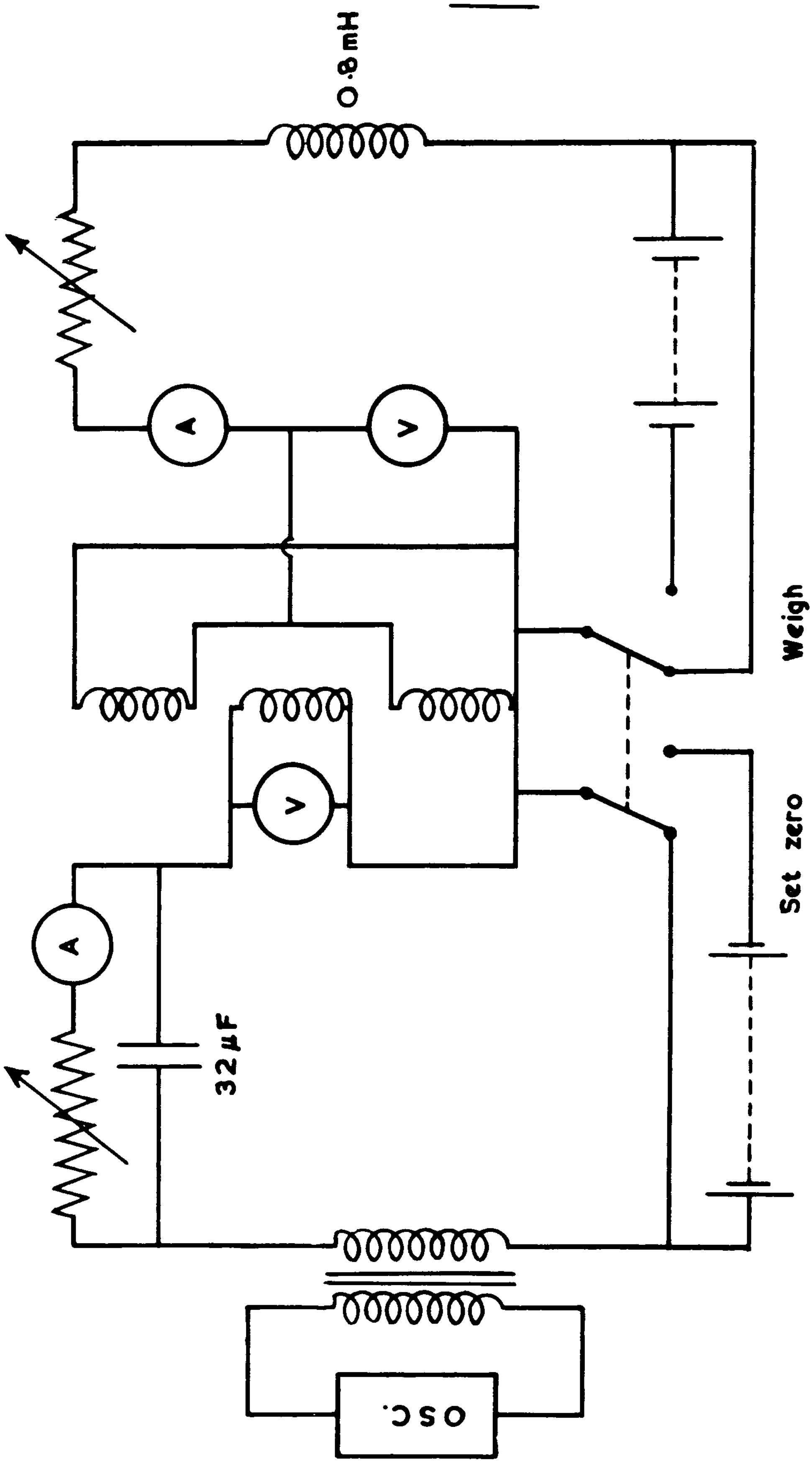
1 Main body: forward half
2 Main body: after half
3 Floating element
4 Floating element: long bolts
5 Forward suspension spider
6 After suspension spider and moving coil
7 Floating element adjusting bolt
8 Third coil adjustment
9, 10 } Suspension shims
11 Second (fixed) coil
12 Body adjusting plate and bolts



