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# Absolute measurements of static-hole error using flush transducers

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Experiments are reported in which the error of a sharp-edged, circular static pressure hole normal to the boundary of a moving fluid is deduced from measurements made with pressure transducers, the diaphragms of which were set flush with the boundary surface. An error curve is presented which covers the range of hole Reynolds number up to a value of 2000.

## 1. Introduction

It has been known for over a century that the most usual method of measuring static pressure, namely, by connecting some manometric system to a hole drilled in and normal to a surface parallel to the local streamlines, is inaccurate. Large errors can be generated if the hole has burrs, rounded edges or other imperfections, but even when the hole is near-perfect a residual error remains. This residual error, which is of considerable importance in many situations (for example, in flow measurement and skin-friction measurements), is due simply to the local change in boundary conditions and the consequent disturbance of the boundary layer.

The problem was known to Darcy, who discussed it in 1857, and probably the earliest measurements are those reported by Mills in 1879. Since then, a great deal of work has been done. Early workers such as Buchner (1904), Schuster (1910) and Furhmann (1912) (who investigated the problem as part of larger projects), Allen & Hooper (1932) and Myadzu (1936) (who investigated the problem in its own right), correlated their data with mean flow properties. More recently, as the problem has become better understood, experimenters have correlated their data using the more appropriate wall conditions. In the subsonic range one notes the work of Ray (1956), Rayle (1959), Shaw (1960), Lester (1960), Bilger (1960), Krause (1960), Stratford & Ascough (1962), Livesey, Jackson & Southern (1962), and Emmett & Wallace (1964), and in the supersonic range that of Rainbird (1967) and Morrison, Sheppard & Williams (1967).

Despite this volume of work the problem is still of interest because of a basic difficulty in the experimental approach used to date. In practically all experiments an attempt has been made to determine the error by measuring the static pressure with holes of different sizes and extrapolating a graph of relative error against hole diameter to zero hole diameter. After making the assumption that the error is zero for a hole of zero size, the absolute errors of all holes may then be deduced. This is a difficult and, as close examination of the data reveals, a questionable technique. A few workers have tried to avoid it but in the event have either ended up with a disguised version of the same technique (Bilger

1960), or have merely adopted another, equally questionable one. (Livesey, Jackson & Southern 1962, for example, shift their experimental data to match a theoretically proposed curve which involves empirical constants deduced from the flow-visualization results of Ray 1956.) The result of this is a feeling of uncertainty about any given set of data, and this is reinforced by some serious discrepancies between data obtained by different workers.

Theoretical studies, notably the numerical solutions obtained by Thom & Apelt (1957), Lester (1960), and Lewis (1964), have produced interesting and instructive results but, being restricted to two dimensions and very low Reynolds numbers, do not bear appreciably on the experimental problem.

Several years ago, Thwaites (1960) suggested that an attempt should be made to determine the static hole error by comparing the readings of static holes with measurements taken with a diaphragm set flush in the surface. The purpose of the present paper is to describe experiments based on this idea and to report fresh and, it is hoped, definitive data.

## 2. Basic procedure and apparatus

The experiments were carried out in the open-circuit, subsonic windtunnel sketched diagrammatically in figure 1. This tunnel, which was built for the present research, has an inlet contraction of area ratio 16:1 leading to an 8 in. × 6 in. working section, 4 ft. long, in which speeds in the range 50–500 ft./sec may be obtained by running various combinations of four axial flow fans situated downstream of a diffuser, intermediate adjustments being made with an exit damper.

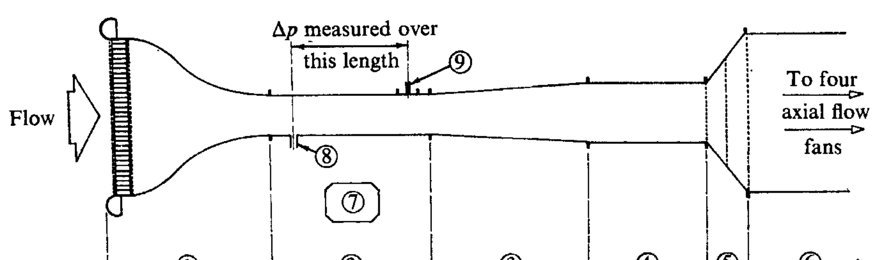


FIGURE 1. Schematic diagram of apparatus: (1) Contraction (area ratio 16:1), with screens and honeycomb. (2) Working section. (3) First diffuser (area ratio 3.85:1). (4) Settling length. (5) Second diffuser with screens. (6) Plenum chamber. (7) Cross-section of working section: size 8 in. by 6 in. (8) Reference static hole. (9) Test plate with test static hole or flush transducer.

The basic measurement in the experiments was of $\Delta p$, the pressure drop down the working section between an upstream position, at which a reference static hole is fitted in the bottom wall of the tunnel, and a downstream, test position, at which provision is made for the fitting of test plates of standard size in the upper wall of the tunnel.

In commissioning the tunnel, considerable attention was paid to obtaining a steady flow, for it was known that the errors to be detected from the measurements of $\Delta p$ were not large and, further, that earlier workers had experienced trouble in this respect. For this reason, after preliminary runs had shown that a separation of the flow in the original diffuser was causing unsteadiness in the flow in the working section, a second two-stage diffuser was designed and fitted. This, together with other adjustments, resulted in an extremely steady flow with low turbulence; the inlet contraction pressure drop varies less than $\pm 0{\cdot}5\,\%$ and the mainstream longitudinal velocity fluctuations are better than $0{\cdot}25\,\%$ over the whole speed range of the tunnel. Subsequent calibration runs showed that the working section boundary layer is fully turbulent at the test position, its thickness varying between 0·8 in. and 0·5 in., with corresponding displacement thicknesses of 0·13 in. and 0·08 in.

Two sets of experiments were carried out. In the first of these, nine test plates were used, each drilled with a static hole, and the pressure drop between the reference and test static holes measured with a Betz micromanometer over the complete tunnel speed range. By cross-plotting these results and choosing a particular test hole as datum, a curve of relative error could be plotted against diameter ratio for any tunnel Reynolds number.

In the second set of experiments, two test plates, each fitted with a flush diaphragm transducer, were used and, with the reference static hole connected to the air-space behind the diaphragm, the pressure drop was measured electronically using a point-by-point calibration against the Betz micromanometer. From these results, points for zero diameter ratio could be added to the graphs of relative error against diameter ratio.

