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A tilting micromanometer with continuous sensitivity control

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CONSTRUCTION AND OPERATION

The coils consist of fifty turns each of insulated 0·002 in. tantalum wire, wound on two 5 mm strips of thin Bakelite. The length of the winding in each coil is approximately 5 mm and the spacing between coil centres about 1·5 cm. The two strips of Bakelite are mounted in the twin magnet system shown in Figs. 2 and 3 such that two coils lie in each air-gap.

The field-windings on the armature are each of approximately 1000 turns of 0·004 in. enamelled copper wire. Each winding has a resistance at 4·2° K of approximately 1 Ω, and a current of approximately 20 mA is required to produce critical field in the gap. Thus with a working current of 40 mA, the power dissipated is approximately 1·5 mW.

Terminals are small strips of copper bonded with Araldite to a terminal board on the back of the steel baseplate.

APPLICATION TO THE MEASUREMENT OF THERMAL ELECTROMOTIVE FORCES

The reversing switch has been used for various measurements of thermoelectric force which will be described in detail elsewhere. Fig. 4 shows some results obtained from a series of measurements of the thermoelectric force of a potassium–lead thermocouple, the "cold" junction being immersed in liquid helium at 4·2° K. It will be seen that potential measurements can be made to an accuracy of ±0·01 μV, which is approaching the limiting noise figure of the galvanometer amplifier[2] used as the measuring instrument. Thermal electromotive forces on the leads were of the order of 0·5 μV.

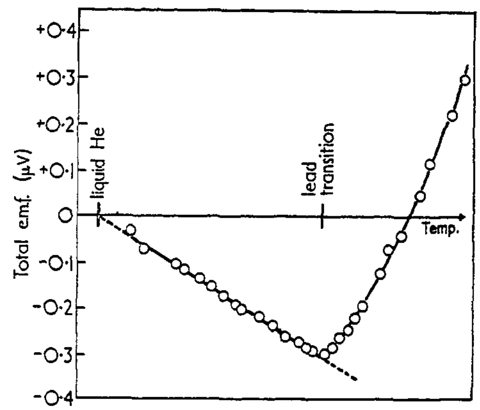

Fig. 4. Total e.m.f. of potassium *versus* lead showing lead transition

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A tilting micromanometer with continuous sensitivity control

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A null-reading liquid manometer is described in which the meniscus is returned to the reading position by varying the angle of slope. Sensitivity automatically decreases as the applied pressure increases; it is highest at zero readings and its absolute level can be continuously varied. A magnification factor can be employed by using different reading positions on the tube which is 0·1 in. bore, pivoted near the reservoir and tilted at its distal end by a standard micrometer-head, so keeping the construction simple and not critical. The prototype, which is wall-mounted, reads easily at air-speeds of 7·5 ft/s with a Pitot-static tube; the highest limits of accuracy assessed are ±0·2 dyn/cm², i.e. 6·5 ft/s ± 0·5%. The upper reading limit is about 0·7 in. w.g. (50 ft/s).

The standard tilting-pattern manometer with two glass reservoirs and a steel frame,[1] is rather complicated. With it pressures down to 0·02 in. w.g. (10 ft/s) can be read with reasonable accuracy, but for pressures below this the Chattock gauge[2] is in general use. This is expensive and, being a laboratory instrument requiring bench-space, may be inconvenient if used only occasionally. Wide bore inclined-tube manometers[3] are not conveniently read from above and require specially made micrometers. A wall-fixing, null-reading manometer has therefore been made with a narrow bore inclined tube, in which the meniscus is returned to zero by varying the angle of inclination, instead of raising or lowering the reservoir as in the type used by Preston.[4] A magnification factor can thus be used to reduce the minimum measuring division, by a factor of up to ×0·1 in the present instrument, by reading at different graduations on the tube. The sensitivity is continuously variable with the angle of inclination and can be increased almost indefinitely by reducing the angle to small or negative values. This is accomplished in the normal reading procedure; the sensitivity is highest at the zero value and automatically decreases with increase in pressure reading and increase in magnification.

The prototype, which was inexpensive and is of simple construction, reads from 0·01 to 0·7 in. w.g. within ±1% limits (6·6 to 50 ft/s ± 0·5%), but it seems likely that it could be developed to read lower pressures if required.

