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Gas Strain Gauges and their Circuitry

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Summary

Compact devices attached to structures for the remote measurement of displacement and strain, utilising pneumatic principles, have potential advantage in long term creep-fatigue conditions, or at very elevated temperature.

The principles and practice of sonic orifice circuitry which is well adapted to such environments have been worked out, and a complete system devised for a specific strain measurement problem.

* Replaces R.A.E. Technical Report 72006—A.R.C. 33 917.

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1. Introduction

The behaviour of resistance strain gauges when a structure is subjected to long term temperature and load cycling is by no means satisfactory, since there is observed drift in the resistance of the gauge and in the gauge factor. Although control tests may be run with a view to applying corrections as a function of time, strain range and number of cycles, the scatter in the results, with the need to extrapolate into the future, introduces much uncertainty.

This drift in resistance gauges might be expected, since the strain gauge element is subjected to the same strain and temperature as the structure itself, and may therefore change in characteristics through creep and fatigue.

A more stable instrument which can be attached to a structure in somewhat similar manner to a strain gauge would be invaluable, even if it were only used as a standard against which a group of gauges might be checked, but there are many problems to be solved if an instrument working on some other physical phenomenon is to have the compactness, distant-reading facility, and temperature compensation of a good quality resistance gauge.

This Report gives an account of developments of the pneumatic principle, which it is believed will meet the requirements of such an instrument. A gas strain gauge has been designed with real structures in mind rather than easy laboratory specimens, e.g. it will accommodate some flexural and torsional deformation of the surface to which it is attached, and it has a very compact 'lead' system. Simple circuits have been developed which are in theory independent of connecting tube resistance, of variations in temperature at all points in the circuit, and of variations in input and ambient pressure, and have potential for high resolution. Being non-electric, except at the instrument station, interference problems do not exist. As pneumatic circuits are subject to time lags, the systems are applicable to static or slowly varying strains only, but this is not specially restrictive if the instruments are used for intermittent reference, which is their envisaged function.

In the course of evolving the systems it has become clear that some of the principles established may well have wider application in displacement measurement, and some of the special hardware, e.g. the tube jointing system, could be useful in associated fields such as fluidics.

2. Gas Gauge Circuitry

The principle of a gas gauge (or pneumatic extensometer) is, in its simple conception, the measurement of variations in the distance between two attachment points by arranging that a valve is opened to a greater or less extent, thus varying the flow of gas. The 'gauge length' variation is in relation to an unstressed piece of metal, and the system is self-amplifying in that large changes in pressure are brought about by small strains in the supporting structure. Such pneumatic extensometers as have been described to date by other workers have been restricted to laboratory specimens, and in this application they have not had much popularity, since their function can be performed equally well by mechanical and electrical instruments.

The attractive features of pneumatic devices are more apparent when there is a temperature and stability problem, and it is desirable to have freedom in materials of construction. In common with electrical systems there is a distant-reading facility, but the fact that measurements are made in relation to an unstressed 'gauge piece' is favourable in comparison with the resistance gauge, all parts of which are subject to stress.

2.1. Low pressure displacement and gauging systems which have been used for many years in fine measurement and inspection, are not well adapted to strain measurement in heated structures since impracticably large diameter connecting tubes are necessary, and observations would be subjected to unacceptable perturbations through variations in the resistance of the tubing.

Early in this development it was decided to investigate the possibility of using sonic, instead of subsonic orifices in appropriate circuitry, with a view to eliminating in part the influence of the tube resistance. A number of circuits were devised, some of which are shown in diagrammatic form in Figs. 2–6, and sufficient experiments were carried out to verify principles, and give an appreciation of the merits of the different circuits. It was shown that sonic orifice circuitry would meet the requirements of the gas gauge problem; in particular, compact small-bore tubing can be used and the circuits are impervious to temperature and tubing resistance variations. All the systems considered have a common feature in that two tubes communicate with the gauge, which generally includes both a variable and a fixed orifice in its construction. It has not been found possible to devise a single tube system which retains all the merits of sonic orifice circuitry, and circuits necessitating more than two tubes have been ruled out on the grounds of excessive elaboration of installations.

2.2. In preparation for an explanation of the function of the various circuits, some working formulae which are derivable from standard text book formulae are recorded in Table 1. SI units are used in this Report; for conversion into other familiar units it is convenient to remember that $100\ \mathrm{kN/m^2}$ = 1 bar = 1 atmosphere =

14·5 psi, and 1 μm^2 = 1 (mm)^2. A mass flow of 20 mg/s is closely equivalent to 1 litre of free air at room temperature per minute.

A sonic orifice is theoretically a sharp-edged aperture between two vessels containing still gas, across which the ratio of downstream to upstream pressure is below a certain value related to the adiabatic exponent; for air or nitrogen this ratio is 0·53. It has been found that the formulae apply well if the upstream vessel is a tube of bore not less than five times the diameter of the orifice, i.e. the incoming velocity is less than 0·03 of the sonic velocity in the throat, taking account of the pressure and temperature reduction within it. An approximate formula for subsonic orifices is included in the table; here it will be noted that the downstream pressure influences the flow. Formulae for the resistance of tubing are put down for the record, but in practice it is best to calibrate the selected tubing by measuring flow and pressure drop. Figure 9 presents such data for 1·5 mm bore tubing, the size on which most of the circuit designs are based. It will be observed that coiling the tubing induces the turbulent régime for small flows, thus it is generally safer to assume the upper curve. The relevance of tube resistance in design is in the assurance that sonic orifice pressure ratios are not infringed, rather than any quantitative influence on performance.

By consideration of the formulae, some of the special characteristics of sonic orifice circuitry may be listed as follows;

(a) Mass flow through a sonic orifice is directly proportional to the upstream pressure and is independent of the downstream pressure provided that the critical pressure ratio is not infringed.

(b) If a stream is passed through two or more sonic orifices in parallel at the same temperature, the mass flow is subdivided according to the area ratios only.

(c) If a stream is passed through two or more sonic orifices in series, at the same temperature, the pressures satisfy the relation $a_{32}p_3 = a_{21}p_2 = a_{10}p_0$ etc. (*see* Code Fig. 1).

(d) With steady input pressure into a sonic orifice circuit, all output flows will be constant despite variations in temperature of the communicating tubing, provided that all orifices are at constant temperature, and that the gas attains the temperature of an orifice before passing through it.

(e) A system consisting of a sonic orifice preceded by a tube of finite resistance (turbulent régime) and/or a subsonic orifice, will behave essentially as if it were a simple sonic orifice of reduced diameter, with upstream pressure that of the input to the system, if the temperature is constant within the system.

These statements are sufficiently accurate for basic design purposes, but small deviations do exist, e.g. the effective area of an orifice is slightly modified by the magnitude of the flow, there is some dependence on downstream pressure at the theoretical pressure ratio, and the orifice coefficients can be affected by factors such as dissociation at elevated temperatures.

2.3. The five circuits shown in Figs. 2–6 represent various methods of taking remote observations of strain with gauges which for the present are assumed to consist schematically of variable orifices with apertures linearly related to the extension of the structure relative to an unstressed gauge piece, and fixed orifices in close proximity. The special code which has been devised to identify circuit parameters is tabulated in Fig. 1. Some BSI and DIN symbols are used, but neither standard code has the simple numeral system for the identification of circuit elements and values, which is found to be convenient for sonic orifice circuitry.

The principles of the various circuits may be summarised as follows:

Figure 2. Gas at constant pressure and temperature is passed through a sonic orifice (32) to the gauge, and out through the variable sonic orifice (10). Observations are taken on the pressure gauge. It is necessary to know the temperature of the strain gauge. With the mass flow to the gauge constant, the reading is inversely proportional to the strain. By operating the system inversely, i.e. adjusting input pressure until the output pressure is constant, the reading can be made linear with strain.

Figure 3. Instead of using a pressure tap, a proportion of the flow is passed through a fixed orifice, back to a flowmeter consisting of a subsonic orifice with pressure gauge upstream. The input pressure is adjusted until the flowmeter indicates a standard value. With constant ambient pressure and temperature at the instrument station, $a_{30} = ka_{54}a_{32}p_5 - a_{32}$.

Figure 4. To avoid correction for ambient pressure and temperature, this circuit includes a reference line against which the output flow is balanced. The input pressure gauge is replaced by a balanced needle valve system in which the constant input flow is divided into two parts. Since $a_{50} + a_{54}$ is constant, the mass flow into the gauge is proportional to a_{54}, thus $a_{30} = k_1a_{54} - k_2a_{32}$. With a linear relation between the balanced valve movement and its area, $\varepsilon = k_3X + k_4$.

Figure 5. A variant on the previous circuit is the insertion of the balanced valve in the reference line, and the incorporation of an additional balanced valve in the gauge. In this case, at balance $\varepsilon = kX$. The circuit is independent of ambient pressure and temperature at the orifices and tubes, provided that the pairs of orifices (98) and (94), (70) and (76), (30) and (32), (50) and (10), are matched in temperature.

Figure 6. In this circuit a micrometer valve of the nozzle-baffle type in the reference circuit is complementary to the nozzle-baffle orifice of the strain gauge, and the micrometer reading is directly proportional to the strain at balance. Again, with precaution taken to match the temperatures of the components of orifice pairs, the system is fully temperature compensated.

The Appendix gives more detail on the circuit functions and formulae.

2.4. To attain the theoretical temperature-independence of sonic orifice circuitry, it is necessary that the operating gas is brought to the temperature of an orifice before it passes through it, although in certain circumstances this condition may be relaxed, e.g. when a stream is subdivided by orifices in parallel which are in thermal contact with each other.

In general, to avoid complication, it is necessary to run the tubing for a minimum distance in an environment at the orifice temperature, but there is usually no special difficulty in doing this.

The most favourable environment for heat transfer is with the tubing in close contact with the structure, so that heat is picked up by direct conduction. The least favourable is with the tubing passing through still air, i.e. with natural convective heat transfer only.

As with tube resistance it is safest to assume the unfavourable case, and the lengths necessary to bring the temperature closely to the environment have accordingly been calculated on this basis.

Considering the 1·5 mm bore tubing which has been selected for general circuitry, and gas at 20°C passing into the tube which is in still air at 200°C, the following lengths have been calculated from Fishenden and Saunders data to bring the gas within 1°C and 0·1°C of 200°C

Tubing	Mass flow mg/s	Length required m	
Stainless steel		1°C	0·1°C
1·5 mm bore	80	2·17	3·12
2·0 mm ext.	20	1·03	1·52

For comparison, the case of Teflon tubing running into a 200°C environment,

Teflon 1·5 mm bore 3·2 mm ext.	80	2·80

3. Gas Gauge Design

Designs of two prototype gauges are shown in Figs. 7 and 8. They are both intended for intermittent readings on structures which are subject to long term cycling load and temperature, the maximum temperature being 120°C. Performance of the gauges will be reported elsewhere; present comments are confined to descriptions of the gauges and the features which have been incorporated.

3.1. The first design comprises two blocks—the orifice block and the stop block cemented to the structure—with a needle bridging them. The orifice block includes the variable orifice (30), which is the annulus between the tapered hole and the ball-ended needle, and the fixed orifice (32). Gas is passed into the orifice block via hypodermic tubing, and is divided into two parts, one passing through the annulus, and the other through the fixed orifice into the outflow hypodermic tube. When no gas is flowing a spring retracts the ball into the cavity behind the orifice so that it bears on a stop, and fretting of the ball against the orifice wall is thereby prevented. To prime the gauge, a pulse of high pressure gas is passed into the gauge, forcing the needle forward to a position where the far end bears on a stop; the flow is then reduced to the normal working level and an observation is taken. The annular jet has a centring action on the ball, but in practice it is found that the needle vibrates laterally. The whole instrument is enclosed in a silicone rubber cover with a simple flap valve, so that the outflowing gas floods the enclosure, thus assisting temperature equilibrium, and, of course, the cap gives essential protection against dust and corrosion. The pressure in the orifice block is not less than 275 kN/m^2, so the pressure in the cap can be as high as 145 kN/m^2, which is 45 kN/m^2 above ambient (5·5 psi), without infringing theoretical sonic conditions.

The instrument can accommodate some flexural and torsional deformation of the surface on which it is mounted. In particular it will be appreciated that bending will introduce a spurious strain, since the needle is located above the surface. If bending is anticipated, instruments mounted on each surface of a sheet will be necessary for compensation; it will also be necessary to extend the range of the instrument and thereby reduce resolution. Therefore this design is only advocated for stiff members not subject to bending.

3.2. The second design, which is depicted in schematic form in Fig. 8, is much better since it is less sensitive to bending and torsion. In this model the orifice block is mounted centrally and the variable orifice (30) is made up of two nozzles in close proximity to the faces of a wedge block which is attached to a thin strip of the structure material. These annular orifices are actually connected in parallel through the holes indicated, and are fed through one of the lateral tubes. The other tube takes the outflow via a fixed orifice (32). A silicone rubber cap covers the whole gauge, and, as in the previous design, the outflow gas bathes the instrument.

The gauge strip, attached firmly to the base at point A, is subject to lateral and normal restraints in directions y and z at points B and C and also to torsional restraints about axis x at these points. The strip is effectively free in the x direction, so as the structure material bends and twists the gauge strip follows this movement, but is not subject to the applied strain. The gauge length is from A to B, the remainder of the strip assisting in applying moments at B about axes x and z. It will be seen that the bridge block and wedge block should remain in the same relation when the structure deforms, so that the orifice apertures are only dependent on the applied longitudinal strain.

The S.I.R.A. Institute, in collaboration with the R.A.E., have constructed several versions of gauges incorporating this basic principle, with improved performance at each step. The most recent has a special spring leaf guidance system for the gauge strip, which applies the appropriate flexural and torsional constraints, with minimum end load on the gauge strip. This design has demonstrated very good performance in respect of linearity and absence of hysteresis, but its long term stability has yet to be ascertained. Results with this gauge will be the subject of S.I.R.A. reports.

4. Circuit Hardware

On inspection of commercial items designed for pneumatics and fluidics it was decided that very little of such equipment would have the optimum compactness and performance which was needed in this specialised application, so in the course of the development various items have been designed and made which meet the requirements of sonic orifice circuitry in a more acceptable manner.

4.1. Tubing and Connections

To keep pressures within reasonable bounds and at the same time retain the facility to locate the gauge at distances up to 50 m from the instrument station, it was decided to standardise on 1·5 mm bore tubing which is thin enough to manipulate into a structure as easily as the screened wires which are used for resistance strain gauges. In early work stainless steel tubing was used throughout, but later nylon tubing became available and could be used in cool environments when suitable plug ends had been devised. Teflon tubing may also be used at elevated temperatures up to 300°C and has the merit of good flexibility. The most compact demountable joint conceivable, is a simple taper machined on to the end of the stainless steel tubing which is plugged into a reamed taper hole. A special carbide cutter (Fig. 14) was devised to form the taper on long lengths of tubing, the technique being to rotate it in the headstock of a lathe, the tube being held stationary; after some experiment it was found that the tool would cut with acceptable finish and concentricity. The corresponding taper hole in mating parts is most satisfactorily prepared by using a five-flat taper broach, followed by burnishing if necessary with a taper pin. It is interesting to note that four-flute taper reamers are not satisfactory for this purpose as the resultant hole is not sufficiently round.

Figure 12 shows the principal tube-joint parts which have been devised using this principle. None of them introduces any constriction into the 1·5 mm diameter passage, except the flexible connection, which is of 1 mm bore. There are five main units,

(i) Straight connector. This is of brass, which has a thermal expansion coefficient nearly equal to that of the austenitic stainless steel tubing, so that the joint remains tight at elevated temperature.

(ii) T-junction and Y-junction, also of brass.

(iii) Stop end. Austenitic stainless steel.

(iv) Plug end for nylon tubing. This consists of a short length of the stainless steel tubing, prepared at one end with a taper, and the other with circumferential grooves. A knurled collar is forced onto the steel tube which is also fine knurled to form an interference key. This assembly is fused into the end of nylon tubing in a jig by heating it gently with a flame.

(v) A short reinforced silicone rubber tube with female taper ends, used at the gauge inlet and outlet to minimise constraint.

The plug and socket system has been found very convenient both for temporary 'bread-board' circuitry, and also for permanent circuitry, although in severe environments it might be desirable to reinforce the joints with adhesive. The joints have been found to be satisfactory up to 2 MN/m^2 (300 psi) though care must be taken to insert taper plugs extra firmly at higher pressures to avoid them blowing out. It goes without saying that all circuit components must be clean; this is generally ensured by dipping them in, and blowing through, trichlorethane and protecting them when not in use by attaching connectors or stop ends.

Transition from nylon to stainless tubing, when passing from a cool to a hot environment, is easily effected with the standard connectors.