Other data recorded during the experiments were the local value of the wall shearing stress at the test position, and the room temperature and barometric pressure which, together with the inlet contraction pressure drop, were necessary for the evaluation of the wall values of the air density and kinematic viscosity at the test position.

All data reduction was carried out on a digital computer.

## 3. Details of procedures and apparatus

### 3.1. *The test static holes*

Great care was taken in the manufacture of the nine test plates in which the static holes were drilled. In the general design, geometric similarity was maintained from the hole entrance to the manometer connexion by making the length of the static hole and the length and diameter of the plastic tubing used to connect the hole to the manometer all proportional to the hole diameter. These dimensions are tabulated in table 1 (cf. figure 2). Further, each plate was positively located in the tunnel wall so that all holes were tested in exactly the same position.

Particular attention was paid to the production of good static holes, for it was known from the work of Shaw (1960) and others that hole imperfections could change the error by as much as five times. Various methods were tried. It was found quickly that burrs such as that illustrated in figure 3 (*a*) were turned out even with the most careful drilling. If the plate surface was then lapped with diamond paste, the hole edge became uneven and slightly rounded, as shown in figure 3 (*b*), and polishing the surface further rounded the edges, as is seen in figure 3 (*c*). Eventually a technique was developed which proved highly successful.

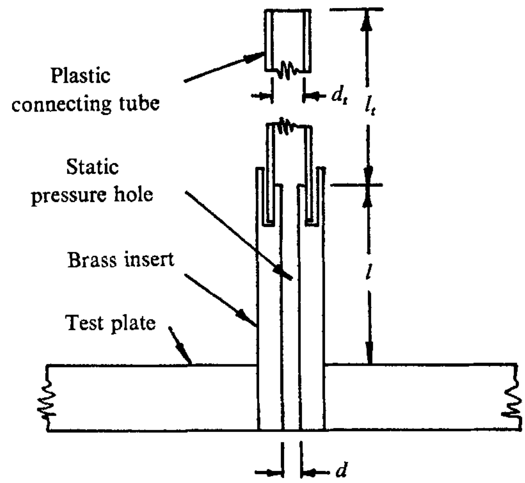


FIGURE 2 (cf. table 1).

| Plate | $d$ (in.) | $l$ (in.) | $d_t$ (in.) | $l_t$ (ft.) |
|---|---|---|---|---|
| 1 | 0·0197 | 0·296 | 0·045 | 2·5 |
| 2 | 0·0354 | 0·531 | 0·079 | 4·5 |
| 3 | 0·0469 | 0·703 | 0·106 | 5·9 |
| 4 | 0·0625 | 0·938 | 0·138 | 7·9 |
| 5 | 0·0709 | 1·062 | 0·157 | 9·0 |
| 6 | 0·0938 | 1·407 | 0·208 | 11·9 |
| 7 | 0·1063 | 1·595 | 0·240 | 13·5 |
| 8 | 0·1606 | 2·410 | 0·359 | 20·4 |
| 9 | 0·2532 | 3·800 | 0·566 | 32·2 |

TABLE 1. Dimensions of test holes (cf. figure 2).

The test-holes were carefully drilled in brass cylinders which were then pressed into holes in the test plates. Tapered brass plugs were now inserted into the holes from the working side until they fitted tightly. Next, the working surfaces of the plates were ground to a fine finish and finally the tapered plugs were pulled through to the back of the plate, thus lightly reaming the holes and leaving them sharp-edged and burr-free. A surface profile, obtained with a Talysurf instrument, and a magnified photograph of a typical hole are given in figure 3 (*d*) and figure 4 (plate 1). All the holes were of this quality except the smallest, which was slightly out of round. This was taken as evidence that the production of smaller holes was probably impracticable.

### 3.2. *The flush transducers*

The transducers required for this experiment had to satisfy several conditions, the most important of which were a high sensitivity combined with a low temperature coefficient, a construction such that the diaphragm could be mounted flush with the test plate surface, a small diaphragm deflexion and the availability of more than one diaphragm size, the last being imposed by the necessity of eliminating possible size effects arising from the fact that the transducer registers a space-average of the pressure.

A search through the literature led to the conclusion that the most profitable approach would be to design mountings for two of the range of four condenser microphone cartridges manufactured by Bruel and Kjaer. This was successfully done, the only real difficulty being the elimination of the groove around the diaphragm where it is stretched over its mounting ring, and this was overcome by covering the face of the assembly with a thin sheet of smooth paper in which a hole had been punched to leave only the diaphragm exposed. The final arrangement is shown in figure 5 and figure 6 (plate 2).

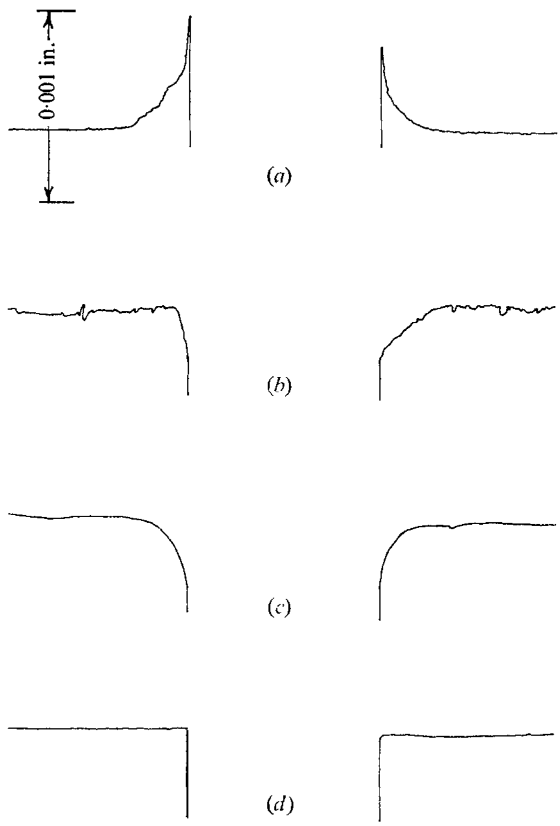


FIGURE 3. Talysurf profiles of a hole of diameter 0·0354 in.: (*a*) drilled, (*b*) lapped, (*c*) polished, (*d*) as produced by technique described in text.