The instrument consists of a cylindrical reservoir connected by a coil of flexible tubing to a graduated glass tube held against a heavy strip of metal, pivoted at one end and supported at a known distance from the pivot by the tip of a micrometer-head mounted vertically. The pivot and micrometer-head are mounted on a metal backboard which is, in turn, mounted on a wooden baseboard screwed to the wall when in use (Fig. 1).

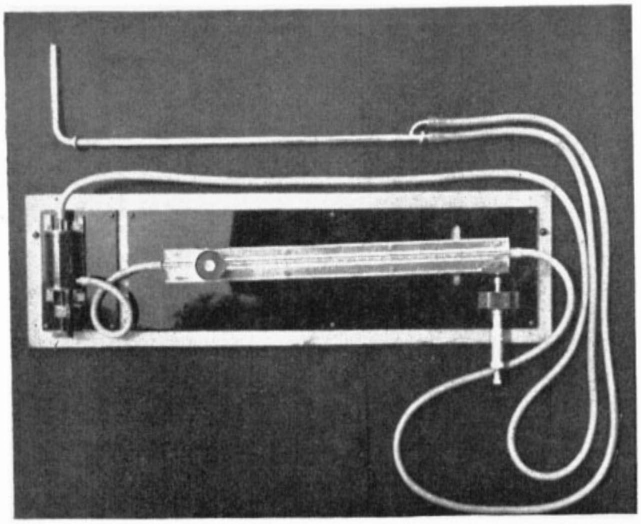

Fig. 1. Inclined-tube manometer fitted to a standard Pitot-static tube

DETAILED DESCRIPTION

The reservoir *A* (Fig. 2) is made from $2\frac{1}{2}$ in. long × $1\frac{1}{4}$ in. internal diameter brass tubing, plugged at the ends with brass disks and with a $\frac{1}{4}$ in. diameter inlet and outlet tube in the top and at the bottom of one side respectively. It is mounted on a flat brass plate, *B*, $2\frac{1}{2}$ in. × $1\frac{1}{4}$ in. × 3/32 in. which slides in grooves *C* fixed to a Duralumin baseplate, and it is supported on the tip of a screw *D* to provide rough adjustment of the liquid level in the reservoir, and hence of the meniscus in the sloping tube.

in 15 in. The thirty $\frac{1}{2}$ in. graduations are numbered and continue right round the glass. Straightness of bore is at least as important as regularity of cross-section, but neither are highly critical if the instrument is calibrated against a standard. The tube in use was specially made yet very cheap.

This tube is held against a heavy brass strip *G* by two transparent Perspex flanges *T* forming a clamp which allows light to reflect from behind the tube on to the graduations but grips the tube firmly. The brass strip is $1\frac{1}{2}$ in. × 3/16 in. and 16 in. long and is pivoted at one end on a cylindrical bearing *I* screwed into the aluminium backboard. The zero point of the glass scale overlies the marked centre of this bearing [see Fig. 2(*b*)]. At a distance of $13\frac{1}{2}$ in. along the brass strip is a peg with a flanged head *K* which slides within a recessed slot *J* and prevents the tube from falling forward. At a point exactly 15 in. from the pivot a piece of steel *L* let into the brass strip is supported on the micrometer-head *M*, the square end of which is covered by a tapered cap with the tip slightly rounded *N*. The weight of the brass strip holds it on to this cap as the micrometer-head is screwed up or down.

As the micrometer is elevated the tip slides against the steel inlay, but the movement is very slight and the effect upon the geometry of the instrument is negligible. For instance, the maximum elevation of 0·9 in. produces the maximum error which is 0·2% of the micrometer reading, i.e. 0·02% of the pressure at high magnification.