The design of compact joints with Teflon tubing has been given some attention. To avoid the necessity of sodium treatment (for adhesion) on site, the recommended procedure is to pretreat whole lengths of tubing and store them in polythene bags. Using gloves, the ends are pushed onto a double-taper internal spigot and an external sleeve is cemented with RTV 731 silicone rubber.

4.2. Orifices

In experimental circuitry several fixed orifices are usually required, and the facility to make precise orifices of any desired size is a necessity. Orifices for general use are punched with a tapered flat-ended punch in dished discs of 0·07 mm light alloy foil which are stamped out by hand on a rubber block with a shaped tool. The jig for punching the orifices is illustrated in Fig. 15. Holes of satisfactory quality down to 90 μm have been made by this method; further details on the effect of variations in the method of making the hole are given in Section 6.

The disc is mounted between the two halves of the brass orifice block which is illustrated in Fig. 16 (left), and the assembly is firmly clamped in a frame shown above. The orifice block has two taper holes in the upper half, which is normally the input side, and one in the lower, so that standard taper ends can be inserted. There is full freedom in the directions of inlets and outlets, which is a convenience. The blocks are designed so that orifices may be easily inspected for obstruction—a very rare event—and so that leaks are made evident with detergent solution. The mating surfaces of the blocks are easily touched up with an Arkansas stone in the lathe—again an infrequent necessity.

The dished form of orifice was developed for pressure differences up to 1·5 MN/m^2, but the need arises for orifice systems which will function at 5 MN/m^2. This entails giving more support to the light alloy disc, and Fig. 16 (right) is a design which has been found satisfactory at pressures of this order. The disc is flat, but there is support beyond a radius of 0·2 mm from the centre of the hole. Such high pressures are only encountered upstream of the input orifices of a circuit, so the other type of block is acceptable for most other purposes. Nylon tube-hypodermic tube joints are not satisfactory in these high pressure situations, so connections must be all stainless steel.

The use of punched orifices for low pressure subsonic application is acceptable, but turbulence does give rise to some wobble on the micromanometer needle. This may be improved by using the subsonic orifice system shown in Fig. 17, here the flow is steadied by the input gas being passed through a straight tube of length at least 30 diameters, with a well-finished entrance cone of 20 degrees included angle.

In a double nozzle-baffle system it is essential that the nozzles should be exactly matched in diameter, sharp-edged, and with the edge planes normal to the axes of the nozzles.

The tool shown in Fig. 18 was specially developed for this purpose, it consists essentially of two D-bits clamped face to face in a split chuck, the intersection of the male and female vees constituting a form tool with an internal edge, the diameter being adjusted by relative longitudinal movement of the two halves. The tool is used for a light finishing cut in a watchmaker's lathe.

4.3. Micrometer Valve

A balanced needle valve was constructed for use in certain circuits, and was brought to an acceptable standard of performance, but completion of this development is in abeyance due to the decision to use a circuit which requires a single outlet calibrated leak instead. Commercial micrometer needle valves were tested, but their performance was unacceptably erratic with sonic conditions in the annular aperture, at high pressures and low flows. The deviations are attributed to the needle wandering eccentrically, and the flow is thereby modified as part of the gap becomes comparable in dimension with the mean free path of the gas. To avoid this effect, it is necessary to guide the needle concentrically to an order of accuracy in the nanometre region, which is not possible except by using a floating principle and self-centring action. Here complications arise through aero-dynamically induced vibration.

A micrometer valve employing a different principle was therefore designed, and this was found to give satisfactory performance, with reproducibility of flow to one part in one thousand of the range, and with potential further improvement to one part in five thousand. It is illustrated in Fig. 19. It uses the principle of a built-in cantilever spring to reduce the movement of the micrometer anvil by a factor of about 300; this reduced movement is applied to the orifice anvil which faces a nozzle. The reduction principle has the special merit of good rigidity in the vicinity of the orifice, no pivots, hinges or screw threads being used except at the micrometer end. The design is the outcome of a number of experiments and modifications in which certain deviations in performance were eliminated. For example, the spring was originally machined integrally with the clamping block from S 28 steel, and the micrometer link took various forms until it was appreciated that extra care must be taken to avoid applying torque or bending moment other than that due to normal pressure via the link. Since the S 28 steel exhibited non-elastic behaviour, it was replaced by standard, prehardened spring steel strip S 513, and again some inelasticity was observed. This trouble was cured by rehardening and tempering in a clamp, shaped to the desired set, to 540 VDP which is above the recommended limit for spring steel.

For small deviations, repeatability of setting for constant flow is $\pm 1\ \mu$m on the micrometer. Since the range is 6 mm this represents a resolution of one part in 6000, and is equivalent to a resolution of 3 nm over a total range of 20 μm at the orifice anvil. Large movements of the micrometer have been found to result in poorer repeatability, for some as yet unexplained reason, but the overall resolution and accuracy is nevertheless as good as one part in 1000.

4.4. Flow Measurement

(a) In the experimental development of systems it was necessary to have a standard flow measurement device for accurate determination of flow through orifices etc., and for general checking. The gas flow vessel illustrated in Fig. 10 was constructed for this purpose; it consists of a silicone-treated glass container into which water can be drawn by a filter pump. A two-way tap permits a steady flow which is vented to the atmosphere, to be rapidly re-directed to the vessel. Two marks A and B are located on the narrow tube extensions of the vessel, and an observation is taken by timing the passage of the water surface between the marks. The ambient pressure and temperature must be noted for precise readings, the actual formula for the mass of air between the marks being

$$G = 5629{\cdot}8(p_0 - 3{\cdot}30)T^{-1} \text{ milligrams}$$

where p_0 is in kN/m^2 and T is in kelvins.

(b) Most circuits entail the accurate matching of two small flows of the order 10 to 20 mg/s. A sensitive differential pressure gauge was first used for this work, connected upstream of two subsonic orifices. To attain sufficient resolution, the total pressure applied to the gauge was about 10 kN/m^2 (1·5 psi) above ambient and it was soon apparent that overload valves would be required if damage to the instrument was to be avoided. Valves were constructed, but did not operate with reliability. In any event the instrument was rather sluggish, so alternative methods of matching two flows were given some attention.

A differential flowmeter consisting essentially of two light rotors spun by jets from the two outflows was designed and constructed. Equality of rotational velocity, which implied equality of mass flow since the jets were at the same temperature, was detected by observing the moiré rings formed by 50 near-radial 'spokes' on each rotor. At balance, the rings were stationary, but they moved outwards or inwards if the velocities were not equal, depending on the sense of the error. Since the rotors were spun at about 40 revolutions per second, and a change in mass flow of unity would result in a change in rotational velocity of about 1·5, a movement of one fringe per second would represent a difference in flow of one part in 3000. It was not, in fact, possible to obtain better repeatability than one part in 500, but with certain improvements in construction, it is believed that the accuracy can be as good as the resolution. The general principles of this device are well adapted to the requirements, since it has quick response, very small back pressure, and it is impossible to overload it.

At this stage, attention was drawn to a commercial micromanometer of high sensitivity which was stated to withstand an overload differential-pressure of 100 times the full scale deflection, and a total pressure up to 1 MN/m^2 (150 psi). It is the Furness Micromanometer Type MDC, made by Furness Controls Ltd., Bexhill, Sussex, and its sensitive unit is a diaphragm which constitutes the common plate of two condensers; variation in capacity in two tuned circuits causing a needle to deflect. An instrument was purchased, with scale range ± 25 N/m^2 and facility to reduce sensitivity by factors of 2 and 5.

This instrument, connected upstream of two subsonic orifices of appropriate pressure drop has functioned with excellent reproducibility; it has rapid response and more than adequate sensitivity for any of the purposes of this development.

4.5. Input Systems

The circuit shown in Fig. 6 requires a high input pressure, especially when it is designed for a maximum distance between strain gauge and instrument station of 50 m. Two possibilities of reducing this pressure are indicated on the diagram. One is to replace the fixed input orifices (98) and (94) by linked variable orifices, i.e. in the sonic orifice formula $g = Cap$ to make a the variable instead of p. The input pressure is then simply defined by the condition that p_1 or p_2 are not greater than 0·3 p_3 (small diagram) at maximum flow, in comparison with the condition in the main circuit that p_4 is not greater than 0·3 p_9 at minimum flow, requiring to be doubled at maximum flow. An experimental dual valve has been constructed, in which two nozzle-baffle orifices are operated together. Its performance in respect of independence of downstream pressure is not satisfactory however, and further work on orifice design is required to improve it.

The second device is a diaphragm pressure equaliser, shown in Fig. 11 and in schematic form as a component of the circuit in Fig. 6. A constant pressure p_3 is applied to one face of each diaphragm and the flows from the subsonic orifices (43) pass to the other faces of the diaphragms and out to the reference and active lines through nozzle-baffle orifices in which the baffles are attached to the diaphragms. It will be apparent that the flows will be self-adjusting to maintain the pressure downstream of the subsonic orifices at the constant value p_3, independent of the resistances of the active and reference lines. In this way, the subsonic orifices are constrained to behave like sonic orifices, with the advantage that the pressure ratio can be much increased.

The performance of the pressure equaliser is satisfactory up to a point, in that flows can be controlled accurately with a maximum value of $p_4 = p_3$ of 500 kN/m^2 and the flow is independent of downstream pressures p_1 and p_2 to an order of one part in 1000. However, a disadvantage which was not anticipated is that there is a time lag when p_4 is adjusted or when p_1 or p_2 vary suddenly, due to the finite volume of the instrument. This can make adjustment of flow in the main circuit, to bring p_1 to a standard value, very tedious.

The conclusion, after experience with the two special input systems, is that for the present it is necessary to accept the high pressures associated with fixed sonic orifice inputs, but it is well worth pursuing the variable sonic orifice system which has potential for satisfactory operation.

5. Design and Assessment of Punched Orifices

5.1. Since no published data appeared to be available on the behaviour of very small orifices, a number of flow tests at room temperature was carried out. The circuit used is shown in Fig. 24. The orifice under test was put in series with a subsonic orifice which had been previously calibrated with the help of the gas flow vessel, and observations of upstream pressure p_3 were taken for selected flows which were related to particular values of $p_1 - p_0$. A table of calculated orifice coefficients C at different flows for a range of sizes is presented (Table 3).

It will be observed that all coefficients are less than the theoretical value, the average being 2·25 compared with 2·36, i.e. about 5 per cent less, in other words, the diameter of the hole appears to be $2\frac{1}{2}$ per cent low from flow measurement. It will be appreciated that the measurement of diameter by microscope is not easy, and some of the scatter may be due to this, but the reduction in coefficient is undoubtedly real. It may be attributed to boundary layers which would be proportionally more important in small orifices; the finite thickness of the orifice disc could also have some significance, and the sonic throat need not correspond precisely with the geometrical throat. From inspection of the table it is not easy to be quantitative about the effects of change in magnitude of flow or increase in diameter, but trends which may be discerned are a dubious increase in orifice coefficient with diameter, and a definite increase with reduction of flow at a constant diameter.

The principal merit of this experiment lies in the demonstration that well prepared, very small orifices, behave substantially according to theory, at the pressures and flows envisaged for sonic orifice circuitry.

The results reported are the outcome of an earlier series of tests in which the method of punching was varied. A set of results was first obtained with little attention being paid to the actual shape of the punch, which was sometimes cylindrical or tapered slightly in either direction. Some of the orifices tested gave coefficients low by as much as 15 per cent—without relation to size or flow. These were inspected under the microscope, compared with good orifices, and reversed in the orifice block, and it was concluded that poor results were more often than not shown by holes that diverged in the direction of flow, converging holes behaving better. The hole is only about 0·1 mm long, nevertheless the conclusion was drawn that the gas could become supersonic in this short passage, giving rise to unpredictable perturbations. A converging hole was found to be rather better than a parallel hole, and sharpness of the exit edge seemed to be beneficial, so the procedure finally adopted was:

(i) A sheet of 0·12 mm aluminium alloy foil was lapped with a wood block, and polished.

(ii) The foil was coated on one face with Durofix 0·1 mm thick.
(iii) The disc was stamped out with the Durofix on the convex side.
(iv) The disc was punched in the jig shown in Fig. 15 from the concave side.
(v) The Durofix was dissolved off with acetone, followed by trichlorethane. The Durofix acted as a support and helped in the removal of the plug.
(vi) The disc was replaced in the jig, and the hole burnished with a 30 degree taper needle to a depth of 0·05 mm.

5.2. To demonstrate the accuracy of the standard formula given in Table 1 in respect of temperature dependence, a test was set up in which the flow through an orifice was measured at room temperature, and at about 170°C. Figure 25 shows the experiment schematically; air was passed from a regulator into 1·5 mm bore stainless steel tubing, 2 m of which were coiled in the oven, on to a standard orifice block with a temporary clamp, and thence through 6 m nylon tubing to the gas flow vessel. At equilibrium the flow, upstream pressure and temperature were measured, and orifice coefficients calculated as shown in Table 2, in which correction of the results to allow for the expansion coefficient is included. The good orifice was prepared as above, and the poor orifice had a diverging hole.

It will be noted that both orifices confirm the $T^{-\frac{1}{2}}$ law quite well, the poor orifice having a lower coefficient but not much evidence of serious deviation from the law.

6. Sonic Orifice Performance

6.1. Effect of Downstream Pressure

Although the theoretical pressure ratio across an orifice for sonic conditions to apply is 0·53 for air and nitrogen, the value must be lower if the flow is to be truly independent of the downstream pressure. This is because the effective area of the orifice tends to be reduced as the downstream pressure increases, even in the sonic mode, due to movement of the 'sonic throat' away from the physical boundary of the orifice. Dependent on the overall accuracy required of a circuit, pressure ratios at all sonic orifices must be such that deviations through variation of downstream pressures are within the required limits.

An experiment has been carried out to determine pressure ratios associated with independence of downstream pressure to different orders of accuracy. The circuit is shown in Fig. 23. The orifice under test is (21). The valve (10) can apply any desired restriction to the flow, which is uniform, thus raising p_1 according to requirements. The differential manometer (24) measures the change in upstream pressure p_2 relative to a nearly equal reference pressure p_4. Since $g_{21} = Ca_{21}p_2$, the proportional change in this mass flow when p_1 is increased is $\Delta g_{21}/g_{21} = \Delta p_{24}/p_2$.

Since p_2 cannot be much below 500 kN/m^2 if there is to be a good range of values of p_1/p_2, the manometer is subjected to this rather high static pressure. It was not therefore possible to use the Furness micromanometer; instead, a differential water manometer was used, which would stand the pressure, but had the disadvantage that it was very sluggish in operation when near equilibrium, through the viscosity of the water.

Some results are shown in Fig. 30. They are by no means as comprehensive as one would wish, but they do give an indication of the relation of pressure ratio to accuracy. It seems that a straight line on the log $\Delta p_{24}/p_2$ plot against p_1/p_2 is an approximation to the results, from which one can infer that a power law applies. The conclusion is that a sonic pressure ratio of 0·4 is suitable for a circuit accuracy of 1:500, of 0·35 for 1:1200, and 0·3 for 1:5000. There is a detectable difference between the performance of a nozzle-baffle orifice and a simple hole.

These results are being used at present for design purposes, but it is clear that they require considerable extension to cover a range of cases, including more values of p_2, d_{21} and g_{21} and variations in hole geometry.

6.2. Performance of Nozzle-Baffle Orifice

Some tests were carried out to determine the conditions for linear response of sonic nozzle-baffle orifices, i.e. proportionality of mass flow g, to gap t, at constant upstream pressure p and temperature T; or proportionality of p to t at constant g. Such tests provide evidence on the validity of the assumption that a double opposed nozzle with single baffle, such as is depicted in Fig. 27, has an effective area independent of the exact position of the baffle block between the nozzles. The mechanical guidance of a wedge block between nozzles cannot be sufficiently precise to avoid deviations in the measured quantity if the nozzle-baffle response is not linear.

Tests on single nozzles. The circuit was as shown in Fig. 21. The test orifice consisted of a nozzle clamped to a microscope base, with a glass plate baffle mounted on an arm which was capable of limited angular adjustment; this special mounting is illustrated in Fig. 26. The rig was clamped to the coordinate stage of a measuring microscope, so that variation of t could be made by the micrometer, and measurements of its value by the micrometer eyepiece. In fact, a more precise means of measuring the gap is strictly necessary for good results, and the observations, although giving useful information leading to improved design of nozzles, could well be repeated using an inductance transducer.