View B

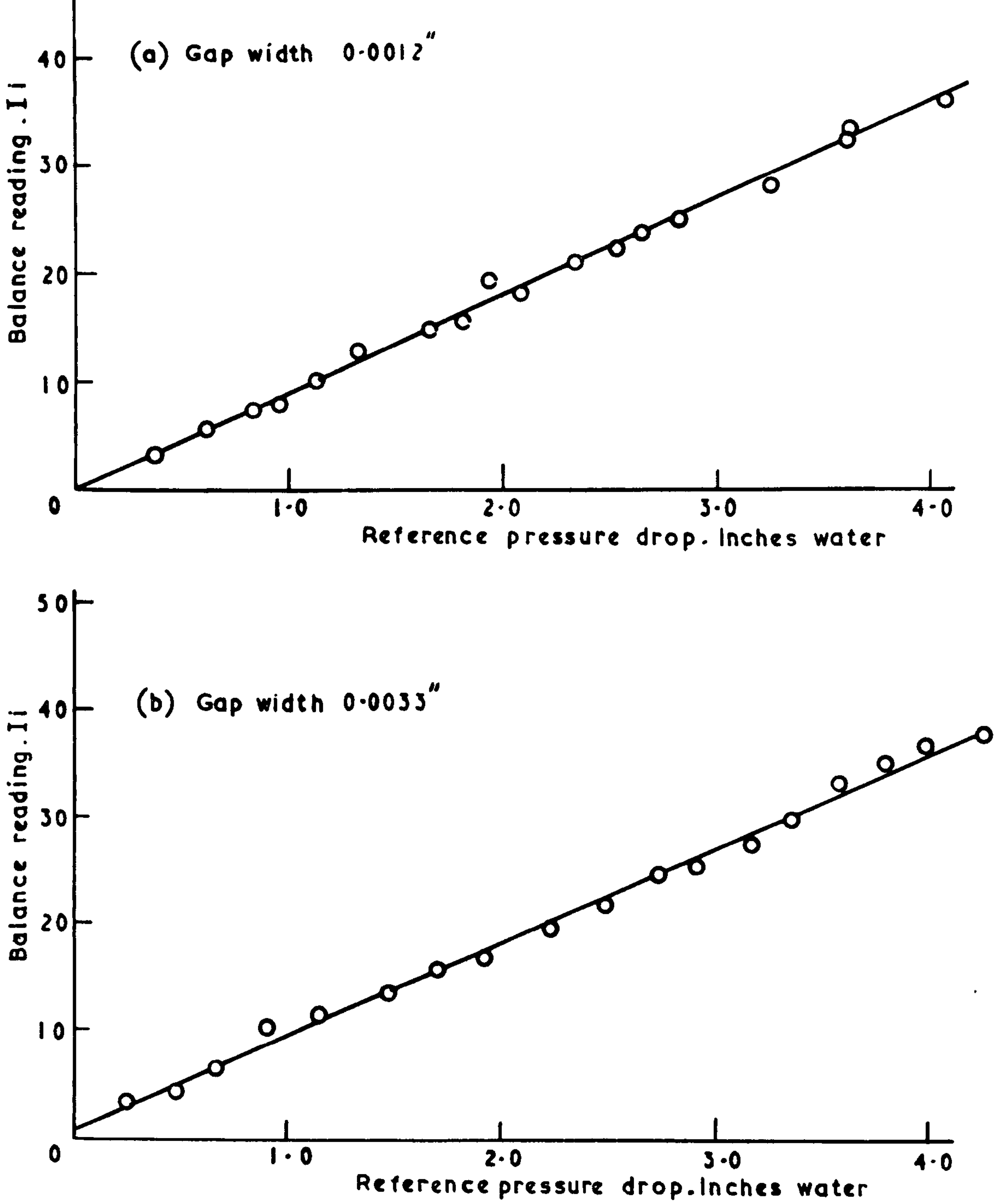
Skin-friction drag balance. General arrangement