The main requirements in the instrument are that the spacing of the pivot and micrometer should be accurately known; that the 0 graduation mark should coincide with the pivot centre; that the micrometer should be vertical to the horizontal position of the graduated tube and that the reservoir and particularly the tube plate *G* should be sufficiently heavy and smoothly pivoted, since they are gravity returned. Absolute ethyl alcohol is used as the manometric liquid and use of the instrument would be facilitated by separate filling and drain holes in the reservoir. When the manometer is firmly mounted, the level position of the tube

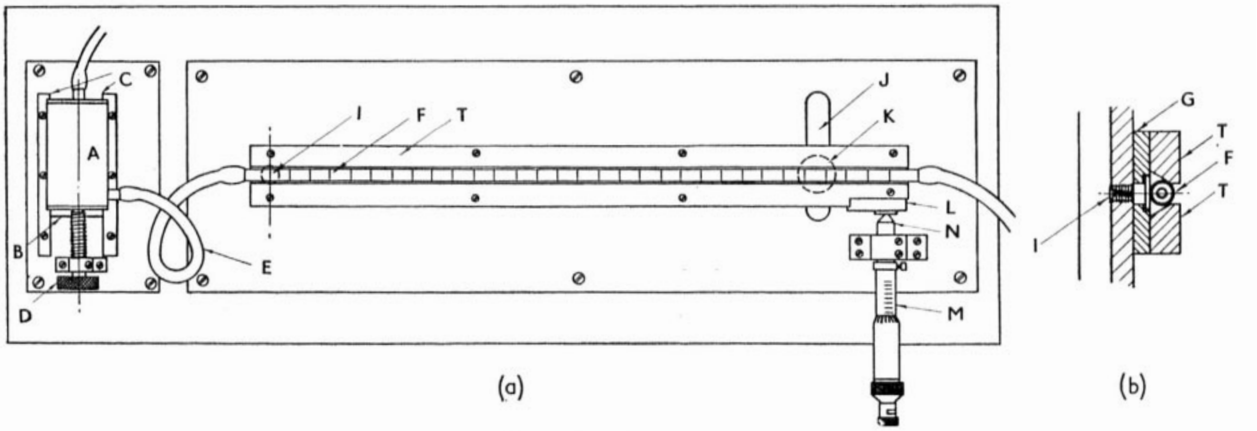

Fig. 2. Plan and section of manometer

The outlet is connected to the graduated glass tube by flexible tubing *E*, made of rubber in the prototype and coiled in a single loop, so that the glass tube may be tilted without undue distortion of the rubber. Though the amount of movement is small a straight connexion, as shown in the Krell pattern,[3] constricts visibly as the glass tube is raised.

The glass tube *F* is 1/10 in. bore × 16 in. long and graduated for 15 in. in 1/20 in. divisions, with a total error of −0·5 mm

can be ascertained by removing the rubber connexion, inserting a small bubble of alcohol and manipulating the micrometer to bring the bubble to a halt at the required graduation.

READING PROCEDURE

The value of magnified readings is based upon similar triangles, graduation 30 on the glass tube traversing 10 times the vertical distance of graduation 3 when the micrometer is elevated and hence a magnification of ×10 is obtained for readings taken with the meniscus at graduation 3. This position can only be used for pressures below $\frac{1}{10} \times 0 \cdot 9$ in. of alcohol (maximum elevation), and if graduations 0, 3 and 30 are in a perfectly straight line. This depends upon the straightness of bore of the tube and in fact the tube now in use is not quite straight, only graduations 3 and 15 being colinear with 0 and 30. However, they give adequate coverage of the range and intermediate positions have not been found necessary. A rough measure of the pressure is taken at graduation 30 and if it is below 0·09 in. of alcohol, position 3 may be used. If it is between 0·09 in. and 0·45 in. position 15 may be used, and if above 0·45 in., position 30.

The meniscus is adjusted to slightly above the chosen position by the reservoir screw and returned accurately by raising the micrometer with the pressure off. The resulting slight tilt of the tube (about 0·25°) facilitates adjustment by reducing sensitivity; a ×10 microscope eyepiece is used to read the meniscus. The micrometer is then read, the pressure turned on, and the micrometer raised to bring the meniscus back to the same graduation. A second micrometer reading is taken and the difference, divided by the magnification factor of the position used and multiplied by the specific gravity of the manometric liquid gives the pressure in inches water gauge. The micrometer-head, which is a stock commercial instrument, is graduated in 1/1000 in. from which 1/10000 in. can be estimated, or it can be obtained with 1/10000 in. graduations.