The principle of the tests was to adjust p_9 at various settings of t_{70} by restricting the flow through valve (10.9) until the outflow through (50) was matched to the outflow through (10) which was maintained constant at 10 mg/s. The measured area of the test orifice a_{70} is $\pi d_{70} t$,

$$a_{10\cdot 4} = a_{98},$$

$$a_{32} = a_{76}$$

and

$$a_{10} = a_{50}.$$

The area derived from the pressure measurements is

$$a_{70} = (a_{30} + a_{32}) p_9/p_{10} - a_{76},$$

thus

$$t = k_1 p_9/p_{10} - k_2.$$

When p_9/p_{10} is plotted against measured t the result should be a straight line.

Some results are shown in Fig. 31 for various diameters of nozzle and various flows. It will be noted that the lines are substantially straight, but there is usually a deviation in slope as t approaches zero.

The tentative conclusions which were drawn from the results were that a sharp edge to the nozzle is beneficial for linearity, and that good linearity can be expected with the gap greater than 7 μm. The strain gauge nozzle-baffle system was therefore designed so that the gap could not be reduced to less than 7 μm. The upper limit of the gap could not be specified from these tests to sufficient precision, but a conservative limit of 25 μm was applied in design. The following tests verified that the assumption of linearity over the selected range was justified.

6.3. Balance of Double Nozzle-Baffle

Figure 27 shows the arrangement used for this test; two nozzles were clamped in the head and tailstock collets of the lathe, and a thin plate baffle was mounted on the slide rest.

The circuit used is shown in Fig. 22. After adjustment of the nozzles to the required separation, by bringing p_8 to a specified value, the baffle could be carefully displaced between them by means of the cross slide, and the variation of flow was reflected in p_5. The circuit was analogous to the standard circuit of Fig. 6, so balance was attained by operating the micrometer valve (30) on which deviations were directly measured. Circuit flows and pressures were such that the full working range of the micrometer (30) was 4·5 mm.

Test (a)

Nozzle diameter = 495 μm
Total flow through (80) = 74 mg/s
p_8 = 570 kN/m^2
Calculated gap $t_1 + t_2$ = 18 μm

Result. Over 15 μm traverse of baffle, deviation on (30) was less than 1 μm.

Equivalent to an accuracy of 1:4500.

Test (b)

As above. No detectable deviation over range of 13 μm.

Test (c)

Nozzle diameter = 438 μm
Flow and pressures as above.
Calculated $t_1 + t_2$ = 21 μm

Over 15 μm traverse of baffle, deviation on (30) was 2 μm.

Equivalent to an accuracy of 1:2250.

There were larger deviations outside the range of traverse noted above, but these are not important as they were for smaller values of t_1 or t_2 than are permissible in the gauge as designed.

6.4. Test on Temperature of Baffle

The general assumption is made, in the design of circuits, that the temperature of the material surrounding the orifice is that of the incoming gas. This is not strictly true, as there is a predictable drop in the temperature of the gas in the sonic throat of $0{\cdot}165T$, so that when equilibrium is attained the metal in its close vicinity acquires a steady temperature distribution, ranging from some value below T up to T, on account of the heat flow in from the surrounding gas and metal at T to the gas at the reduced temperature in the throat. In practice, equilibrium is attained very quickly, and the temperature distribution is defined quite precisely for particular values of T, p and a, so no special complication arises.

However, it follows that there can be a small modifying factor to the theoretical behaviour of an orifice, especially of the double nozzle-baffle type, since expansion of the block has a direct effect on the orifice area.

To give some idea of the temperature drop which is experienced in practice, a test was carried out as in Fig. 28, the two jets being mounted in a watchmaker's lathe with a $T_1 T_2$ thermocouple between them. Aluminium alloy discs were cemented over the junction, forming some simulation of a baffle block, but the thermal equilibrium was almost entirely associated with forced convection and radiation, without the beneficial effect of metallic conduction which would apply to a practical system. The test conditions were: nozzle diameters 0·3 mm, total mass flow 60 mg/s, upstream pressure 370 kN/m^2.

The measured temperature drop turned out to be 10°C which is considerably less than the theoretical 48°C drop in the temperature of the gas as it passes through the orifice.

There is full recovery of temperature through turbulence at a short distance from the orifice. Increasing the flow, and thereby maintaining the sonic condition in the jets, the latter were separated from the thermocouple and the temperature recorded. It was found that the temperature rose progressively to the incoming value at a distance of 6 mm from the nozzles, so it was verified that the temperature deviation is quite local.

7. Tests on Micrometer Valve

With a view to determining the performance of the micrometer valve shown in Fig. 19 and at the same time getting further information on the behaviour of nozzle-baffle annular orifices, a circuit, shown in Fig. 20, which simulates in some degree the circuit of Fig. 6, was set up.

It will be seen that there are two lines, one of which includes the micrometer valve, and the other has in its place a multiple orifice, formed from standard orifice blocks. These are all fed in parallel, with short, equal-length tubes from a 12 mm diameter tube which acted as a manifold, the intention being to ensure that the applied pressure was exactly the same at each orifice of the group. The orifices v_1, v_2, etc., could be opened in turn by withdrawing stop ends, and since they discharged to the atmosphere they are termed the standard vents. The diameters of the vents, nominally equal, were such that the range of leak available was equivalent to the proposed range of the micrometer valve, thus with from 3 to 7 vents open, and the flowmeter stream issuing from an eighth orifice of the same size, the system was equivalent in principle, if not in absolute magnitude, to the two lines of the gas gauge circuit.

For calibration of the micrometer valve, it was desired to have strict linearity of increment of leak in the complementary line but the vents were not precisely equal. To give the required linearity an averaging system was devised.

With 3 and 7 vents open, the micrometer valve was adjusted until balance was obtained and single readings were taken at these two settings. For each intermediate value 4 readings were taken, with the vents 4, 5, 6 and 7 opened in cyclic order, and the average calculated. For example:

$$(v_1 + v_2 + v_3) + v_4 + v_5 \quad \text{first reading,}$$

$$(v_1 + v_2 + v_3) + v_5 + v_6 \quad \text{second reading,}$$

$$(v_1 + v_2 + v_3) + v_6 + v_7 \quad \text{third reading}$$

and

$$(v_1 + v_2 + v_3) + v_7 + v_4 \quad \text{fourth reading.}$$

If

$$(v_1 + v_2 + v_3) = \Sigma_0$$

and

$$(v_4 + v_5 + v_6 + v_7) = \Sigma_r,$$

the increments become

$$3 \text{ vents} = \Sigma_0 \qquad \text{(single reading)},$$

$$4 \text{ vents} = \Sigma_0 + \frac{\Sigma_r}{4} \qquad \text{(average of 4 readings)},$$

$$5 \text{ vents} = \Sigma_0 + \frac{\Sigma_r}{2} \qquad \text{(average of 4 readings)},$$

$$6 \text{ vents} = \Sigma_0 + \frac{3\Sigma_r}{4} \qquad \text{(average of 4 readings)}$$

and

$$7 \text{ vents} = \Sigma_0 + \Sigma_r \qquad \text{(single reading)}.$$

By this device exact linearity is attained.

A typical result is shown in Fig. 29, although a graph on this small scale cannot indicate the real precision of the test. It will be seen that the results are acceptably linear, so that it is possible to determine the zero by extrapolation. From the known areas of the vents, and assuming the measured diameter of the annulus, an estimate of the orifice gap was made, and the derived scale is inscribed on the right hand of the graph.

If the diameter of the sonic throat corresponds with that of the geometrical annulus, there should be negligible effect on the result if the feed pressure to the circuit is changed, but this is not in fact so. The insert graph shows the deviation from the original line when the flow is increased, which is attributed to increased diameter of the sonic throat at higher pressure, but it will be noticed that the error is virtually a straight line passing through zero flow. The implication is that if a system is such that a circular hole orifice is balanced against the nozzle-baffle orifice of the micrometer valve, it is necessary to set the output flow by adjusting the input to higher precision than was originally thought. However, since the gas gauge utilises nozzle-baffle orifices, there should be a fair degree of cancellation of this effect, with consequent reduction of criticality of setting of the input flow.

There was, as is expected with any circuitry in which gas flows are subject to sudden changes in direction, some turbulence within the system which manifests itself as fluctuation in pressure. The true amplitude of these fluctuations is difficult to measure, since there is always some attenuation through the appreciable volumes of the tubes and measuring instruments. The fluctuations are not of great consequence as they are small, and the average readings over short periods of time accurately represent those which would apply if the fluctuations did not exist.

As an indication of the order of the perturbation, the fluctuations of the differential micromanometer in the above experiments were ± 2 N/m^2 at a flowmeter pressure of 10 kN/m^2; this was equivalent to ± 1 μm on the micrometer, which is about one part in 6000 of the range.

8. Circuit Values for a Specific Problem

The circuit used is shown in Fig. 6 with some analysis in the Appendix. The strain gauge is the R.A.E.-S.I.R.A. design, with g_{94} ranging from 60 to 120 mg/s, g_{10} adjusted to the constant value of 15 mg/s and the permitted maximum length of 1·5 mm bore tubing between gauge and instrument station is 50 m. It is, of course, permissible with sonic orifice circuitry to use any length within this limit without modification to the circuit or operating conditions. The conditions of the structural test are assumed to be such that, at the limiting length, 30 m of tubing are always at 20°C, and the remaining 20 m can have any temperature between -40 and $+120$°C. The resistance of 1·5 mm bore tubing is given by $p_a^2 - p_b^2 = ALT/293$, A being read off from Fig. 9 for a particular mass flow. For a total length of tube made up of section ΔL at different temperatures, a modified value L' is calculated from $L' = \Sigma \Delta L'$ where $\Delta L' = \Delta L T/T_{20}$. For calculation T is of course in kelvins.

Three cases are of interest

Case 1. Strain gauge and 20 m of tubing at -40°C, 30 m at 20°C.
Case 2. Whole system at 20°C.
Case 3. Strain gauge and 20 m of tubing at $+120$°C, 30 m at 20°C.

The respective values of L' are 45·9, 50, and 56·8 m. The diameter of (32) is 120 μm, thus a_{32} is 0·0113 μm^2. The mass flow at -40°C through (32) is given by

$$g_{32} = 2{\cdot}36 \times 0{\cdot}0113 \times p_3(233/293)^{\frac{1}{2}}$$

i.e.

$$p_3 = 42{\cdot}1\, g_{32}. \quad (1)$$

For the sonic condition to apply at orifice (32) to an accuracy of 1 in 5000, p_2 must not be greater than $0{\cdot}3\, p_3$. With $p_1 = 110\,\text{kN/m}^2$ we have

$$p_2^2 = 45{\cdot}9\,\text{A} + (110)^2$$

therefore

$$p_3 \text{ not} < (510\,\text{A} + 13444)^{\frac{1}{2}}. \quad (2)$$

On plotting lines (1) and (2) they are found to intersect at $g_{32} = 14{\cdot}2$ mg/s and $p_3 = 600\,\text{kN/m}^2$.
At maximum temperature condition (120°C), and the minimum total flow g_{94} of 60 mg/s,

$$(p_3)_{120} = 600(393/233)^{\frac{1}{2}} = 732\,\text{kN/m}^2.$$

Thus

$$p_4^2 = 2800 \times 56{\cdot}8 + (732)^2,$$

$$p_4 = 835\,\text{kN/m}^2.$$

Therefore

$$p_9 = 835/0{\cdot}3 = 2{\cdot}783\,\text{MN/m}^2.$$

At maximum flow of 120 mg/s,

$$p_9 = 5{\cdot}566\,\text{MN/m}^2.$$

The area of (94) is given by the pressures corresponding to the above flows, i.e.

$$a_{94} = 60/(2{\cdot}36 \times 2783) = 0{\cdot}00913\,\mu\text{m}^2$$

and

$$d_{94} = 108\,\mu\text{m}.$$

The intermediate pressures have been calculated for the three cases, and they are tabulated below.

	mg/s	p_9 MN/m²	p_4 kN/m²	p_3 kN/m²	p_2 kN/m²	p_1 kN/m²
Case 1	60	2·783	699	600	178	110
	120	5·566	886	600	178	110
Case 2	60	2·783	770	671	183	110
	120	5·566	950	671	183	110
Case 3	60	2·783	835	732	191	110
	120	5·566	1032	732	191	110

In all cases p_4 is less than $0{\cdot}3p_9$, and p_2 is less than $0{\cdot}3p_3$, so the sonic condition is observed throughout, with flows through orifices independent of downstream pressure to 1 part in 5000.
From the specified flows, and the pressures of case 2 (room temperature throughout) orifice sizes are defined.

Input

$$60 \text{ mg/s at } 2{\cdot}783 \text{ MN/m}^2,$$

$$120 \text{ mg/s at } 5{\cdot}566 \text{ MN/m}^2,$$

$$a_{94} = a_{98} = 0{\cdot}00916 \ \mu\text{m}^2$$

and

$$d_{94} = 108 \ \mu\text{m}.$$

Variable orifice of gauge

$$\text{Minimum} \quad 45 \text{ mg/s at } 671 \text{ kN/m}^2,$$

$$\text{Maximum} \ 105 \text{ mg/s at } 671 \text{ kN/m}^2,$$

$$a_{30} \min = 0{\cdot}0284 \ \mu\text{m}^2$$

and

$$a_{30} \max = 0{\cdot}0663 \ \mu\text{m}^2.$$

Fixed orifice of gauge

$$15 \text{ mg/s at } 671 \text{ kN/m}^2,$$

$$a_{32} = 0{\cdot}00948 \ \mu\text{m}^2$$

and

$$d_{32} = 110 \ \mu\text{m}.$$

Subsonic orifice

$$a_{50} = a_{10} = 0{\cdot}127 \ \mu\text{m}^2$$

and

$$d_{50} = 402 \ \mu\text{m}.$$

9. Conclusions

The circuits and equipment which have been developed for gas gauge systems show good promise of meeting the requirement for the remote-indication of strains in adverse environments.

The principles of gas gauge circuitry have been discussed, and sufficient experiments have been carried out to demonstrate that high resolution and accuracy can be attained.

To achieve acceptable compactness in the gas gauge and circuitry, and to minimise the quantity of feed gas required, very small orifices are employed, and it has been shown that, provided simple precautions of cleanliness are observed, the circuits will behave with reliability and consistency over long periods of time.

The actual performance of gas strain gauges, which are under construction by another establishment, will be the subject of a future publication.

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LIST OF SYMBOLS

A	tube resistance coefficient	
a	area of orifice	μm^2
α	linear expansion coefficient	
C	sonic orifice coefficient	
K	subsonic orifice coefficient	
d	diameter of orifice	μm or mm
ε	strain	
θ	temperature difference from standard	K
g	mass flow	mg/s
h	constant	
$k_1, k_2, k_b,$ k_c, k_d, k_e	constants	
L	length of tubing	m
L'	equivalent length of tubing	m
μ	viscosity	
M, m, N, n	constants defining baffle or needle movement	
N_R	Reynolds number	
p	pressure	N/m^2, kN/m^2, or MN/m^2
Δp	pressure difference	N/m^2
t	nozzle-baffle orifice gap	μm
T	temperature	K
T_s	standard temperature	293 K
x	displacement of strain gauge needle or baffle	μm
X	displacement of micrometer valve needle or baffle	μm

Further suffixes are defined in Fig. 1.

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APPENDIX

Circuit Formulae

Formulae for the strain gauge circuits Figs. 2–6 are given below. The assumptions are made that orifice coefficients have the same value for all types of aperture, and that the temperature of the material of an orifice is that of the incoming gas. These assumptions are not strictly true, but the effects are such that readings will be subject to small modifying factors which will be taken out in calibration.

The basic formula for the flow through a sonic orifice is

$$g = Cap$$

where C and a are the values at the standard temperature of 20°C (293 K). Let $\theta = T - T_s$. At some temperature other than standard the flow is given by

$$g = Ca(1 + 2\alpha\theta)(1 + \theta/293)^{-\frac{1}{2}}p.$$

At standard temperature, the area of the strain gauge variable orifice is given by $a = m\varepsilon + n$ and of the micrometer valve by $a = Mx + N$, where x is the micrometer reading.

Figure 2

With the whole system at T_s

$$g_{32} = g_{10}$$

i.e.

$$Ca_{32}p_3 = Ca_{10}p_1, \qquad a_{10} = a_{32}p_3/p_1.$$

Therefore

$$\varepsilon = (a_{32}p_3/p_1 - n)/m.$$

With p_3 held constant ε is inversely related to p_1. In the other mode of use, with p_3 adjusted to bring p_1 to a standard value, the strain is linearly related to p_3.

When temperatures are not standard

$$Ca_{32}(1 + 2\alpha_{32}\theta_3)(1 + \theta_3/293)^{-\frac{1}{2}} = Ca_{10}(1 + 2\alpha_{10}\theta_1)(1 + \theta_1/293)^{-\frac{1}{2}}.$$

Thus a knowledge of the temperatures at both instrument station and strain gauge is necessary for accuracy.