The microphone cartridges were made sensitive to static (rather than fluctuating) pressures by using them in conjunction with an F.M. system. In this system, the cartridge capacitance forms part of the circuit of an oscillator. A change in cartridge capacitance caused by an applied pressure thus changes the oscillator frequency and this is translated into a d.c. output by a pre-amplifier containing a discriminator circuit. The d.c. output is read on a high-impedance voltmeter.

From the outset difficulties were experienced with zero drift. These were greatly reduced by a careful stabilization of the power supply but, even so, the remaining drift was felt to be unacceptable. The problem was eliminated by the construction of dummy transducers which could be substituted for the active transducer by operating a simple two-way switch, thus making it possible at all times to check the zero.

In the initial stages of the experiment, each transducer was calibrated by applying pressure differences across the diaphragm, measuring these with a Betz micromanometer and plotting a graph of pressure difference against transducer output. However, during protracted runs it was found that the room temperature rose sufficiently to cause an appreciable change in the transducer calibration.

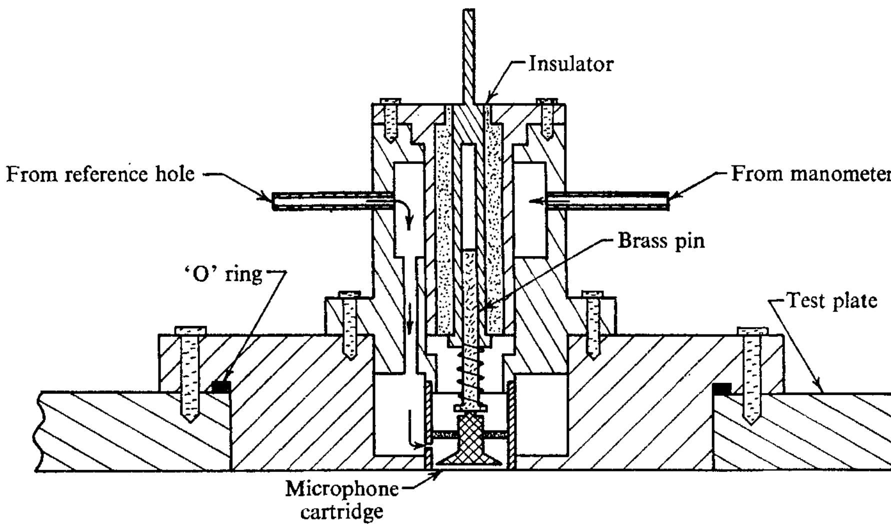


Figure 5. Sketch of flush transducer mounting.

For this reason (and for all the data reported here), a more accurate method of point-by-point calibration was adopted. In this method, the transducer is set up in the tunnel and the output noted (together with the zero check) for a given running condition. The tunnel is then shut down and a two-way valve moved so that a pressure may be applied to the back of the diaphragm to give the same voltage, again with a check on the zero. The applied pressure is then measured with the Betz micromanometer, the valve re-set and the next tunnel condition set up. This procedure was systematically applied over the whole tunnel range for each transducer in turn. A schematic diagram of the electrical and manometric systems is given in figure 7.

### 3.3 *Skin-friction measurements*

The modern practice is to non-dimensionalize the static-hole error with the local value of the wall shearing stress. In the present experiments it was proposed to deduce the wall shearing stress from the dynamic readings of two surface Pitots, one on each side of the test static hole or transducer.

When this was tried it was discovered that small changes in the alignment of the surface Pitots from one run to another could appreciably effect the reading of the tunnel pressure drop. To overcome this a standard test-plate was fitted with a surface Pitot and a careful calibration made of the reading of this surface Pitot with that of another fixed in the opposite wall a little distance upstream. In subsequent runs the wall shearing stress at the test position was then deduced from the reading of the fixed surface Pitot after a correction taken from the calibration curve (which was checked several times) had been made. The surface Pitots had an outside diameter of 0·08 in., and so lay well within the low of the wall region of the boundary layer for the complete range of tunnel speeds.

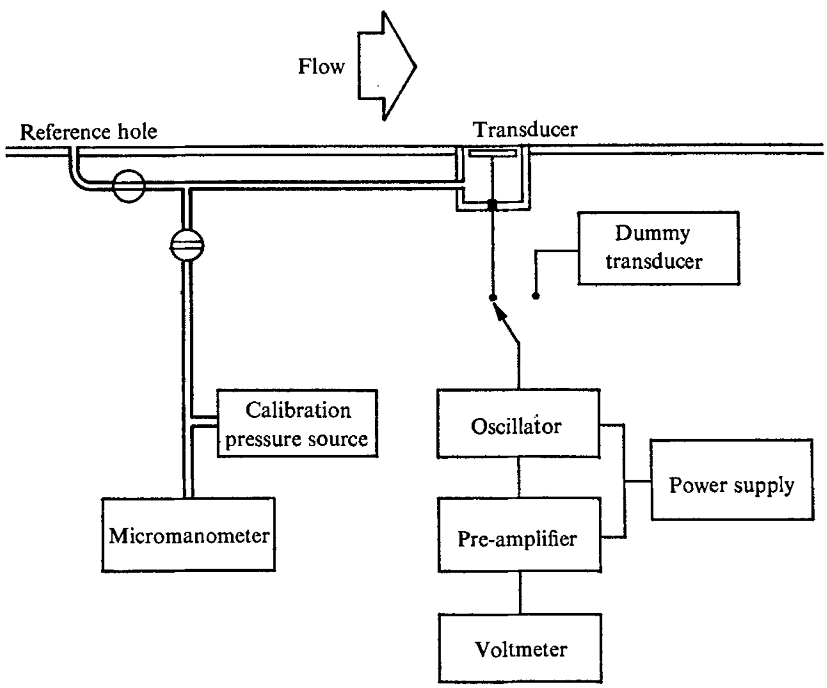


FIGURE 7. Electrical and manometric systems for flush transducers.

The expression used to deduce the shear stress from the readings of the surface Pitot was that due to Smith & Walker (1958), namely,

$$\log_{10}\left\{\frac{\tau d^2}{4\rho\nu^2}\right\} = -1{\cdot}366 + 0{\cdot}877\log_{10}\left\{\frac{(p-p_0)\,d^2}{4\rho\nu^2}\right\}$$

in which $\tau$ is the wall shearing stress, $\rho$ and $\nu$ the fluid density and kinematic viscosity evaluated at the wall conditions, $d$ the Pitot diameter and $(p - p_0)$ the dynamic pressure.