FIG. 2



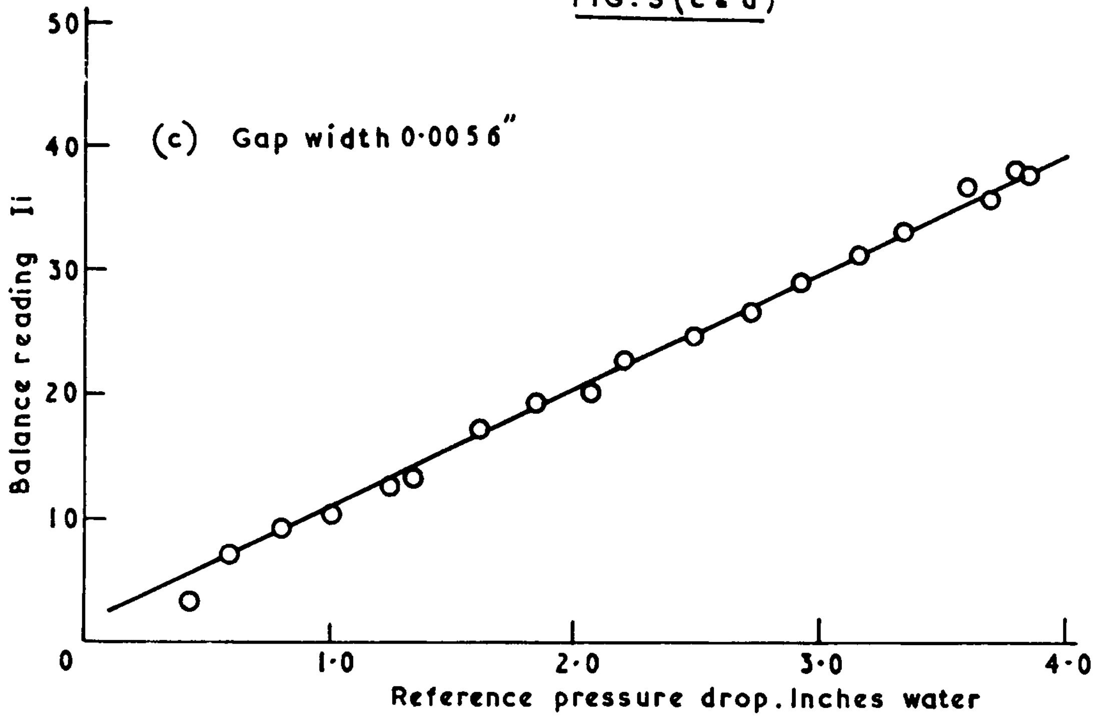
Circuit diagram.

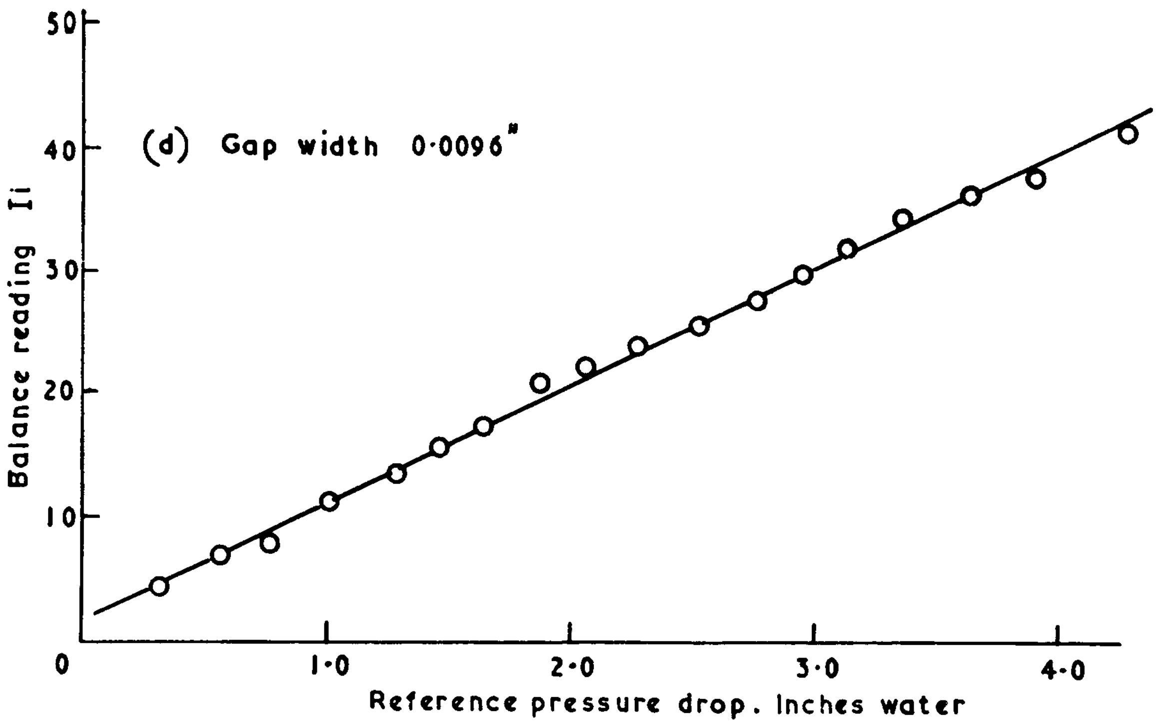
FIG. 3(a & b)