Figure 3

p_5 is adjusted to bring p_1 to a standard value, which implies that g_{10} is held constant if T_1 and p_0 are constant. We have

$$g_{54}/g_{10} = (Ca_{30}p_3 + Ca_{32}p_3)/Ca_{32}p_3$$

$$= (a_{30} + a_{32})/a_{32}.$$

Thus

$$a_{30} = a_{32}(g_{54}/g_{10} - 1) = m\varepsilon + n$$

$$\varepsilon = a_{32}(Ca_{54}p_5/g_{10} - 1)/m - n/m,$$

which is of form

$$\varepsilon = k_a p_5 - k_b.$$

Note that $(a_{30} + a_{32})/a_{32}$ is independent of the gauge temperature if the orifices are of the same material. However, readings will be dependent on temperature to the extent of

$$g_{54} = Ca_{54}(1 + 2\alpha_{54}\theta_5)(1 + \theta/293)^{-\frac{1}{2}}p_5$$

and

$$g_{10} = C'a_{10}(1 + 2\alpha_{10}\theta_1)(1 + \theta/293)^{-\frac{1}{2}}(p_1^2 - p_0^2)^{\frac{1}{2}} \quad \text{(subsonic)}.$$

Also, variations in the ambient pressure p_0 will affect the observation.

Figure 4

The micrometer balanced valve is adjusted so that p_{71} is zero, i.e. $g_{10} = g_{70}$, since $a_{10} = a_{70}$. As (54) and (50) are at the same temperature

$$g_{54} = g_{96}a_{54}/(a_{50} + a_{54}).$$

The valve needle is designed so that the total orifice area is constant, i.e.

$$a_{50} + a_{54} = a_{40}.$$

Therefore

$$g_{54} = g_{96}(Mx + N)/a_{40}.$$

At the gauge $a_{30} = a_{32}(g_{54}/g_{10} - 1)$

$$m\varepsilon + n = a_{32}\{(Mx + N)g_{96}/g_{10}a_{40} - 1\}. \tag{A.1}$$

Now

$$g_{96} = Ca_{96}p_9(T_9/T_s)^{-\frac{1}{2}}$$

and

$$g_{98} = Ca_{98}p_9(T_9/T_s)^{-\frac{1}{2}}$$

therefore

$$g_{96} = g_{98}a_{96}/a_{98}.$$

Also

$$g_{10} = ka_{10}(p_1^2 - p_0^2)(T_1/T_s)^{-\frac{1}{2}}$$

and

$$g_{70} = ka_{70}(p_7^2 - p_0^2)(T_7/T_s)^{-\frac{1}{2}}.$$

As $p_1 = p_7$ at balance, and $T_1 = T_7$,

$$g_{10} = g_{70}a_{10}/a_{70} = g_{98}a_{10}/a_{70},$$

therefore

$$g_{96}/g_{10} = a_{96}a_{70}/a_{10}a_{98}.$$

Substituting in (A.1)

$$\varepsilon = a_{32}\{(Mx + N)a_{96}a_{70}/a_{40}a_{10}a_{98} - 1\}/m - n/m$$

which is of the form

$$\varepsilon = k_c x - k_d.$$

The reading is independent of temperature provided that

$$T_{96} = T_{98}, \quad T_{54} = T_{50}, \quad T_{32} = T_{30} \quad \text{and} \quad T_{10} = T_{70}$$

which should be easy to observe with the components of the pairs in close proximity.

Figure 5

Here the active line [943 $\bar{0}$ 210] and the reference line [987 $\bar{0}$ 650] are fully analogous, but the flow in the reference line is a multiple h of that in the active line, the areas of orifices being in this ratio. As with the previous circuit, provided that the components of orifice pairs are at the same temperature:

$$g_{10} = g_{94}a_{32}/(a_{30} + a_{32}) = g_{94}a_{32}/a_{20}$$

$$g_{50} = g_{98}a_{76}/(a_{70} + a_{76}) = g_{98}a_{76}/a_{60}.$$

Since $g_{50} = hg_{10}$ at balance and $g_{94} = hg_{98}$,

$$a_{32}/a_{20} = a_{76}/a_{60}$$

and

$$(m\varepsilon + n)a_{60} = (Mx + N)a_{20}.$$

The valve is designed so that $N/n = a_{60}/a_{20}$, therefore

$$\varepsilon = (M/m)x.$$

The relation between ε and x is thus direct and fully independent of temperature.

Figure 6

This circuit is recommended for general use. Again, the reference and active lines are analogous, but in this case, following the development of an accurate cantilever valve, the flows g_{98} and g_{94} can be made equal. Equality of temperature of orifice pair components is again implied. We have:

$$g_{94} = g_{98},$$

$$g_{10} = g_{50} \quad \text{at balance}$$

and

$$g_{30} = g_{70}, \quad g_{32} = g_{76}.$$

Since $a_{32} = a_{76}$, it follows that $a_{30} = a_{70}$ at balance. So

$$m\varepsilon + n = Mx + N$$

$$\varepsilon = (Mx + N - n)/m.$$

Thus x is proportional to ε and the system is independent of temperature.

However, the sensitivity of detection of balance on operation of the micrometer valve will vary throughout the range. This sensitivity can be expressed as dp_5/da_{70}.

At the subsonic orifice (50)

$$g_{50} = Ka_{50}(p_5^2 - p_0^2)^{\frac{1}{2}},$$

$$dp_5/dg_{50} = g_{50}/K^2a_{50}^2p_5.$$

As $p_5 - p_0$ is small, p_5 can be assumed to be constant. Calling the constant denominator $1/R$,

$$dp_5/dg_{50} = Rg_{50} = Rg_{98}a_{76}/(a_{76} + a_{70}),$$

$$g_{76} = g_{50} = g_{98}a_{76}/(a_{76} + a_{70}),$$

$$dg_{50}/da_{70} = -g_{98}a_{76}/(a_{76} + a_{70})^2,$$

therefore

$$dp_5/da_{70} = -Rg_{98}^2a_{76}^2/(a_{76} + a_{70})^3.$$

If g_{98} is maintained constant

$$dp_5/da_{70} \propto (a_{76} + a_{70})^{-3}.$$

If $p_1 = p_5$ is brought to a constant value before balancing by adjusting p_9

$$g_{98} = g_{50}(a_{76} + a_{70})/a_{76}.$$

So

$$dp_5/da_{70} \propto (a_{76} + a_{70})^{-1}.$$

The change in sensitivity over the strain range is thus much less, and this is the recommended mode of use of the circuit.

Alternative forms of input are shown in the figure. These permit the input pressure to be reduced—an advantage when lines are long. The first device is a double valve. Pressure p_3 is maintained constant, and $g_{31} = g_{32}$, these being varied by opening or closing the linked baffles.

The second type of input makes use of a pair of diaphragm pressure equalisers. The leaks into the two lines, g_{31} and g_{32} automatically adjust to maintain the downstream pressures of the subsonic orifices $(43)_a$ and $(43)_b$ at the constant value p_3. The flows are changed by changing p_4 which can be considerably lower than p_9 of the main circuit. The flow in either line is given by

$$g_{43} = Ka_{43}(p_4^2 - p_3^2)^{\frac{1}{2}},$$

thus it does not have a linear relation with p_4.

TABLE 1

Quantity	Symbol	Basic SI unit	Practical SI unit
Length	L	m	m
Diameter	d	m	mm or μm
Area	a	m	μm^2
Pressure	p	N/m^2	N/m^2 or kN/m^2
Temperature	T	K	K
Mass flow	g	kg/s	mg/s

Resistance of tubes

Transition from laminar to turbulent flow (for straight tube) occurs at N_R about 2100

$$N_R = 70\,g/d,$$

Laminar $\qquad p_1^2 - p_2^2 = (150\,gL/d^4)(\mu/\mu_0), \qquad \mu/\mu_0 \simeq 1 + 0{\cdot}00320\theta,$

Turbulent $\qquad p_1^2 - p_2^2 = (4{\cdot}5\,g^2L/d^5)(T/293).$

Sonic orifice

$$g = [(\gamma m/R)\{2/(\gamma + 1)\}^{(\gamma+1)/(\gamma-1)}]^{\frac{1}{2}} apT^{-\frac{1}{2}}.$$

For air $\gamma = 1{\cdot}401$, $R = 8314$, $m = 28{\cdot}97$. Thus

$$g = 2{\cdot}36ap(293/T)^{\frac{1}{2}}.$$

Sonic pressure ratio for air = 0·53,

Pressure in throat = $0{\cdot}532p$,

Temperature in throat = $0{\cdot}835T$.

Subsonic orifice

$$g = 2{\cdot}58a(p_1^2 - p_2^2)^{\frac{1}{2}}(293/T)^{\frac{1}{2}}.$$

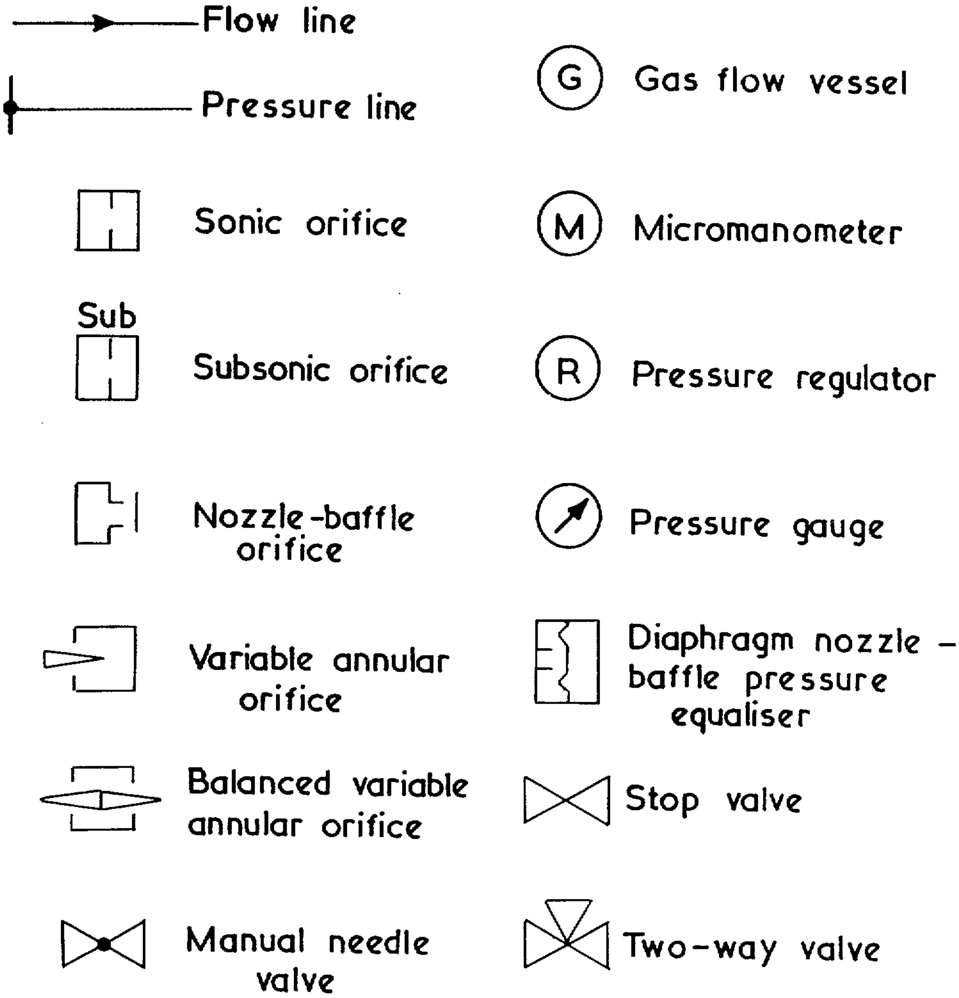
TABLE 2

Orifice quality	Diameter μm	Oven temperature C	K	Flow mg/s	C
Good	112·5	22	295	29·07	2·29
				11·73	2·30
		174	447	27·32	2·30
				14·32	2·29
Poor	109	22	295	28·12	2·20
				14·12	2·15
		172	445	23·88	2·16
				12·66	2·15

TABLE 3

Coefficients of Punched Orifices from Flow Measurement
Nominal Value = 2·36

Mass flow mg/s	38·14		33·49		28·78		23·46		16·58		11·78		8·22	
Orifice diam., μm	p_3 kN/m^2	c	p_3	c	p_3	c	p_3	c	p_3	c	p_3	c	p_3	c
96							1446	2·24	1020	2·25	726	2·24	507	2·24
124·5	1393	2·25	1228	2·24	1054	2·25	852	2·27	598	2·28	421	2·30	294	2·30
157·5	872	2·25	769	2·24	658	2·25	531	2·27	374	2·28	264	2·29		
170	755	2·24	664	2·23	567	2·24	461	2·24	323	2·27	228	2·28		
183	645	2·25	565	2·25	484	2·27	390	2·29	274	2·30				
184	645	2·23	563	2·24	484	2·24	390	2·27	274	2·28				
190	607	2·22	533	2·22	458	2·22	370	2·24	260	2·25				
205	521	2·22	459	2·22	393	2·22	317	2·24	222	2·27				
208	496	2·27	437	2·26	374	2·27	302	2·23	212	2·30				
238	382	2·24	335	2·25	288	2·25	231	2·28						
257	323	2·28	285	2·27	244									
283	275	2·21												



Digits on a circuit diagram are pressure suffixes, decreasing in magnitude in the direction of flow, thus: $p_5 > p_4$. Ambient pressure is p_0. Positions with the same digit have negligible tube resistance between them. Lines can be identified by a succession of these digits in square brackets, branches being indicated by a bar, viz., [954$\bar{0}$3210]. A component such as a valve or orifice is specified by the straddling digits in curved brackets thus: (32). Quantities such as mass flow, orifice area, and temperature are identified by suitable suffixes, e.g. g_{95}, a_{32}, or T_3.

FIG. 1. Circuit code.

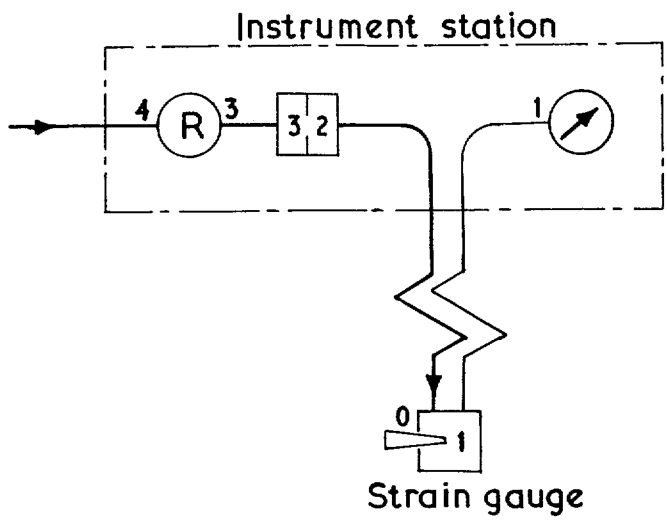


FIG. 2

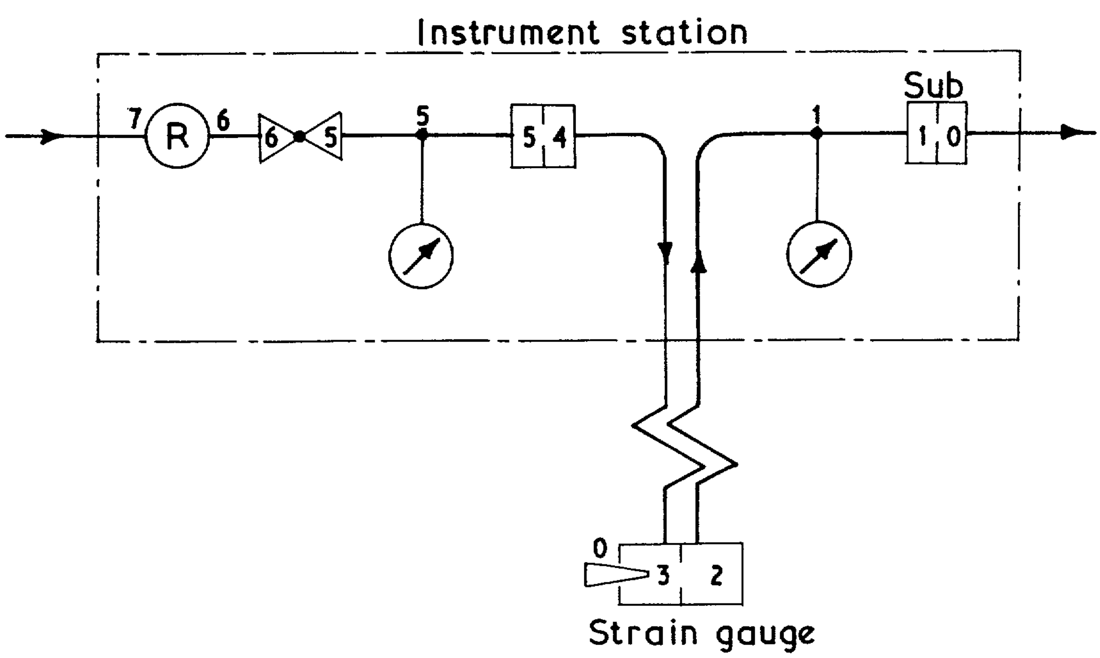


FIG. 3

FIGS. 2 and 3. Circuit diagrams.