Because of the importance of this measurement, the results were checked against readings of wall shearing stress made by Osborn with two floating element skin-friction balances (Franklin & Osborn 1969), the calibration of which may be established exactly by a tilting technique. A comparison of the measurements made with these instruments and the results deduced from the surface Pitots is shown in figure 8, where the agreement is seen to be very good. On this basis, the measurements of skin-friction are felt to be of the same accuracy as those of the static-hole error.

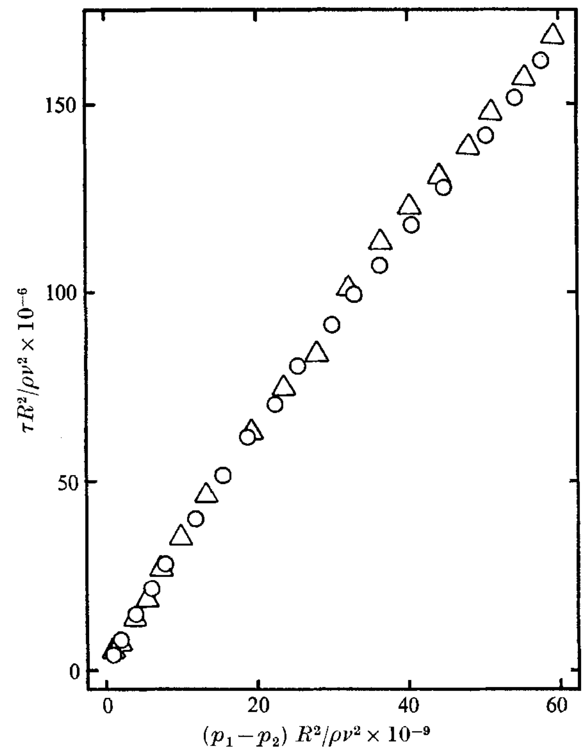


FIGURE 8. Comparison of skin friction data deduced from surface Pitot readings with measurements made with floating element balances ($R$ is hydraulic radius of tunnel and $(p_1 - p_2)$ the contraction pressure drop).

## 4. Analysis and discussion of results

### 4.1. *Analysis*

The current approach to the static-hole error problem is based on recognition of the fact that the error arises from a local disturbance of the boundary layer. Taken with the well-known fact that near to the wall there is a local region of dynamical similarity in which conditions are determined solely by $\tau$, the wall shearing stress, $\rho$ and $\nu$ the fluid density and kinematic viscosity evaluated at the wall conditions and a characteristic length, this leads one to write an equation for the error of the form,

$$e = f_1(\tau, \rho, \nu, d) \tag{4.1}$$

in which the characteristic length $d$ is taken to be the diameter of the hole. It is conventional to re-write this in the non-dimensional form

$$\frac{e}{\tau} = f_1\left\{\frac{u_\tau d}{\nu}\right\} \tag{4.2}$$

where $u_\tau = (\tau/\rho)^{\frac{1}{2}}$, the so-called friction velocity.

If the static pressure is $p$, then one can write

$$p + e = f_2(\tau, \rho, \nu, d), \tag{4.3}$$

and so, in the present experiments the pressure drop, which is given by

$$\Delta p = (p_r + e_r) - (p_t + e_t),$$

where the suffices $r$ and $t$ identify the reference and test positions, may be written

$$\Delta p = f_2(\tau_r, \rho_r, \nu_r, d_r) - f_2(\tau_t, \rho_t, \nu_t, d_t).$$

After noting that the values of $\tau$, $\rho$, $\nu$ at the reference section are not independent of the values at the test position, this last equation becomes

$$\Delta p = f_3(\tau_t, \rho_t, \nu_t, d_r, d_t). \tag{4.4}$$

In analyzing the data it would, at first sight, seem proper to non-dimensionalize this in the form

$$\frac{\Delta p}{\tau_t} = f_4\left\{\frac{u_{\tau t} d_r}{\nu_t}, \frac{d_t}{d_r}\right\}, \tag{4.5}$$

for the pressure drops measured with different static holes are to be compared at the same tunnel (and therefore reference hole) condition. When this was tried, however, it proved unsatisfactory for, plotted in this way the data became very scattered at the lower end of the range of tunnel conditions, as illustrated in figure 9.

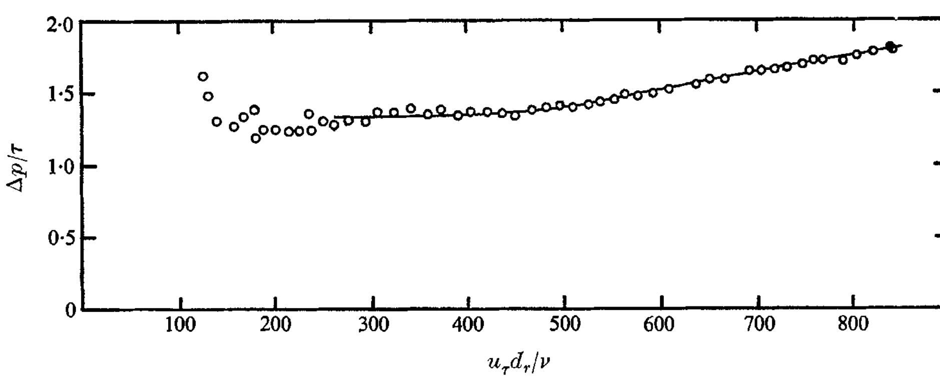


FIGURE 9. Example of data plotted using conventional parameters. Hole diameter 0·0469 in.

A little thought shows that this difficulty arises from the fact that at the lower values of $\tau$ the pressure drop $\Delta p$ is small and changes only very slowly with $\tau$, so that the inevitable inaccuracies in the measurements are magnified on dividing by $\tau$.

Consideration of the fact that the purpose of writing $\Delta p$ in non-dimensional form is to take account of variations from one run to another of the fluid properties leads one to write (4.4) in the alternative non-dimensional form†

$$\frac{\Delta p \,.\, d_r^2}{\rho_t \nu_t^2} = f_5\left\{\frac{\tau_t d_r^2}{\rho_t \nu_t^2}, \frac{d_t}{d_r}\right\}, \tag{4.6}$$

† It was later noticed that an equation of this form had earlier been suggested for the static-hole problem by Preston (1954).

which will be referred to in the form,

$$\Delta p^* = f_5(\tau^*, d_t/d_r), \tag{4.7}$$

and when the data are plotted in this way the scatter is eliminated, as will be seen below.