Data from balance

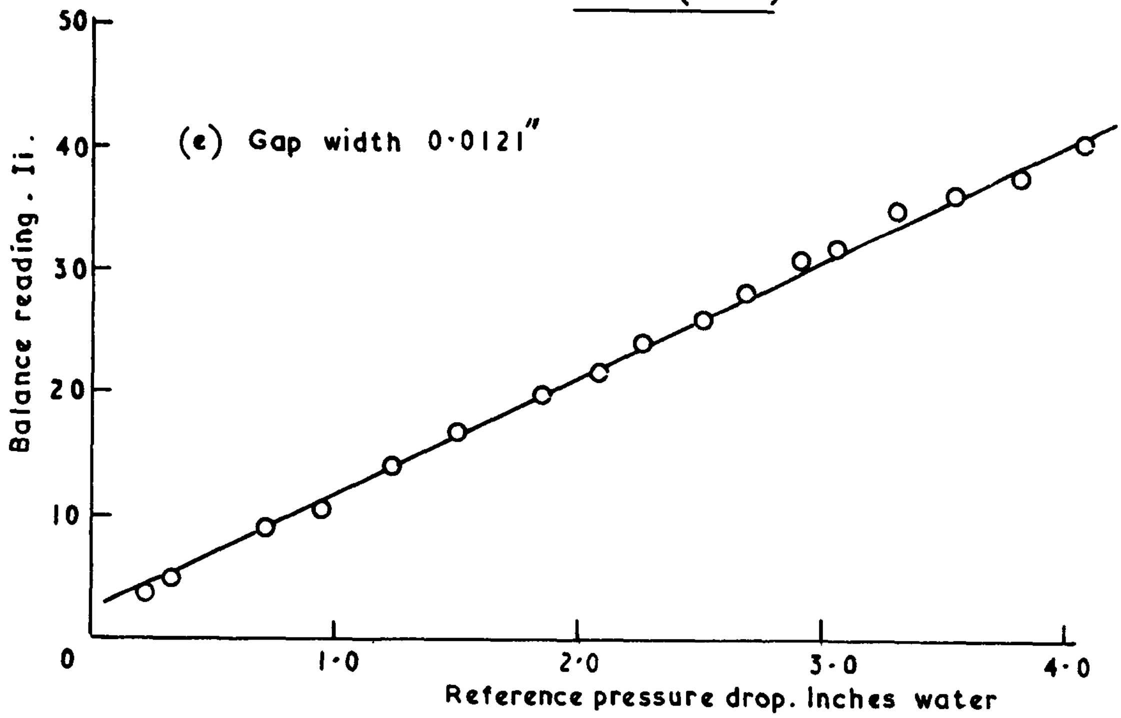
FIG. 3 (c & d)