CALIBRATION

The conversion of readings to pressure involves the specific gravity of the liquid and the geometry of the instrument. With absolute alcohol the usual precautions are necessary to prevent change of specific gravity by water uptake;[4] the use of *n*-octane obviates this risk, but raises other problems discussed later. A brief consideration of the geometry shows that tangential displacement of the tube axis from the pivot centre of up to 0·05 in., and displacement of the micrometer axis from the vertical of up to 1° will not produce measurable errors. However, if the bore of the tube is out of line by 0·01 in. at the reading graduation, or if the tube zero is displaced axially from the pivot centre by 0·01 in., errors of the order of 0·00025 in. appear with readings at a magnification of ×10. It is therefore important that the tube should be held firmly in the Perspex clamp, and its position relative to the pivot centre made clearly visible without removing the tube.

Calibration of the present instrument, from 0·03 to 0·64 in. w.g., against a standard 13 in. Chattock gauge gave a rectilinear relation with $\tan \phi = 1 \cdot 95$ at graduation 15 and 0·98 at graduation 30, where $\tan \phi$ = true magnification (Fig. 3). The expected values M are consistently high at +2·5 and +2·0% respectively so that calibration consists of making a simple proportional correction over the whole range for each reading position, i.e. correcting M. Zeros were obtained at an inclination of 0°23′ and on this occasion the meniscus was too active at the "on" readings to obtain a reliable calibration at position 3, i.e. the sensitivity was too high for a magnification of ×10 to be used with the system concerned.

The readings were compared by dripping water into an airtight flask connected to the system; the two manometers were in parallel. It seems probable that temperature changes were the cause of the fluctuations in pressure; these were not evident with the system open, i.e. at zeros, and therefore are not likely to have been effective within the manometer itself. The effect of cold water entering such a closed system is, however, considerable and was examined in detail by Preston[4] who surmounted the difficulty by using a system connected to the atmosphere only through a water buffer, by which the temperature fluctuations were almost eliminated. This was impracticable in the present circumstances when the main object was straightforward calibration.

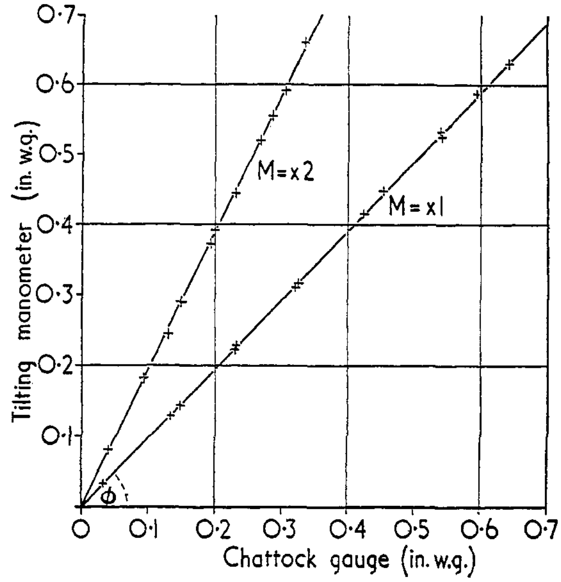

Fig. 3. Calibration curve at expected magnifications of ×1 and ×2 against a standard 13 in. Chattock gauge

SENSITIVITY

The sensitivity is considered as dI/dQ where I is the index of movement (the meniscus) and Q is the quantity measured (pressure). It is given by MacMillan[5] as:

$$\left(\frac{a}{A} + \sin \theta\right)^{-1} \tag{1}$$

where a = the cross-sectional area of the inclined tube,
A = the cross-sectional area of the reservoir,
θ = the angle of inclination of the tube.

When a geometrical magnification is used, the sensitivity at a given pressure is *reduced*; for $\theta \propto M$ where M is the magnification factor. The magnification applies only to the scale of measurement, i.e. the smallest reading is equal to the smallest micrometer division $\times 1/M$.

It may be necessary to reduce sensitivity by setting to zero with θ positive if the pressure is not steady. By raising the reservoir and increasing θ with the pressure on, an inclination can be selected at which the sensitivity is just sufficiently low to be unresponsive to small pressure fluctuations. The sensitivity, which can be further increased by making θ negative, is 150 with $\theta = 0°$; 100 with $\theta = 0°12'$, and is at a minimum of 15 with $\theta = 3°30'$ (maximum elevation). In most of the work for which the manometer was made and for which it has been used, zero settings have been obtained with $\theta \simeq 0°20'$, and air-speeds of 7–10 ft/s have been read without difficulty arising from undue sensitivity.