### 4.2. *Results of measurements of relative error*

The results of the set of experiments in which the tunnel pressure drop was measured with nine different test static holes are shown in figure 10 as a plot of $\Delta p^*$ against $\tau^*$ as defined in (4.7).

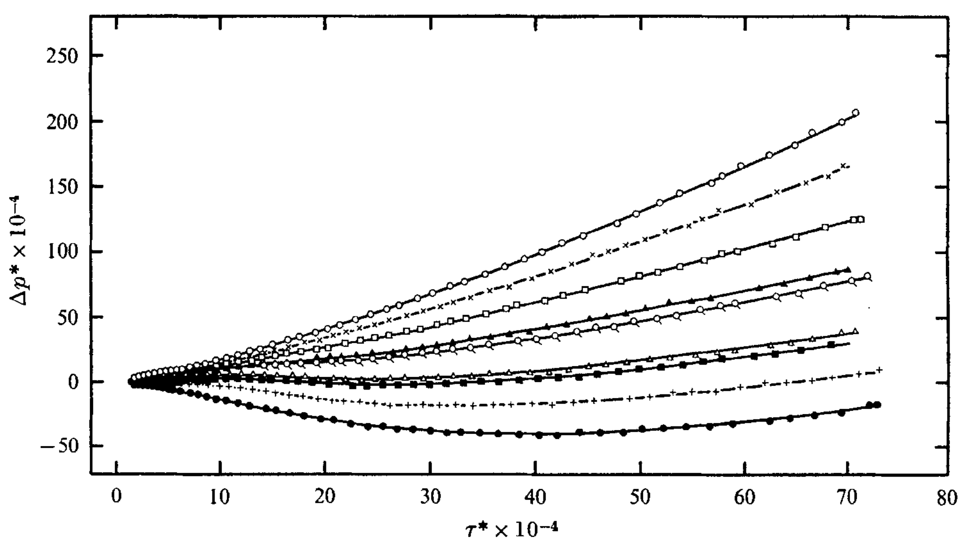


FIGURE 10. Pressure drop data obtained with test static holes.

By cross-plotting at any given value of $\tau^*$ and choosing the curve of $\Delta p^*$ for a particular hole as datum, a graph of relative error against diameter ratio may be drawn. An example of such a cross-plot is given in figure 11 and this illustrates well the difficulty of the usual method of obtaining the absolute error by the extrapolation of curves of this form to zero diameter ratio, for two curves have been drawn either of which (in the absence of the other) could be regarded as reasonable. As will be noted, the two zero diameter ratio intercepts differ by 20%.

To complete the determination of the absolute error curve using this method, many such cross-plots should be made at different values of $\tau^*$ and the intercepts used to correct the original data. Two situations then seem possible, for the estimates of the intercepts might either be randomly distributed about their true values (in which case the final curve would be drawn through data exhibiting considerable scatter), or systematically in error. One is therefore inclined to view error curves obtained in this way with some caution.

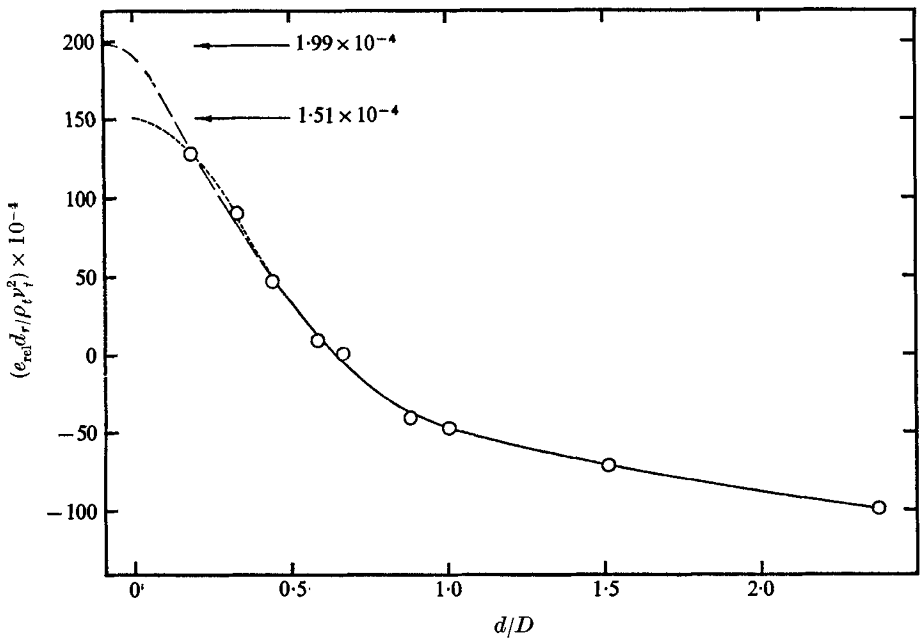


FIGURE 11. Example of a cross-plot from figure 9 giving relative error as a function of diameter ratio. Cross-plot made at $\tau^* = 70\cdot10^4$ taking as datum the test hole of diameter $D = 0\cdot1063$ in.

### 4.3. *Results of the measurements with flush transducers*

The data from the flush transducers are shown in figure 12, again as a plot of $\Delta p^*$ against $\tau^*$, the dotted lines being the smooth curves drawn through the earlier static-hole data presented in figure 10. The agreement between the data from the two transducers disposes of the possibility of a size effect and, together with the fact that the diaphragms are known to have very small displacements (of the order of the surface roughness, which is $10^{-5}$ in.) and therefore unlikely to disturb the boundary layer at all, the inference is that the resulting curve is the correct one for $\Delta p^*$ when no error is incurred at the test position. This set of curves may now be used to determine the absolute error of each static hole at all tunnel conditions, for, if at a particular value of $\tau^*$ the ordinate of the transducer curve is

$$(\Delta p^*)_1 = (p_r^* + e_r^*) - p_t^*,$$

and that of a particular hole is

$$(\Delta p^*)_2 = (p_r^* + e_r) - (p_t^* + e^*),$$

then the difference in the ordinates is

$$(\Delta p^*)_1 - (\Delta p^*)_2 = (p_r^* + e_r^*) - p_t^* - \{(p_r^* + e_r^*) - (p_t^* + e_t^*)\} = e_t^*.$$