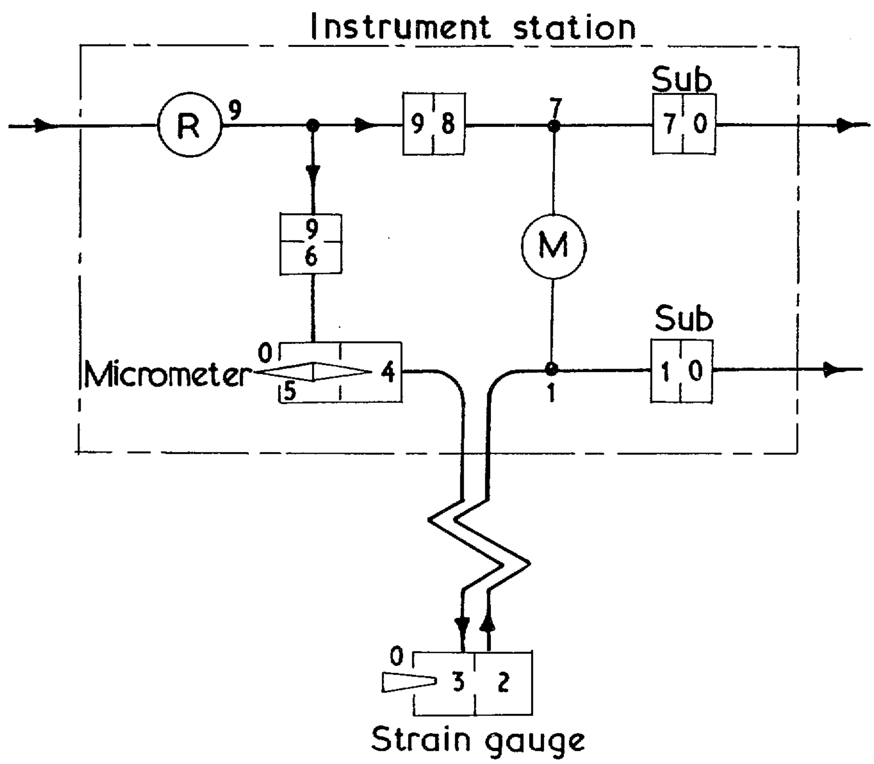


FIG. 4

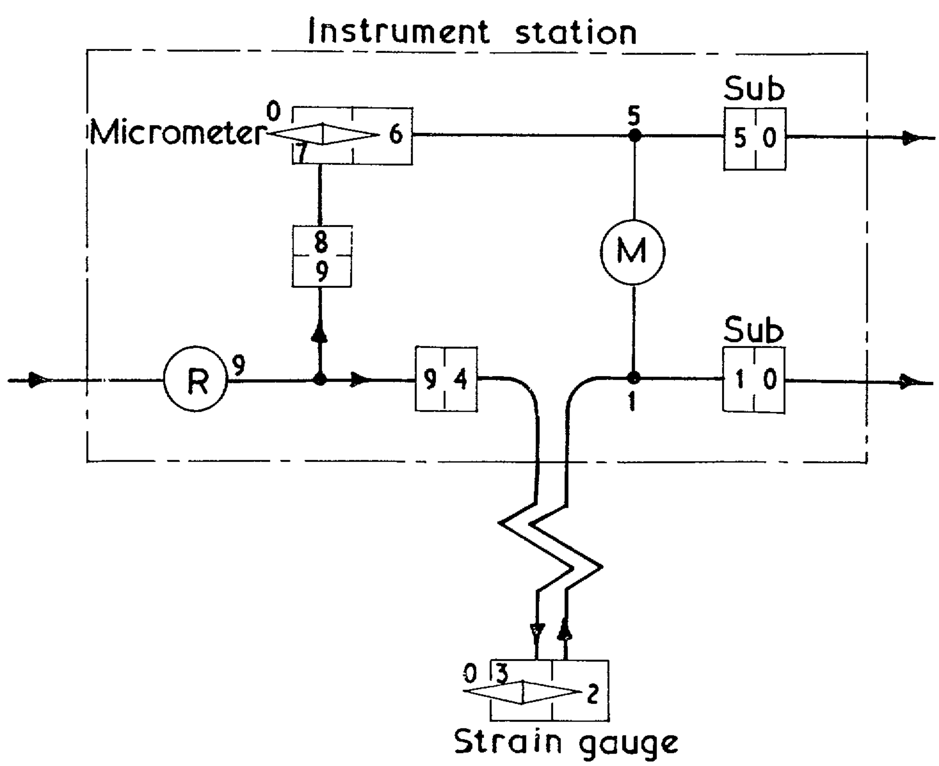


FIG. 5

FIGS. 4 and 5. Circuit diagrams.

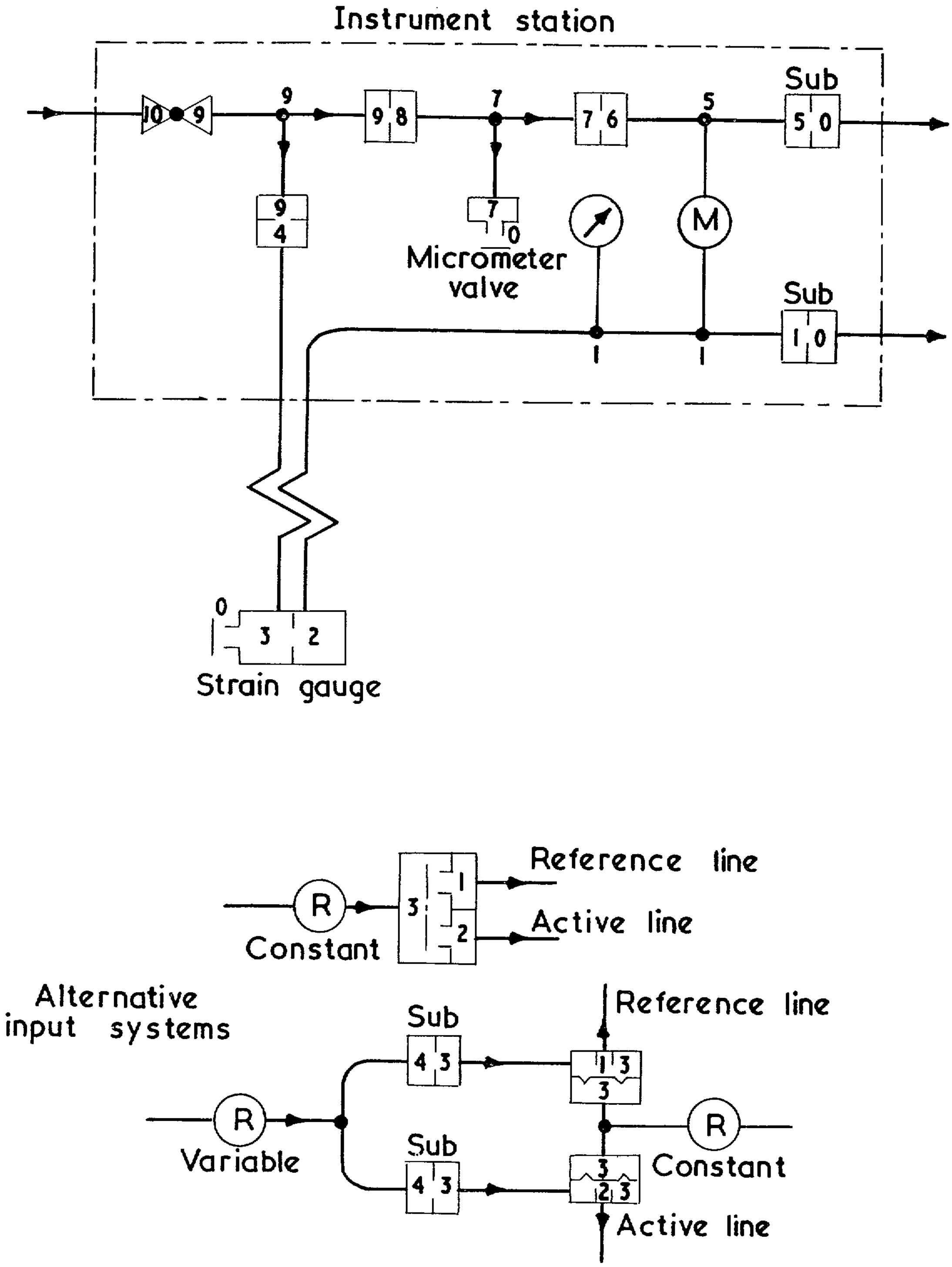


FIG. 6. Circuit diagram and alternative inputs.

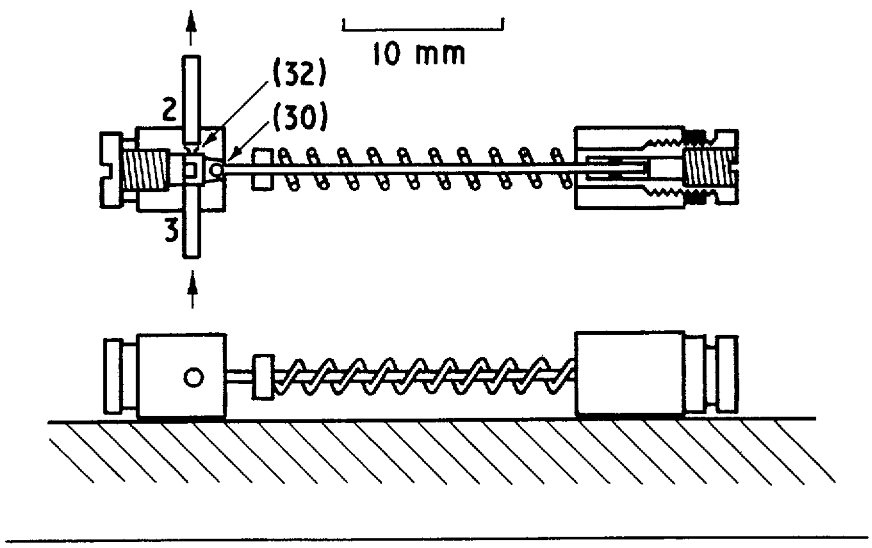


FIG. 7

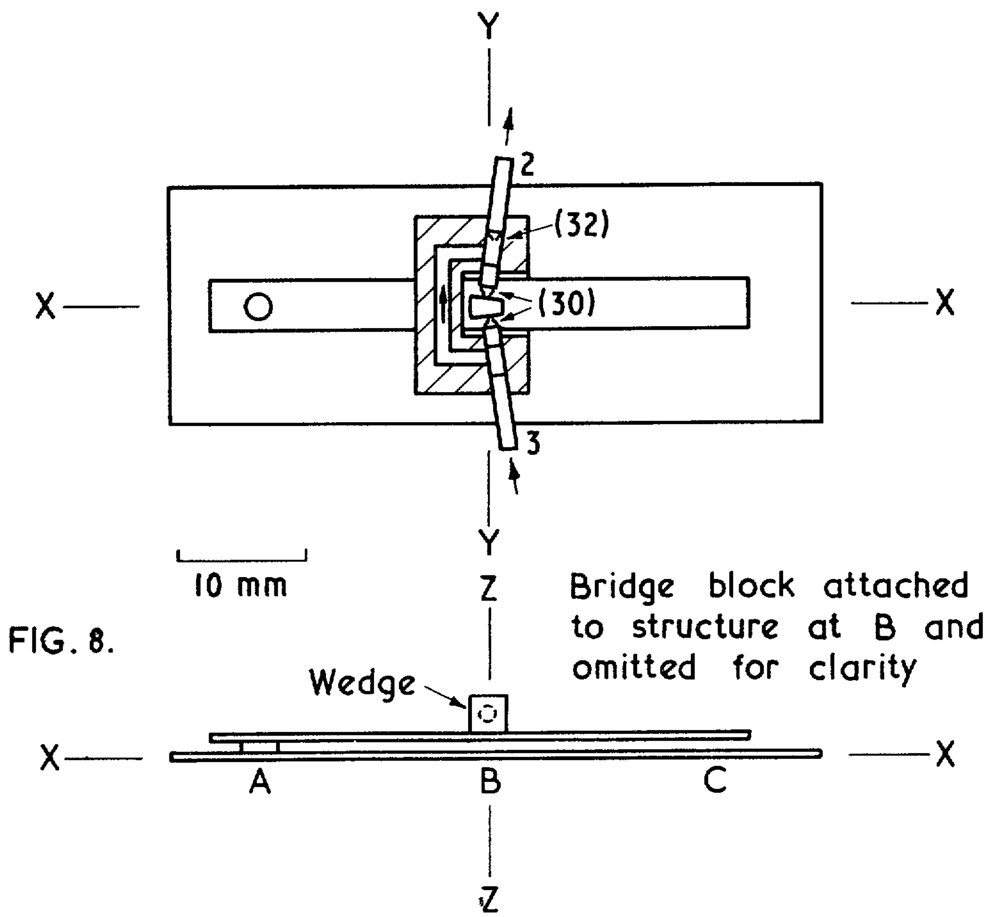


FIG. 8

FIGS. 7 and 8. Two designs of strain gauge.

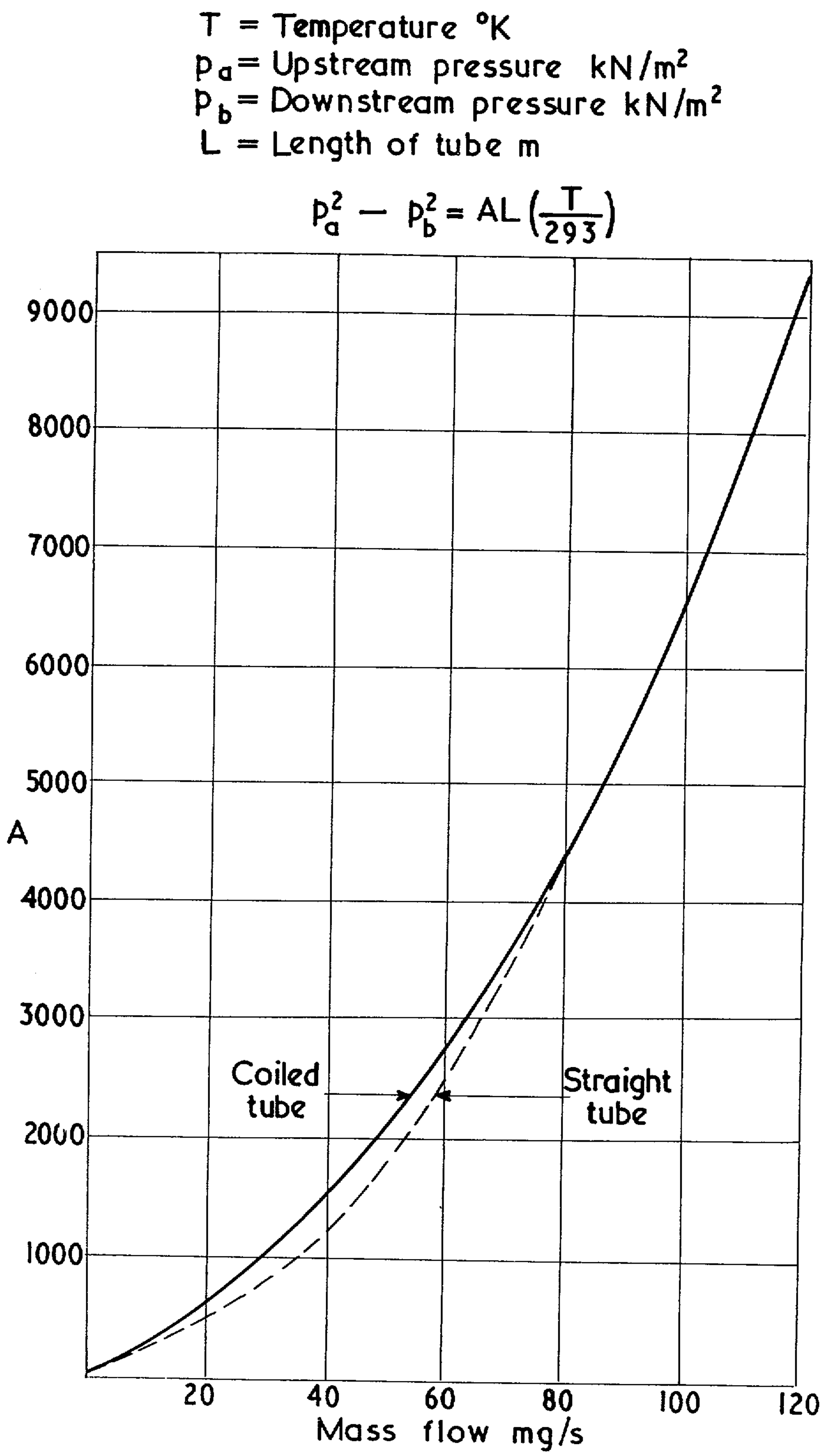


FIG. 9. Resistance of 1·5 mm bore tubing.