THE ACCURACY OF THE PROTOTYPE

The practical limits of accuracy are determined by the stability of the zeros and the minimum observable movement of the meniscus at zeros and at readings. Zero stability depends mainly upon differential temperature effects on the liquid, its containers and on the surface tension, and upon evaporation of the liquid; with a wall-fixing instrument, errors caused by tilting the base can be neglected.

Temperature effects cannot be eliminated with the present model, as suggested by MacMillan,[5] because the amount of liquid required by the equation:

$$Vr/A = 0\cdot145 \text{ cm}^2 \qquad (2)$$

where V = the volume of liquid and r = the radius of the tube, is $0\cdot55$ in.^{3} which is insufficient to fill the rubber coil. As a result the zero drifts irregularly. This is shown in Fig. 4 by zero readings which were taken from actual records made in a greenhouse and have been selected to illustrate major

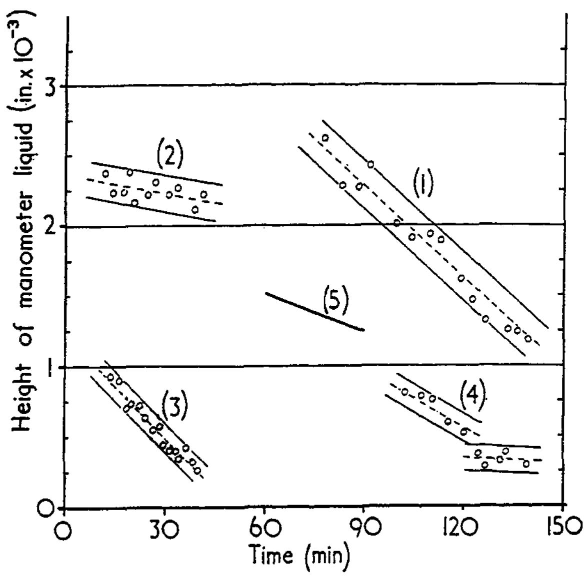

Fig. 4. Drift and scatter of zero readings (in. alcohol) on a time base (min). Four sets of data for various conditions in a greenhouse:

(1) 21 August 10·42–11·44 h, temperature 23·3–23·9–23·7° C.
(2) 22 August 13·11–13·41 h, temperature 29·5–29·7–29·3–29·4° C.
(3) 21 August 18·33–18·59 h, temperature 22·7–21·7° C.
(4) 20 August 19·52–20·29 h, temperature 18·2–17·1° C.
The parallel lines are the regressions and 5% fiducial limits.
(5) Zero drift caused by evaporation of n-hexane at $\theta = 1°$

changes in drift not likely to occur in the laboratory. However, by taking zero readings as frequently as is found necessary for the level of accuracy required, the general trend can be found, intermediate zeros interpolated and the large effect eliminated as in normal procedure. This also largely removes evaporation effects, which are fairly regular.

The minimum observable movement is included, in practice, in the residual scatter of points about the mean zero line which, in Fig. 4, is the regression line assumed for convenience to bear a linear relationship to time. Also included are minor temperature and evaporation fluctuations and defects in the micrometer screw, for although meniscus movement may be visible with high optical magnification, it may not be possible to record it accurately. No attempt was made to return the meniscus from a particular direction. It was returned roughly to the required position as the pressure was turned off, left for a moment to become steady and then "tuned" to the graduation mark with the right eye close to the microscope eyepiece. With the head in this position the micrometer is out of the field of vision (see Fig. 1); it is therefore unlikely that a personal bias towards the expected reading could influence the results without a conscious effort to control the number of micrometer turns by touch.

There is no reason to suppose that the factors involved in the scatter when the pressure is on differ from those when the pressure is off, except in relation to actual pressure fluctuations for which the manometer is not responsible, and to sensitivity which changes with θ (time-lag is not considered here).