Having deduced in this way the form of $f_6$ in

$$\frac{e_t d_r^2}{\rho_t \nu_t^2} = f_6\left\{\frac{\tau_t d_r^2}{\rho_t \nu_t^2},\ \frac{d_t}{d_r}\right\},$$

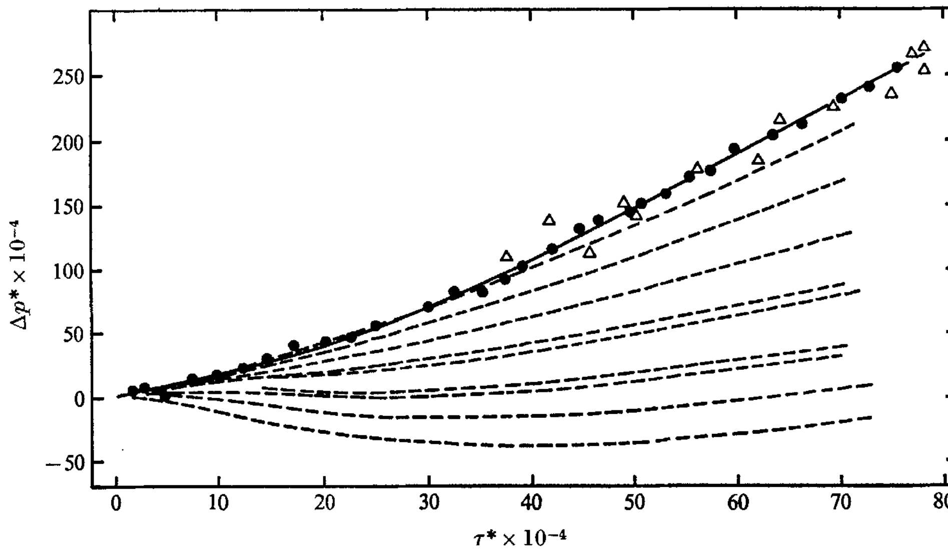


FIGURE 12. Pressure drop data obtained with flush transducers. Dotted lines repeated from figure 9. ●, diaphragm, dia. = 0·72 in.; △, diaphragm, dia. = 0·36 in.

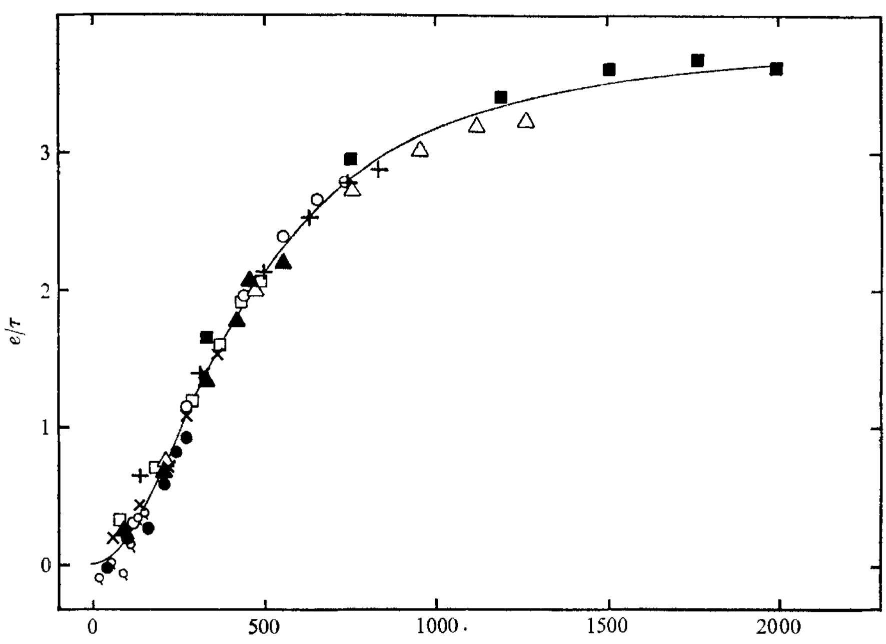


FIGURE 13. Non-dimensional error curve. Hole dia. (in.):

| | | | |
|---|---|---|---|
| Q | 0·0197 | ○ | 0·0938 |
| ● | 0·0354 | × | 0·1063 |
| + | 0·0469 | △ | 0·1606 |
| □ | 0·0625 | ■ | 0·2532 |
| ▲ | 0·0709 | | |

one may divide $e_t^*$ by $\tau_t^*$ and combine $(\tau_t^*)^{\frac{1}{2}}$ and $d_t/d_r$ to find

$$\frac{e_t^*}{\tau_t^*} = \frac{e_t}{\tau_t} = f_1\left\{(\tau^*)^{\frac{1}{2}}\cdot\frac{d_t}{d_r}\right\} = f_1\left\{\frac{u_{\tau_t} d_t}{\nu_t}\right\} = f_1(R^*),$$

which is the conventional form of the error curve, viz. (4.2).

The result of these operations is shown in figure 13, where the small scatter of the data is impressive.

## 5. Comparisons with other work

The volume of work on the static-hole problem is so great that comparison with all other work would be a rather extravagant undertaking. Accordingly, three representative researches have been chosen.