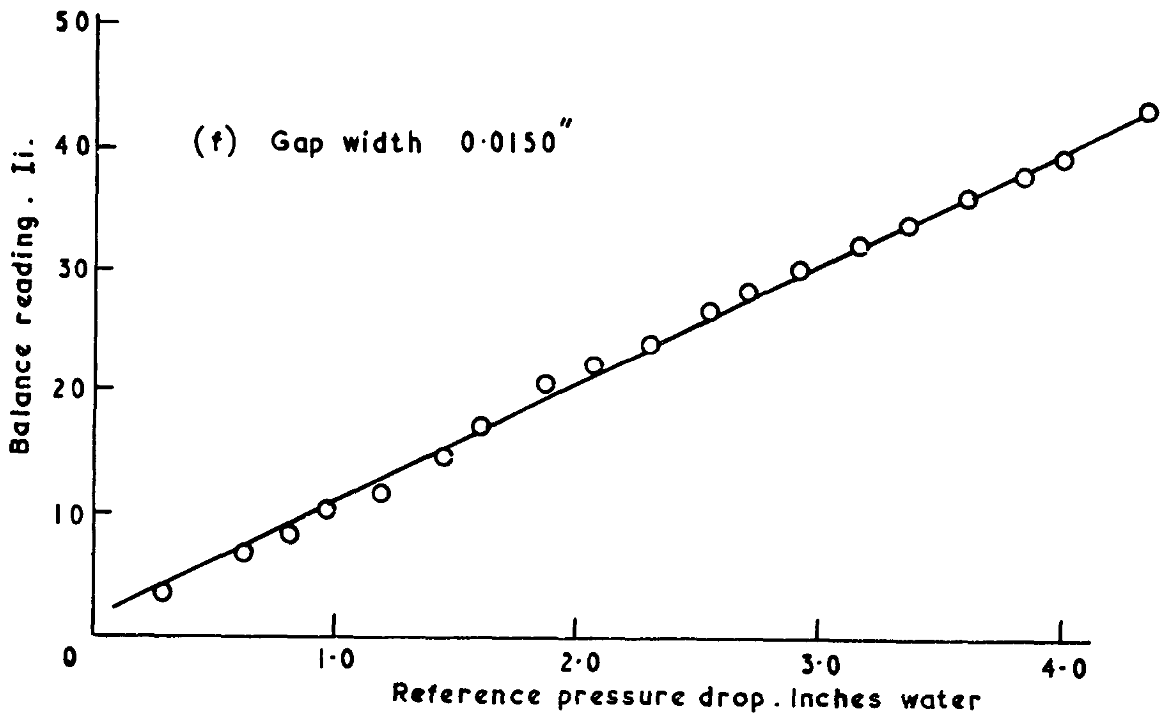




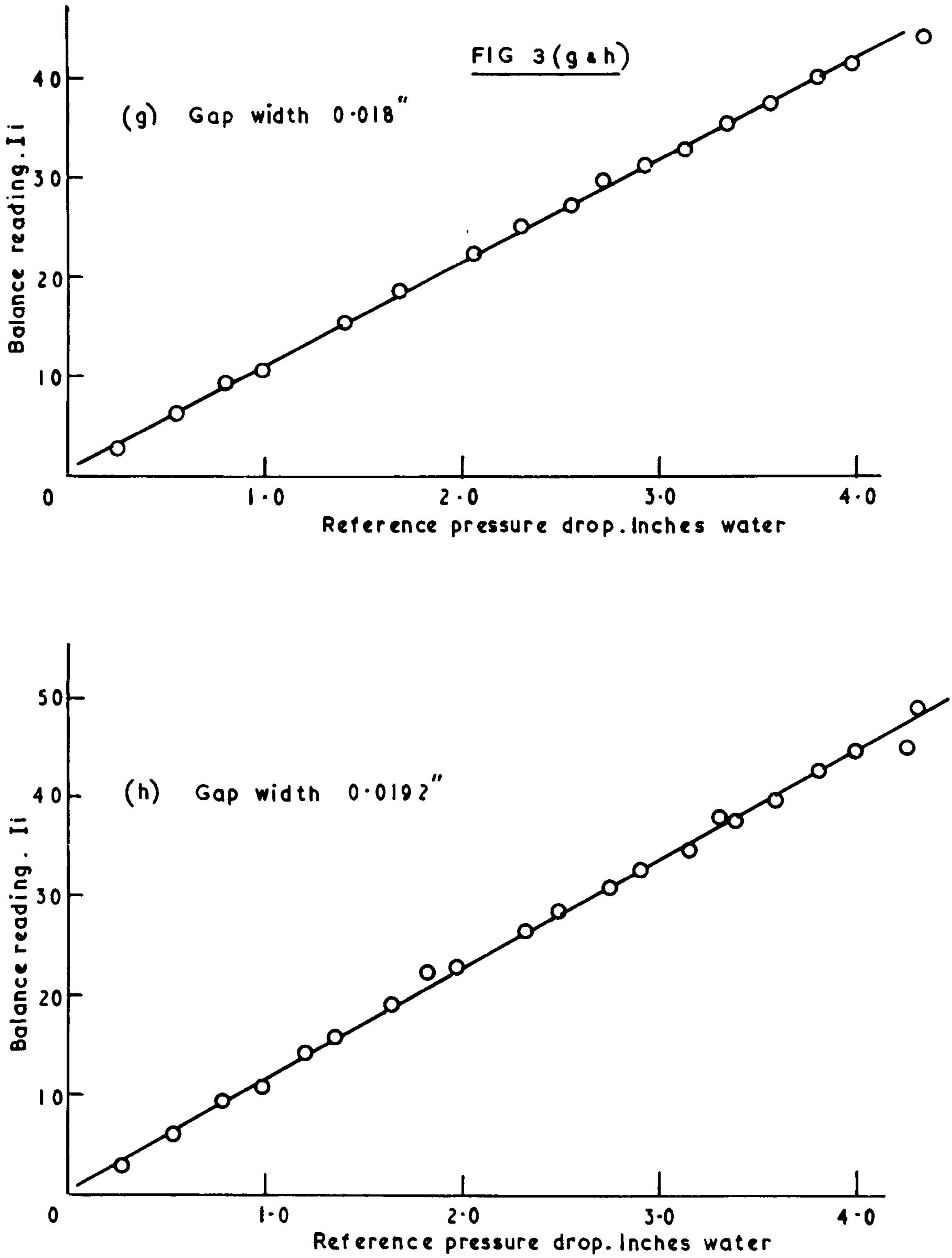
Data from balance

FIG. 3 (e & f)