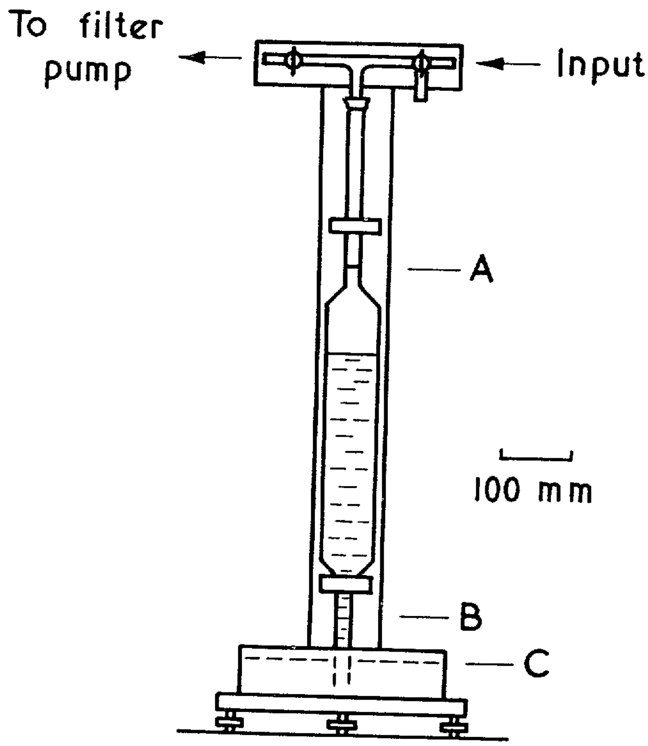


FIG. 10. Gas flow vessel.

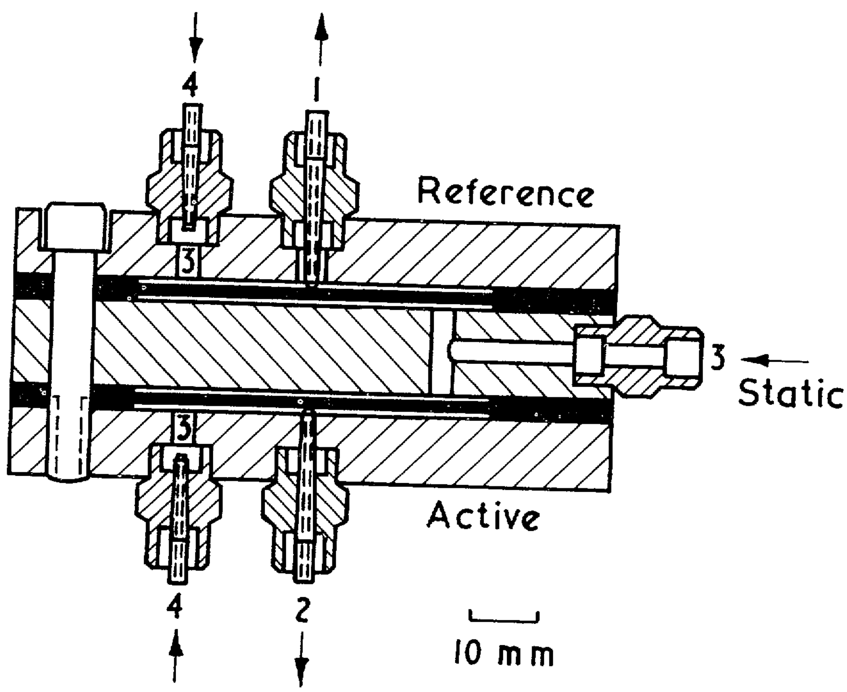


FIG. 11. Diaphragm pressure equaliser.

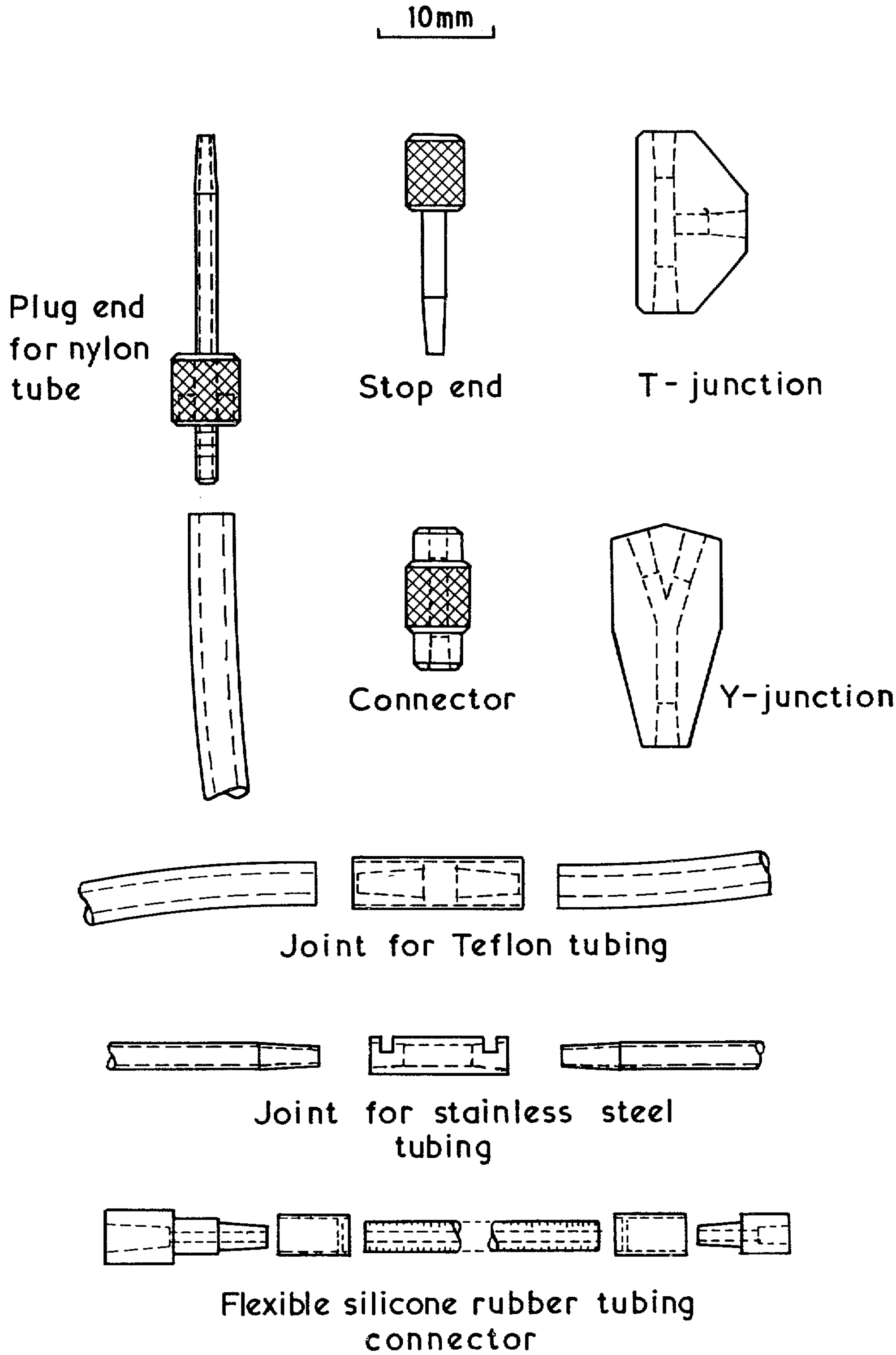


FIG. 12. Tube connections.

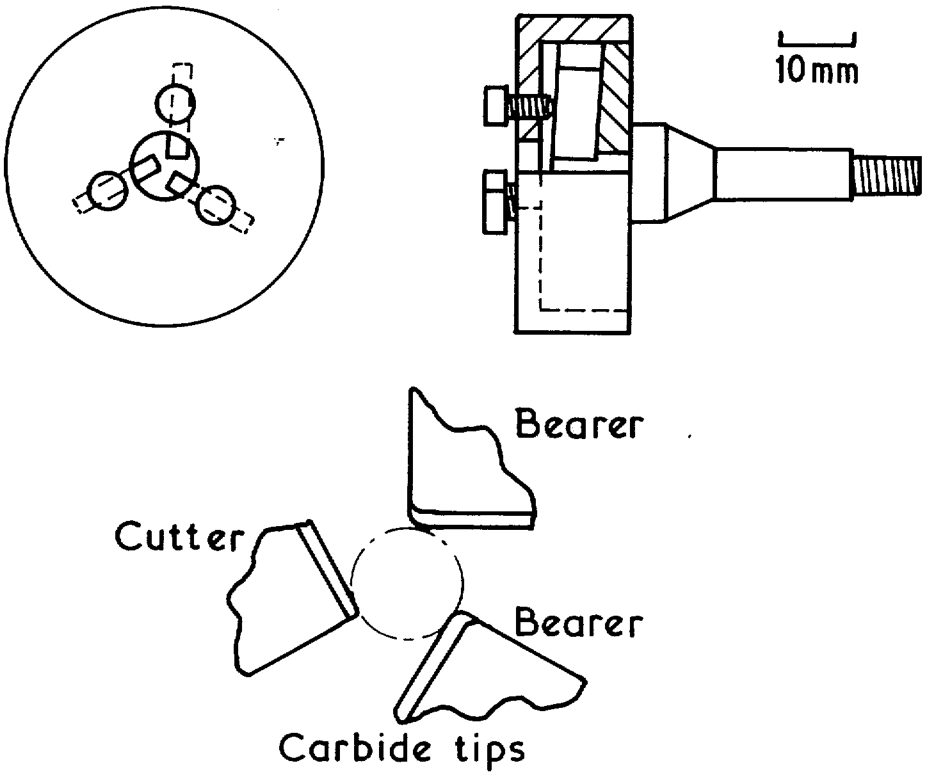


FIG. 13. Taper cutter for stainless steel tubing.

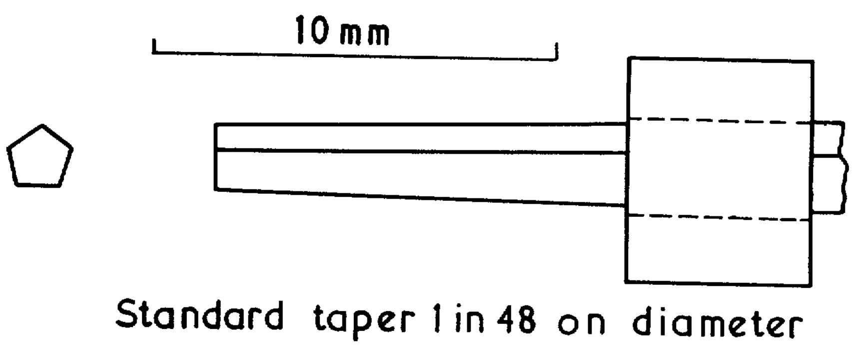


FIG. 14. Broach for brass sockets.

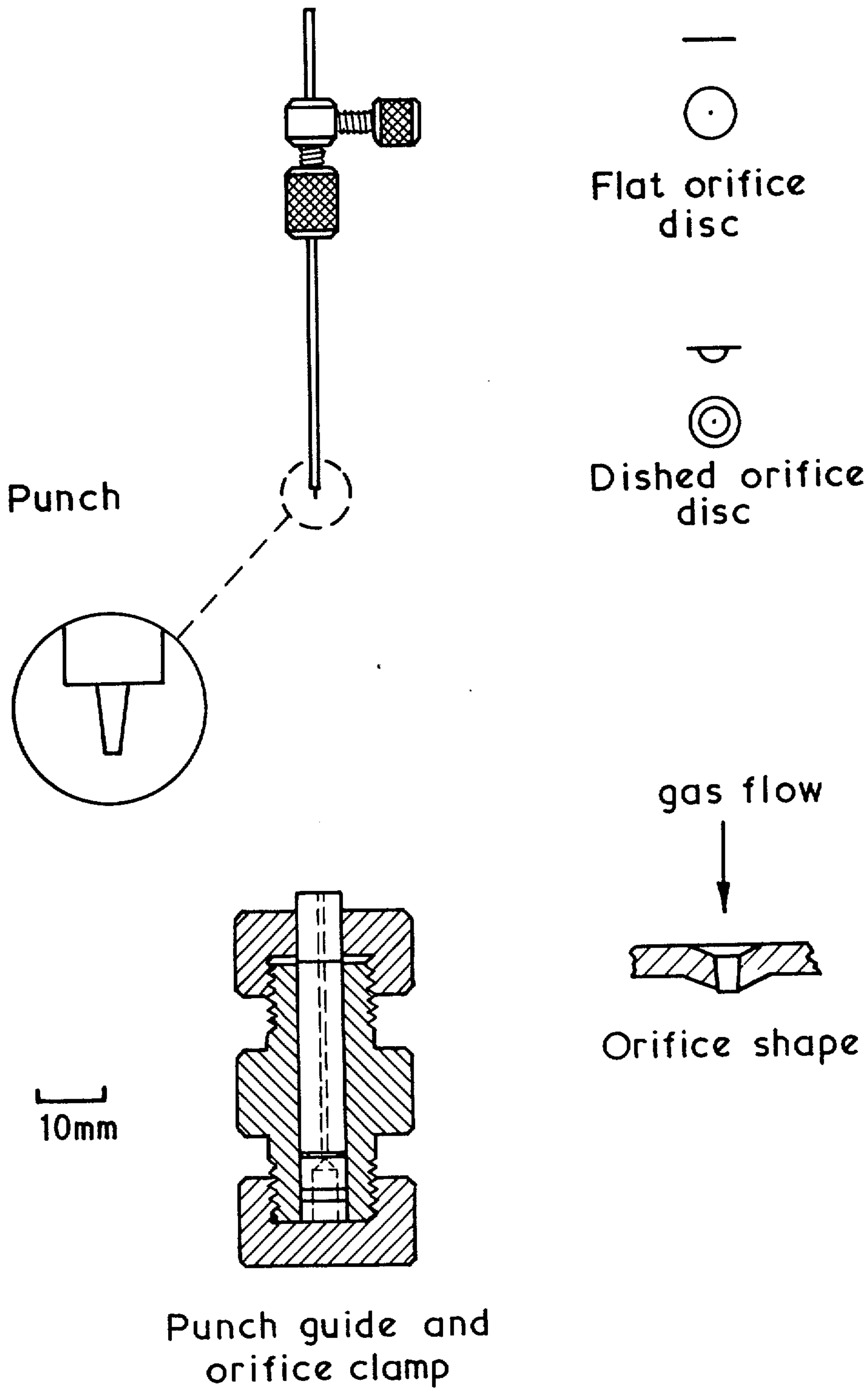


FIG. 15. Orifice punch.