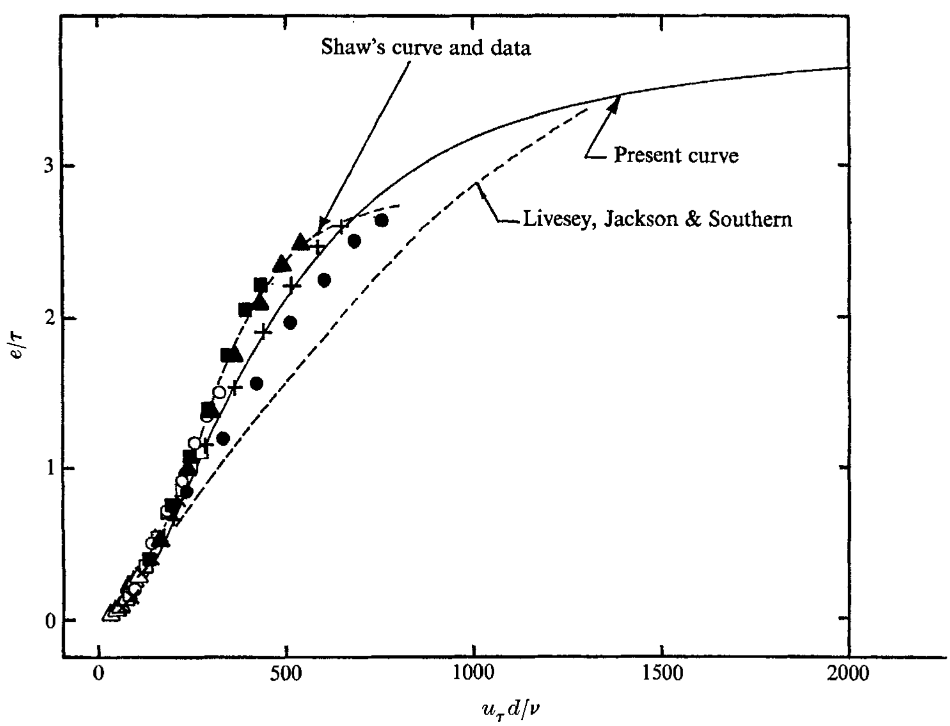


FIGURE 14. Comparison with the work of Shaw, and with that of Livesey, Jackson & Southern. Hole dia. (in.), Shaw's data:

| | | | |
|---|---|---|---|
| △ | 0·025 | ■ | 0·100 |
| + | 0·050 | ▲ | 0·125 |
| □ | 0·0635 | × | 0·150 |
| ○ | 0·075 | ● | 0·175 |

The first comparison is with the work of Shaw (1960). In his analysis, Shaw used the usual extrapolation method and his curve and data are compared with the present error curve in figure 14. The agreement is seen to be reasonably good, especially with the data he obtained from a static hole of diameter 0·150 in.

(which, together with his data from a hole of diameter 0·175 in., he appears to have ignored in drawing his curve), but the present curve is still increasing rapidly at $R^* = 800$, in contrast to Shaw's curve.

Livesey, Jackson & Southern (1962) employed an analysis different from the usual one. In their work an error curve relative to the absolute error at $R^* = 250$ was drawn and then shifted to fit a curve suggested by Jackson on semi-theoretical grounds. Their curve (they presented no data points), is also compared with the present curve in figure 14, where the agreement is seen to be poor, for there are differences in both magnitude and shape.

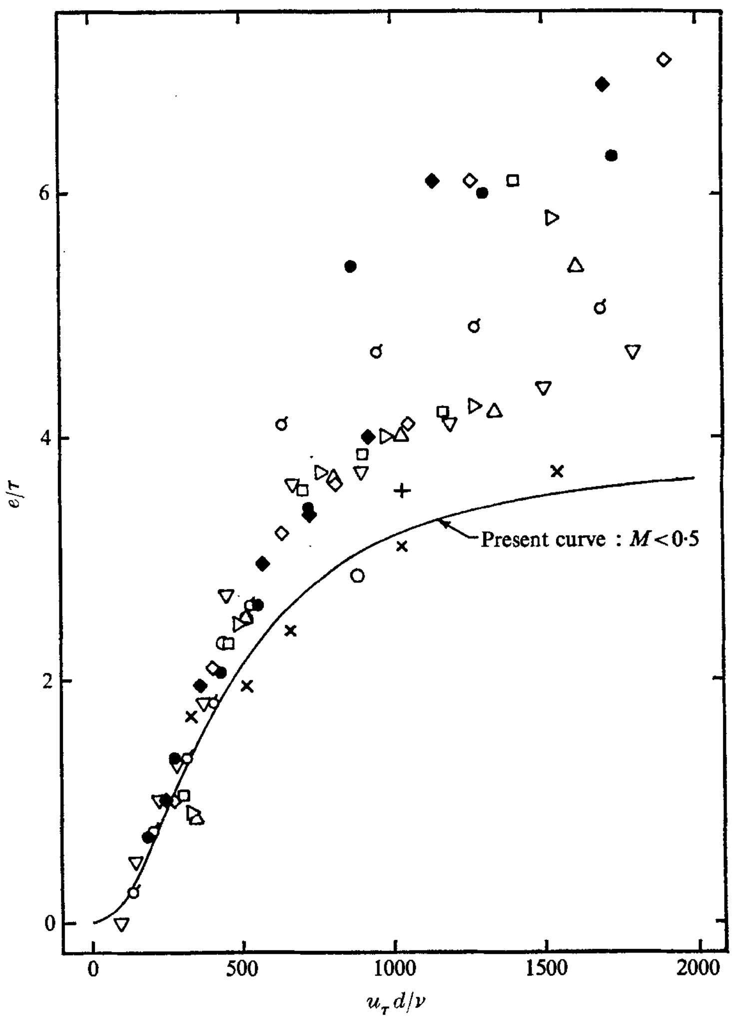


FIGURE 15. Comparison with the work of Rainbird. Rainbird's data, $M$:

| | | | |
|---|---|---|---|
| × | 0·56 | □ | 1·98 |
| ○ | 1·21 | ◆ | 2·41 |
| + | 1·35 | ● | 2·80 |
| △ | 1·59 | ơ | 3·19 |
| ▷ | 1·77 | ▽ | 3·56 |

One of the most recent investigations, and the first to be done for supersonic flow, is that of Rainbird (1967). These experiments were carried out in a blow down wind-tunnel using static holes normal to the surface of a cone under zero pressure gradient conditions. A comparison of his data with the present curve is shown in figure 15, and shows fairly good agreement for values of $R^*$ less than 400 at all Mach numbers. For higher values of $R^*$ Rainbird's data are considerably higher and exhibit a good deal of scatter. It is interesting to note that those data which show good agreement over the whole range of $R^*$ are those for a Mach number of 0·56. The Mach number in the present experiments was always less than 0·5, and one therefore suspects a Mach number effect at the higher values of $R^*$. Rainbird suggested that the scatter of his data might be due to the influence of a third non-dimensional parameter, this being the ratio of static-hole diameter to the boundary-layer displacement thickness, $d/\delta^*$, which in his experiments ranged over the interval $0{\cdot}7 < d/\delta^* < 10{\cdot}9$. The present work, in which a similar variation of this parameter occurred (namely $0{\cdot}15 < d/\delta^* < 4{\cdot}0$) fails to confirm this idea.