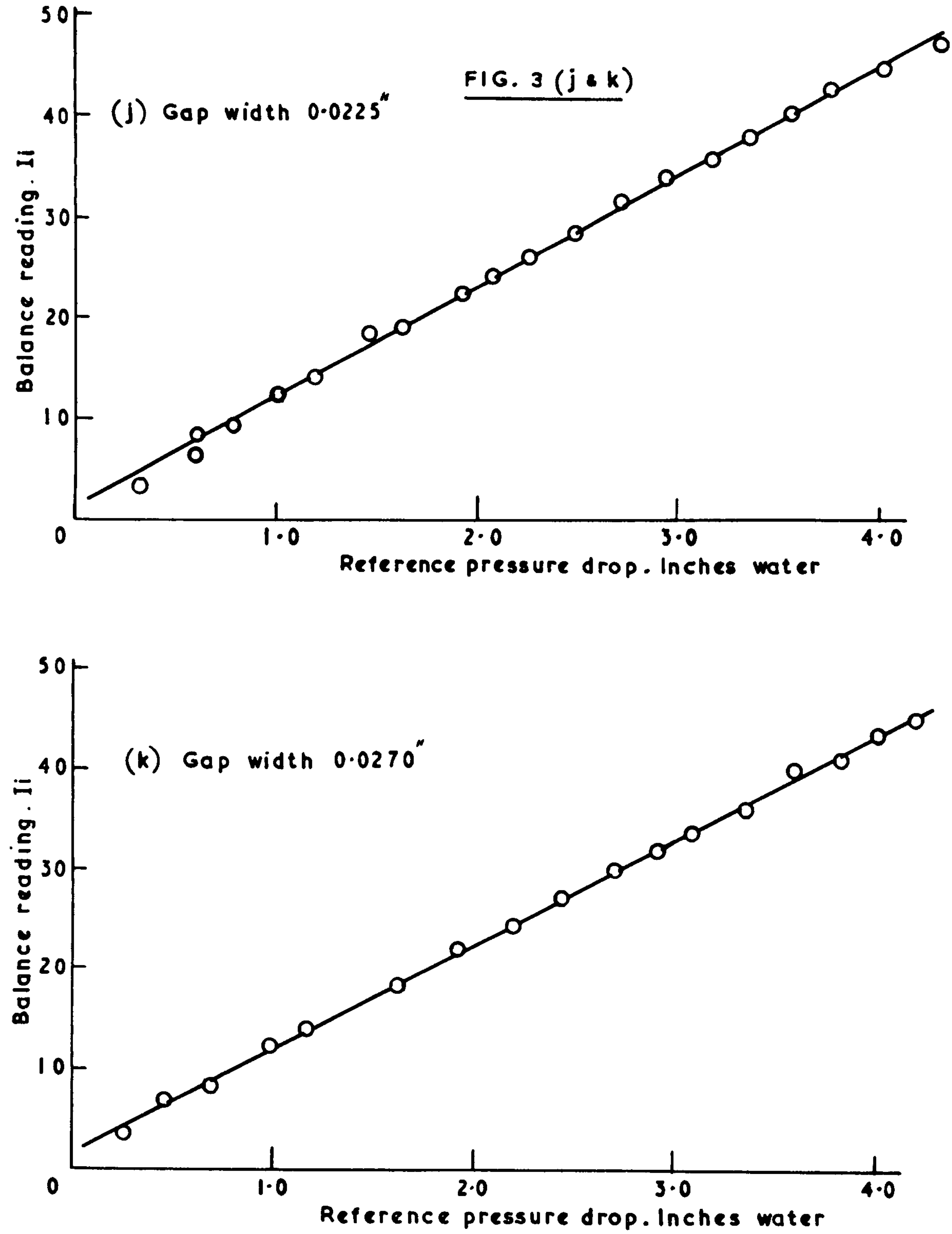


Data from balance



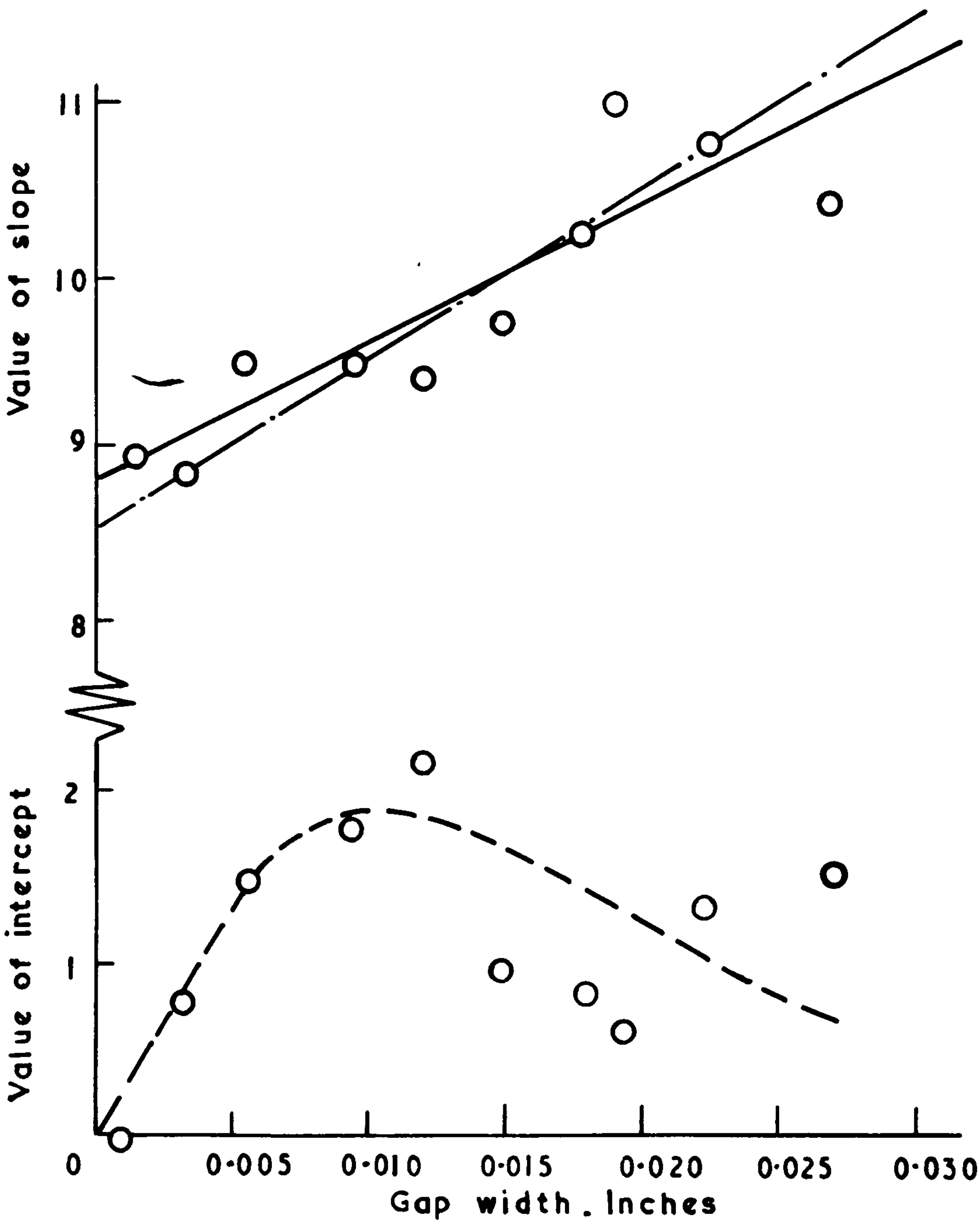
Data from balance

FIG. 3 (j & k)



Data from balance

FIG. 4



Extrapolation of data to zero gap width

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