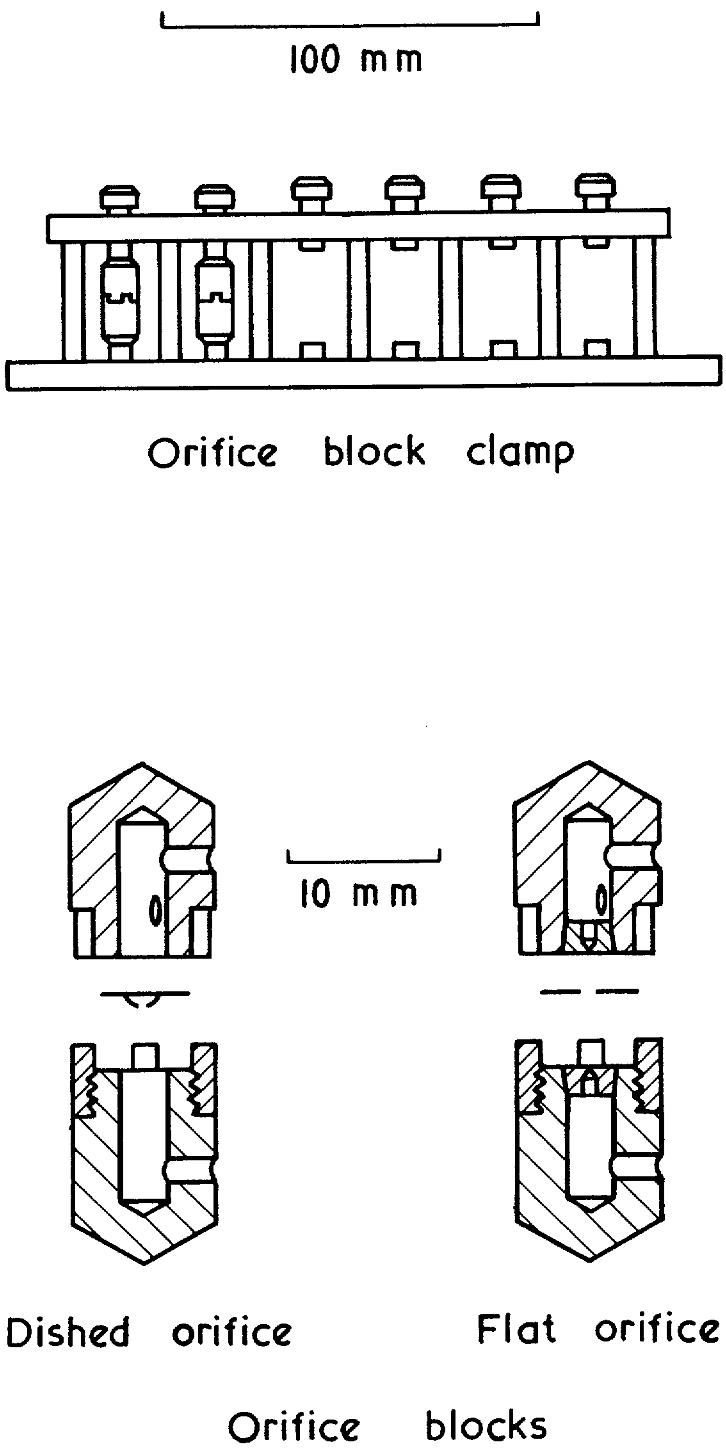


FIG. 16. Orifice blocks and clamp.

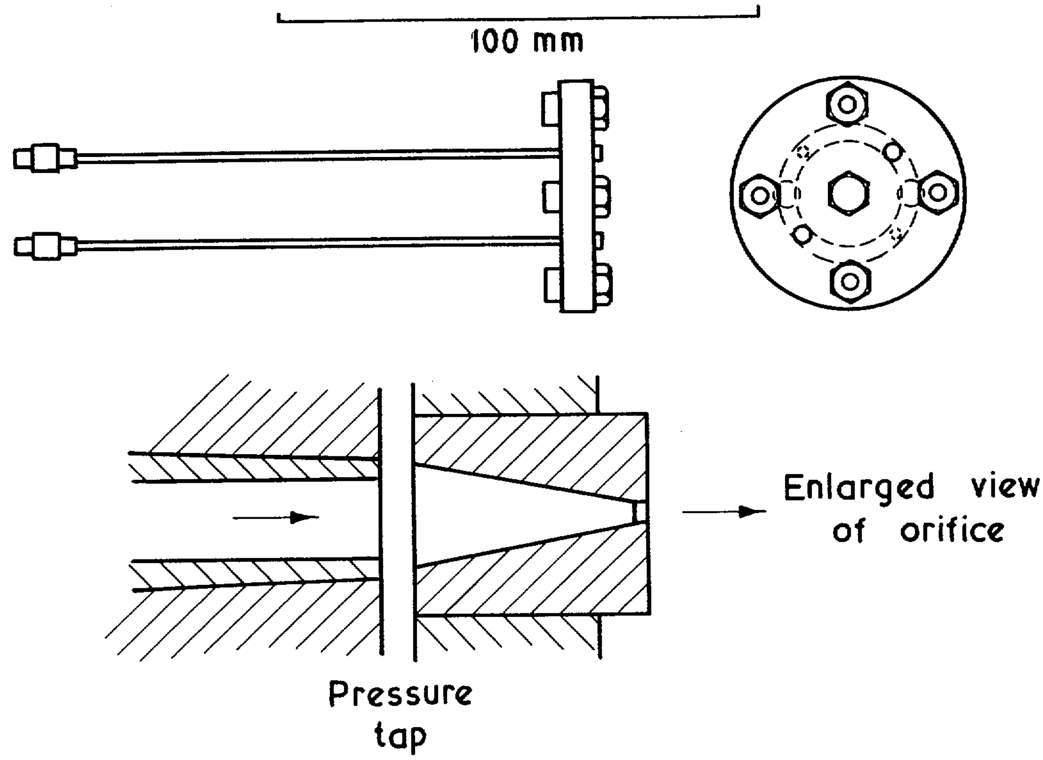


FIG. 17. Outlet subsonic orifices.

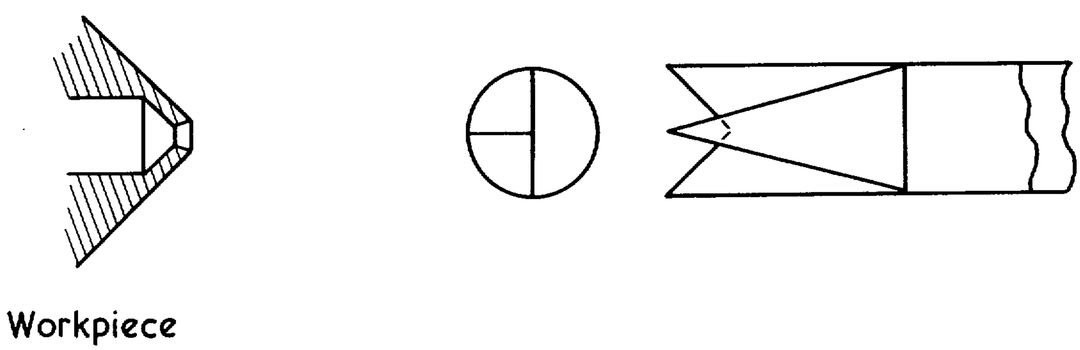


FIG. 18. Cutter for sharp-edged orifice.

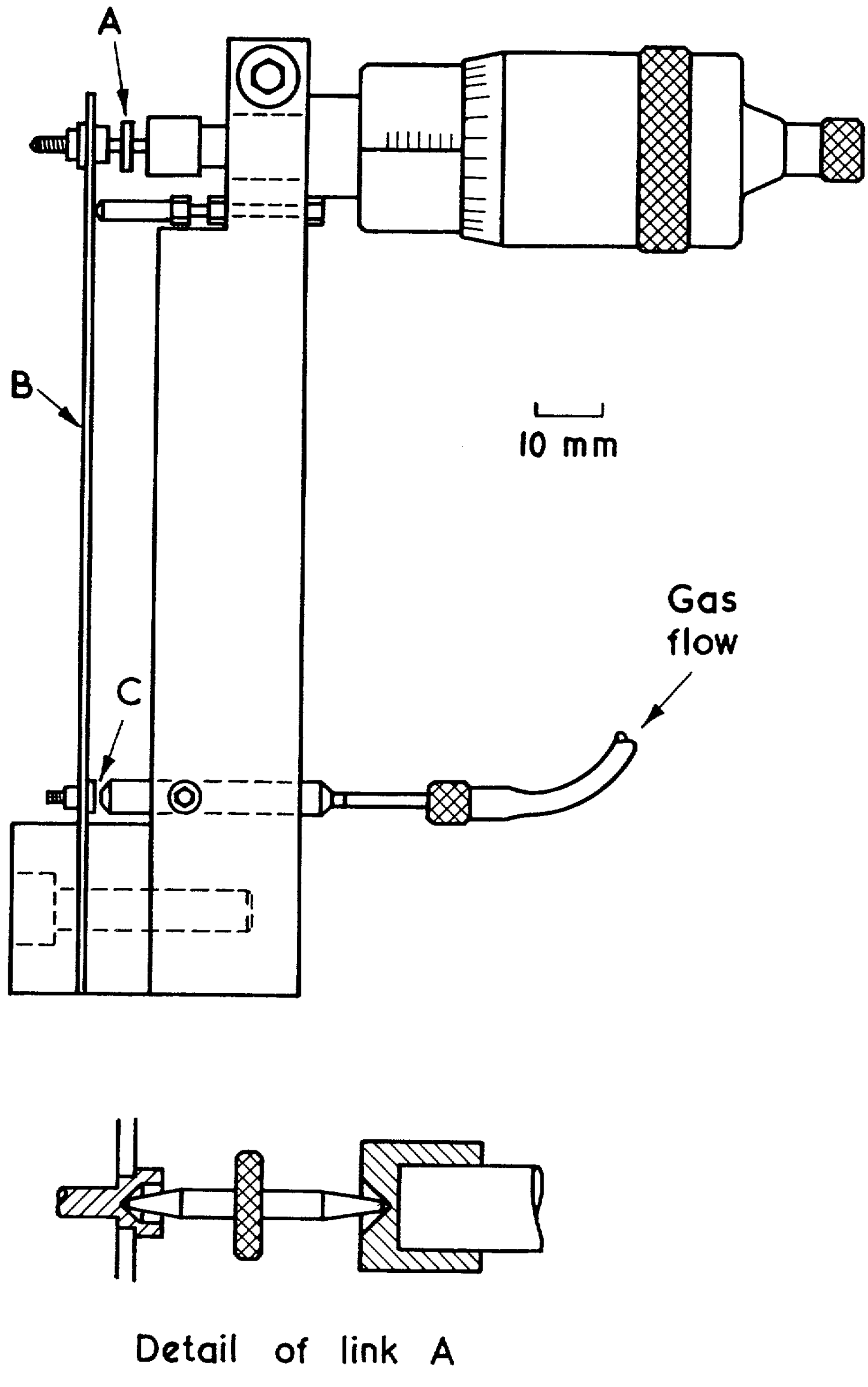


FIG. 19. Micrometer leak valve.

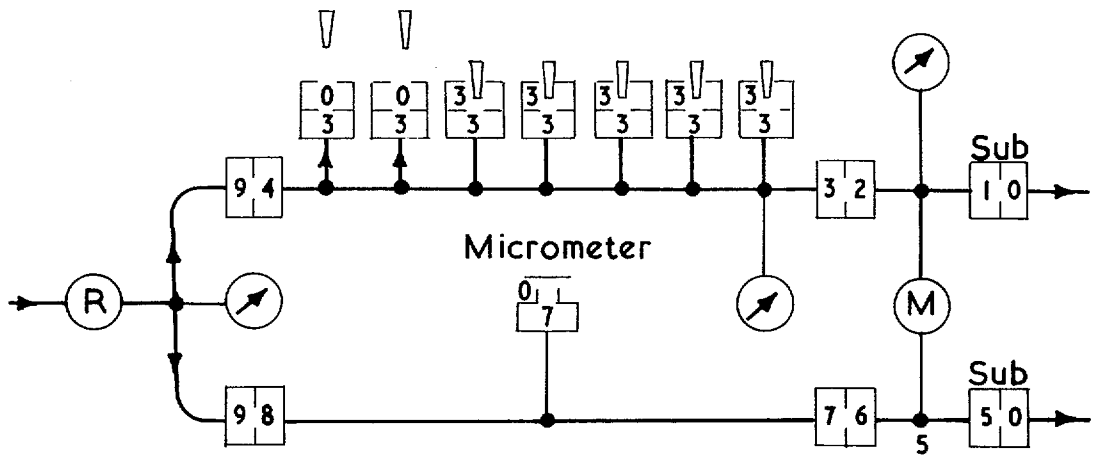


FIG. 20. Test on performance of micrometer valve.

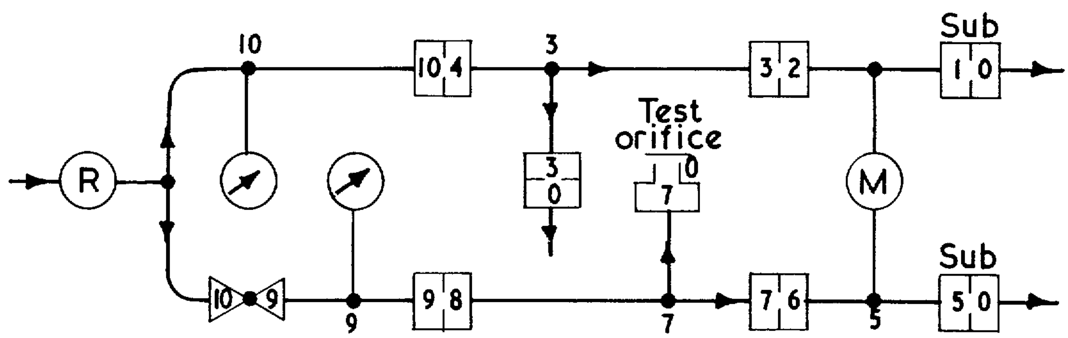


FIG. 21. Test on linearity of nozzle-baffle orifice.

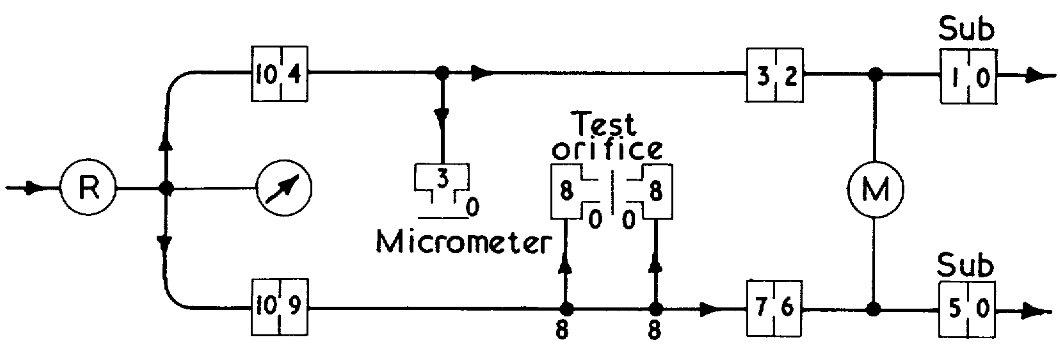


FIG. 22. Test on balance of double nozzle-baffle orifice.

FIGS. 20, 21 and 22. Test circuitry.

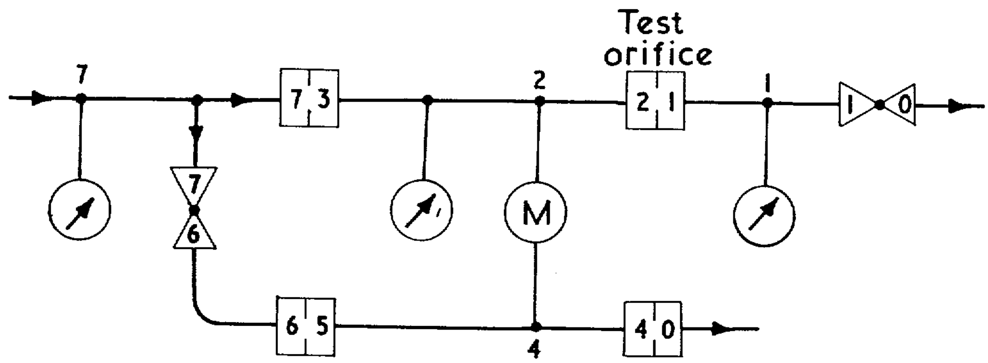


FIG. 23. Test to determine limiting pressure ratio across orifice (21) for flow to be independent of downstream pressure.

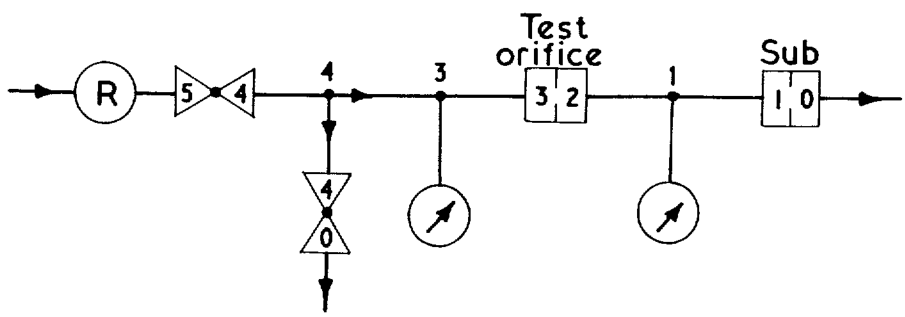


FIG. 24. Test to determine orifice coefficient.