## 6. Conclusion

The principal result of this paper is the error curve of figure 12, which gives the error incurred with sharp-edged, circular static holes normal to the boundary for the values of $R^*$ lying between zero and 2000. In view of the precautions taken in the acquisition and analysis of data, it is thought that these data are reasonably definitive.

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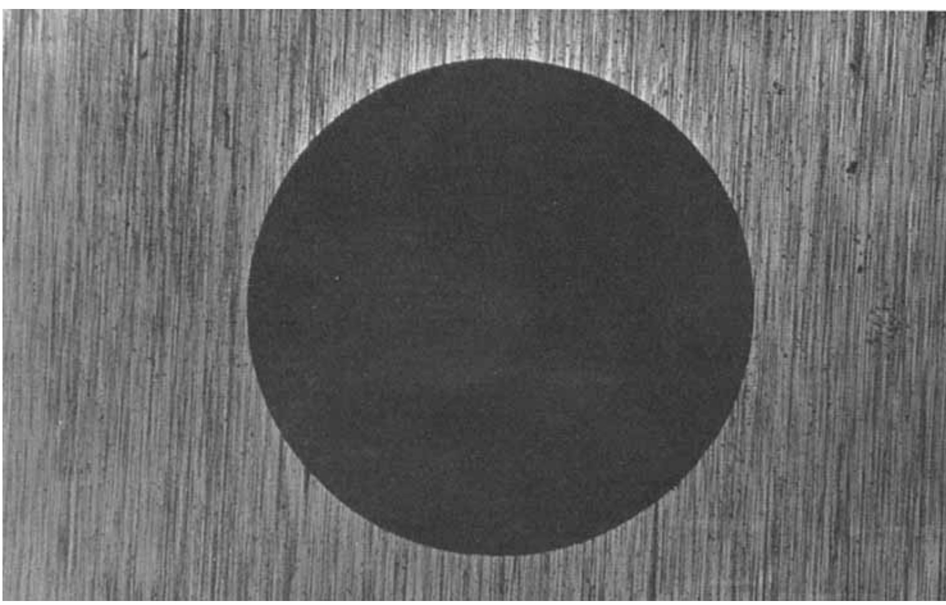

FIGURE 4. Magnified photograph of test hole of diameter 0·0354 in.

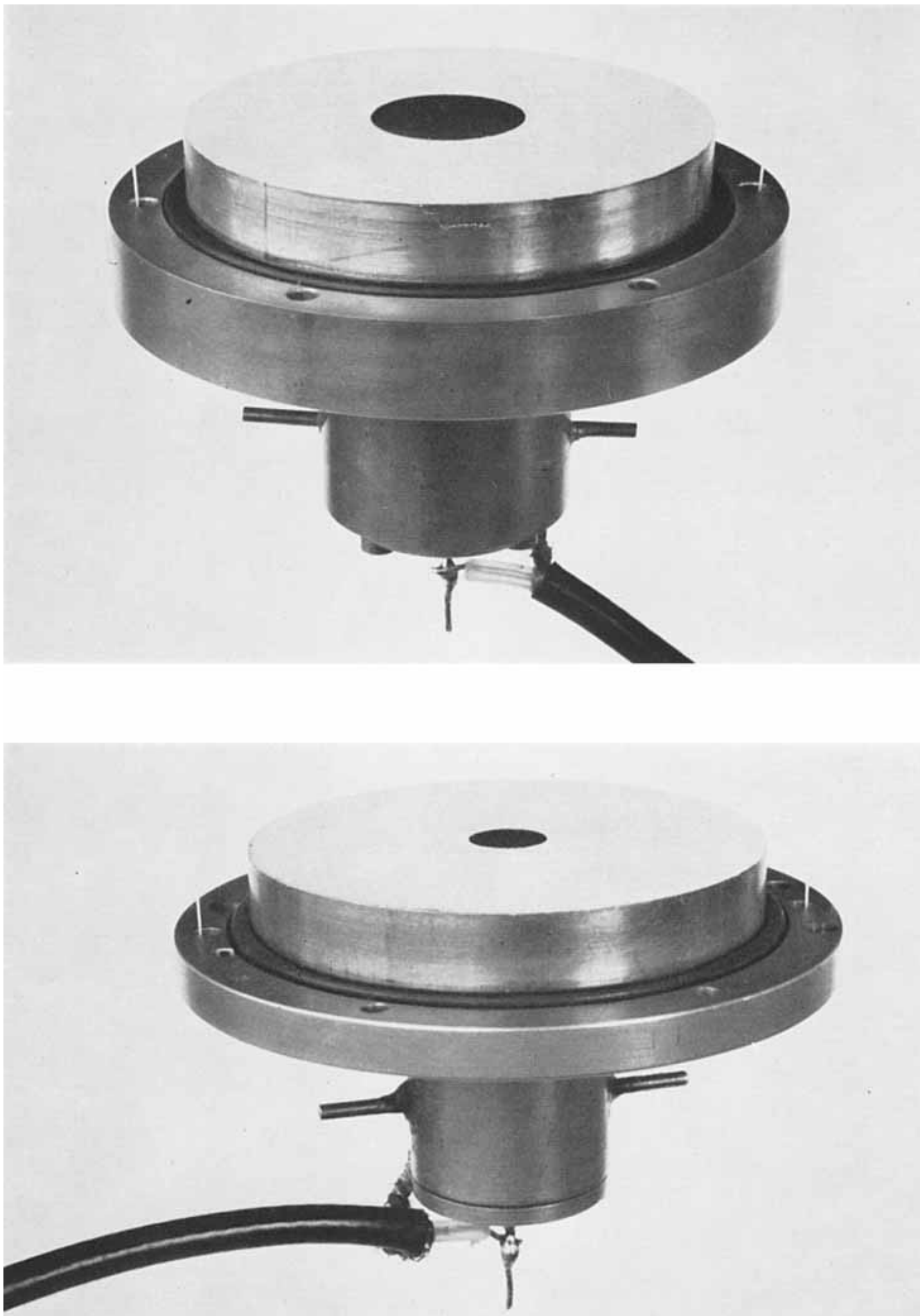

FIGURE 6. Photographs of mounted transducers. Upper: diaphragm diameter 0·36 in. Lower: diaphragm diameter 0·72 in.