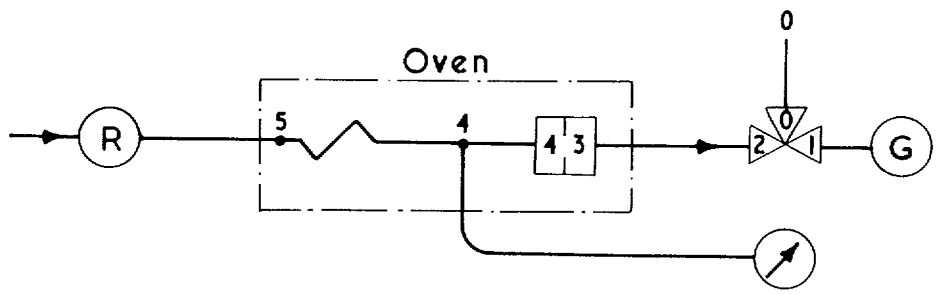


FIG. 25. Test to verify dependence of mass flow on temperature.

FIGS. 23, 24 and 25. Test circuits.

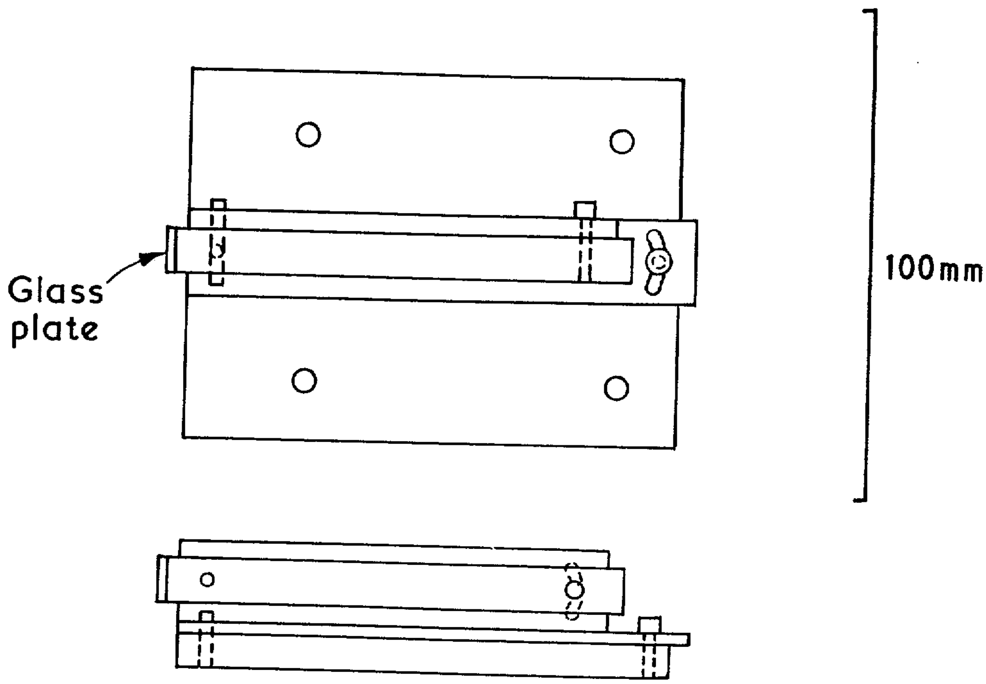


FIG. 26. Baffle with angular adjustment.

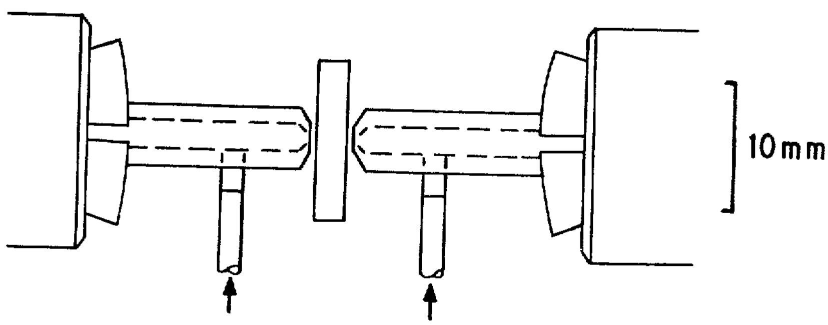


FIG. 27. Test on balance of double nozzle-baffle.

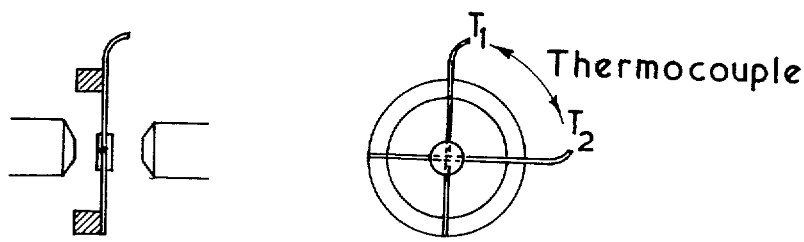


FIG. 28. Test on temperature of baffle.

FIGS. 26, 27 and 28. Equipment for tests on nozzle-baffle orifices.

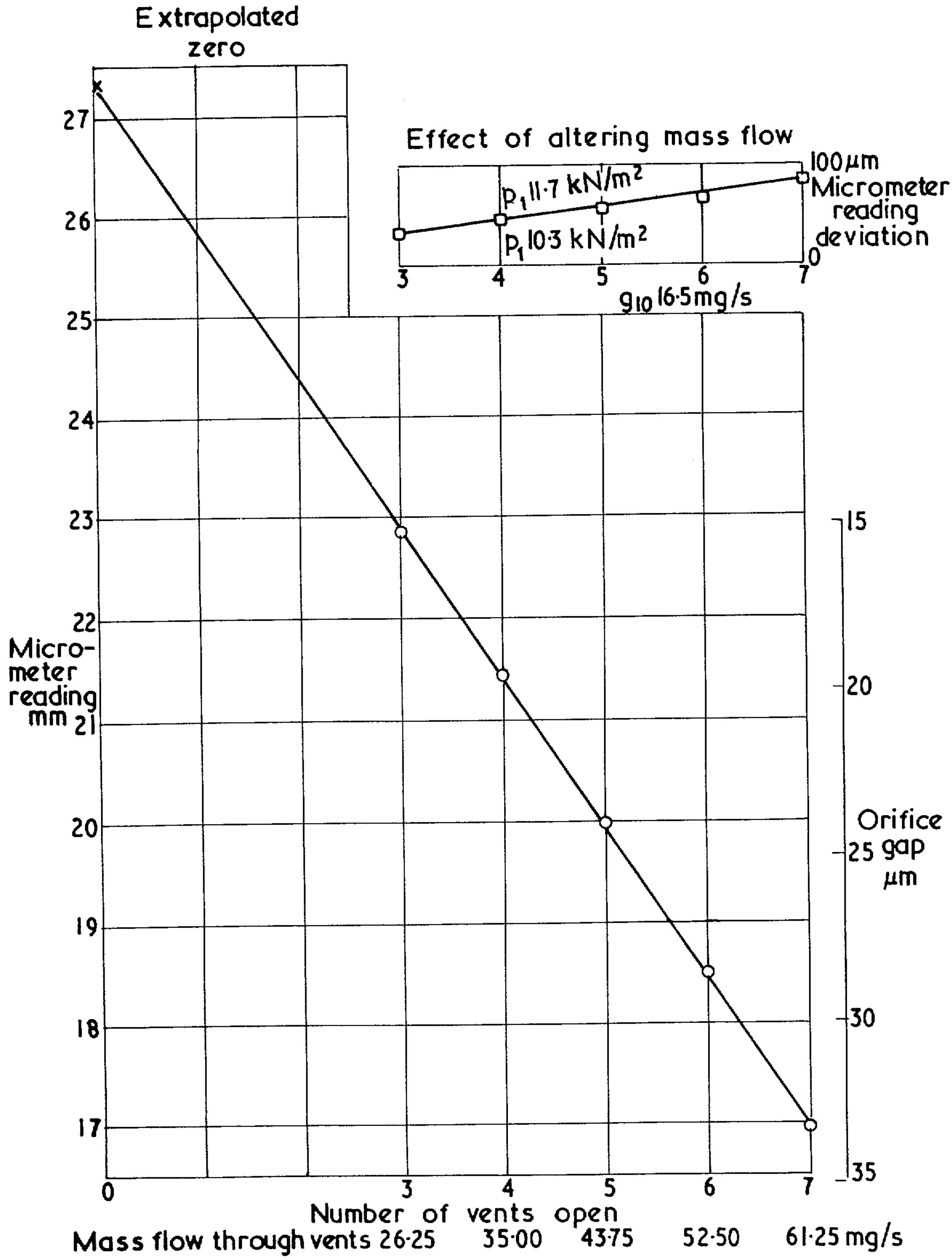


FIG. 29. Performance of micrometer valve.

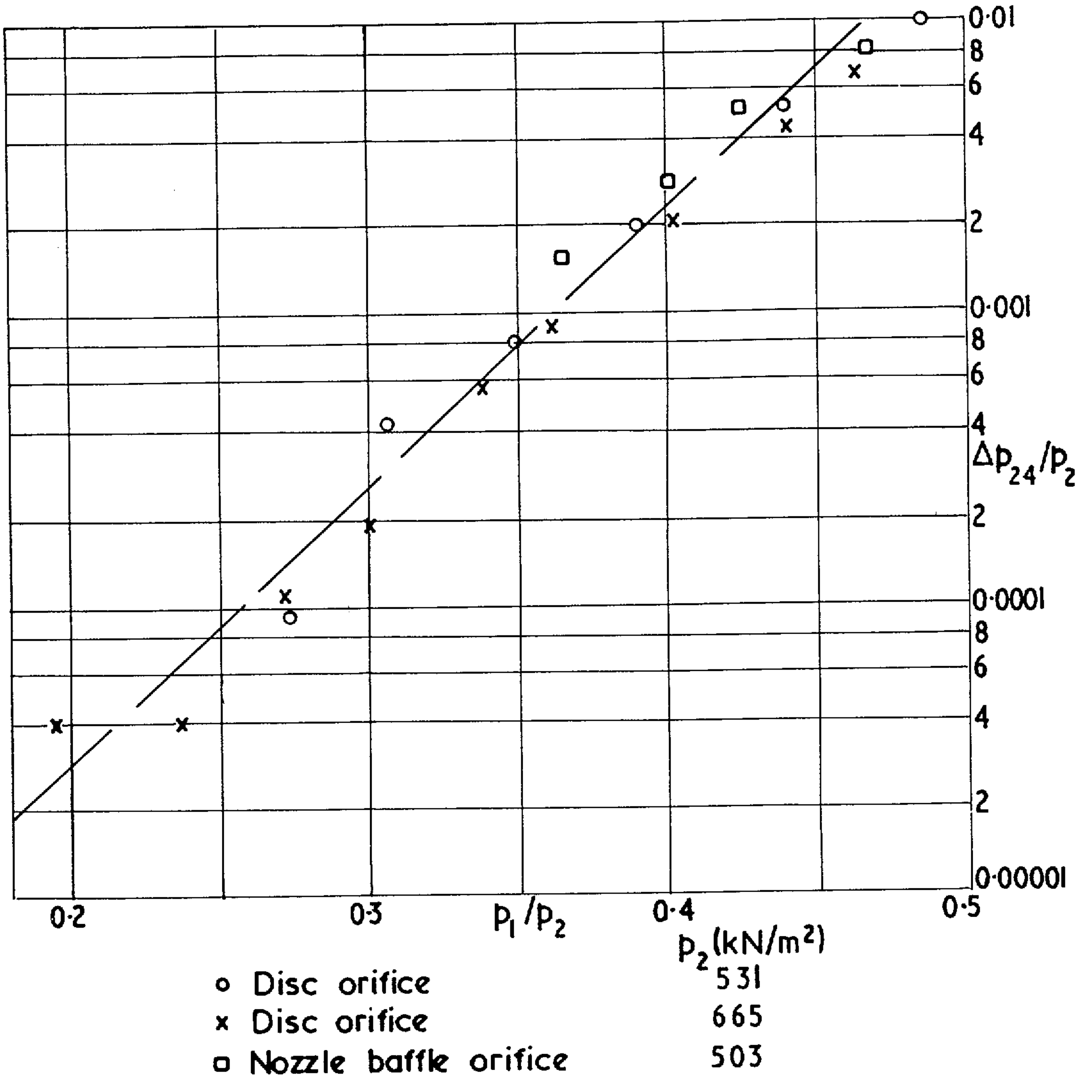


FIG. 30. Effect of downstream pressure on mass flow through sonic orifice.

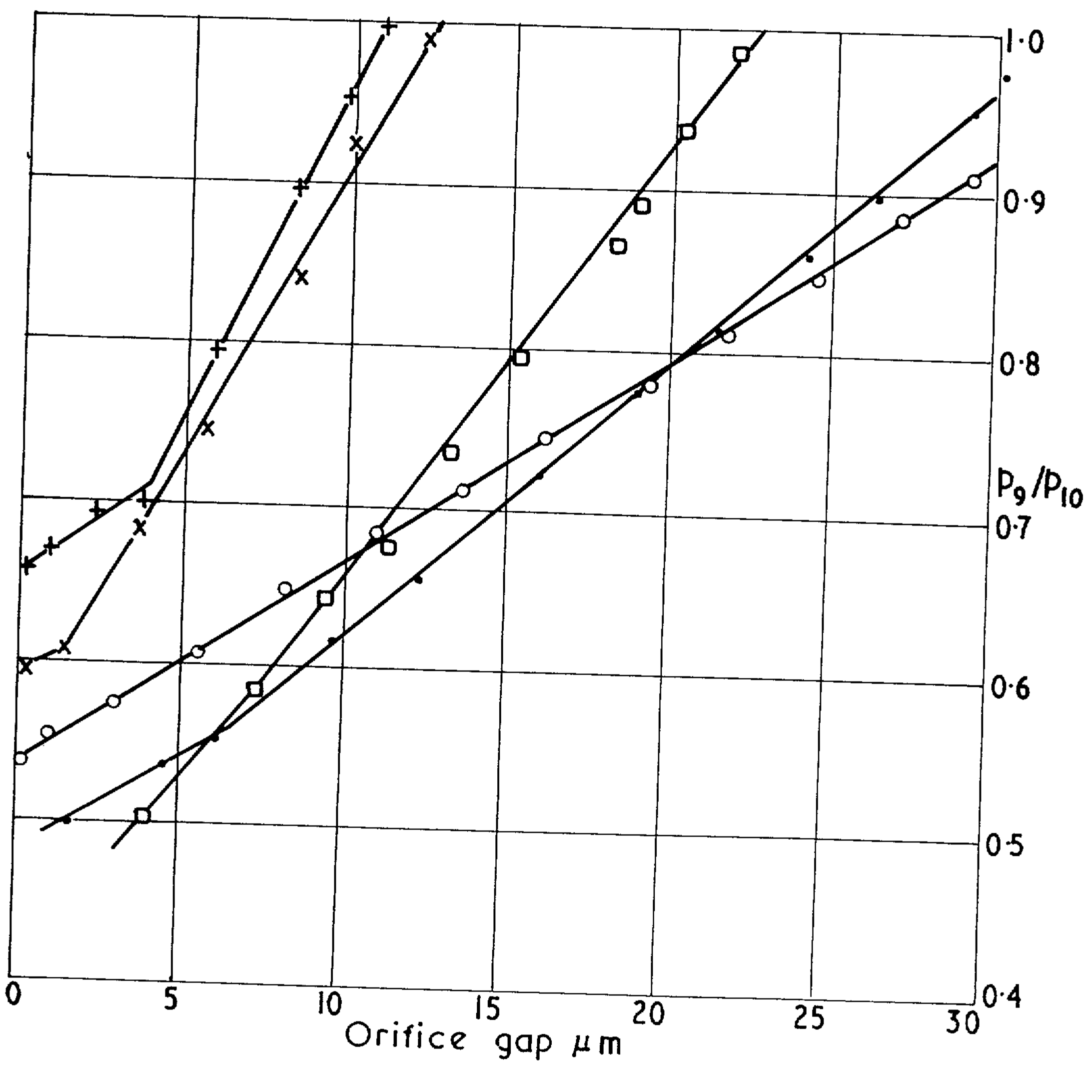


FIG. 31. Linearity of nozzle-baffle orifice.

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