If the zero is obtained with $\theta = 0°17'$ (micrometer at 0·07 in.; sensitivity 90), the inclination at 0·0128 in. w.g. (7·5 ft/s) will be $\theta = 1°9'$ (micrometer 0·24 in.; sensitivity 40). The four sets of zeros shown in Table 1 were obtained at

Table 1.—*Change of zero settings with time*

Run 1		*Run 2*		*Run 3*		*Run 4*	
T	*M*	*T*	*M*	*T*	*M*	*T*	*M*
0	0·0	0	0·0	0	0·0	0	0·0
6	−3·4	3	−1·4	3	−0·8	5	−0·3
4	+0·1	3	0·0	2	−2·0	3	−0·2
4	+1·4	3	−0·7	2	+0·3	5	−1·4
8	−4·0	4	+0·4	2	+0·1	5	+0·1
5	−1·1	2	+1·1	2	−0·9	4	−1·7
5	+0·3	4	−0·9	2	−0·9	2	−0·8
3	−0·4	3	+0·5	2	+0·2	5	+0·7
6	−2·8	5	−1·5	1	−1·4	2	+0·3
3	−1·4	3	+1·2	2	−0·3	6	−0·9
4	−1·6			2	−0·1		
7	−0·6			1	−0·4		
3	−0·2			2	+0·6		
4	−0·5			2	−1·0		
				1	−0·6		

T = Time interval between readings in minutes.
M = Difference between successive micrometer settings in thousandths of an inch.

sensitivities of a similar range, i.e. 45, 57 and 77, taken from actual records in which readings of about 0·0125 in. w.g. were taken after each zero using a magnification factor of ×10. In Table 2, the scatters of these zeros are given as standard deviations compared with sensitivity. It is evident, from the standard deviations in Table 2, that differences of sensitivity of this order did not appreciably affect the readings within the range considered and that other factors had a greater effect. As this is so, the errors of this instrument may be assessed from the scatter of these zeros about the mean. With this kind of reading there will inevitably be a large number of small errors which can only be treated as a statistical population and for this purpose the limits of accuracy are those within which 95% of the population of points will fall, i.e. the mean $\pm 1\cdot96\,\sigma$ where σ is the standard deviation about the regression. Thus a 95% accuracy is equal to $2 \times 1\cdot96\,\sigma$.

The micrometer is read twice for each pressure measurement; at zero and at "on"; both of these readings will have a standard deviation (σ_z and σ_0) which is a measure of the

Table 2. *Zero scatter compared with sensitivity*

	Average micrometer elevation (in.)	*Angle of inclination* (θ)	*Sensitivity* $(a/A + \sin\theta)^{-1}$	*Standard deviation* ($\sigma_z \times 10^{-4}$ in.)	*95% limits* ($\pm 1\cdot 96\,\sigma_z \times 10^{-4}$ in.)	*Number of observations n*
Run 1	0·1558	0°30′	57	9·1	±17·8	14
Run 2	0·0912	0°23′	77	7·1	±13·9	10
Run 3	0·1556	0°31′	57	4·8	± 9·4	15
Run 4 (1)	0·2315	0°55′	45	4·0	± 7·8	5
(2)				5·1	± 9·9	5

uncontrollable errors in the instrument. Because of the magnification factor, the standard deviation of the required pressure (σ_P) is $\frac{1}{10}$ of the standard deviation of the difference of the micrometer readings (σ_D), i.e.

$$\sigma_P = \tfrac{1}{10}\,\sigma_D = \tfrac{1}{10}\sqrt{(\sigma_z^2 + \sigma_0^2)} \tag{3}$$

As there is no evident correlation between sensitivity and σ over this range, equation (3) can be reduced to

$$\sigma_P = \tfrac{1}{10}\sqrt{2\sigma_A^2} \tag{4}$$

where σ_A^2 is the variance of any of the available sets of zeros, or a weighted average. Such an average, using all the data, including the wide deviation at the beginning of run 1, gives the general level of the limits of accuracy in uncontrolled conditions as $\pm 14\cdot 84 \times 10^{-5}$ in. w.g.

In better conditions this is improved upon. Apart from the two sections of run 4 in which the data are rather limited, the most consistent results are in run 3. Using these in equation (4) the maximum accuracy of the instrument in its present form, may be obtained, i.e. $\sigma_P = 6\cdot 86 \times 10^{-5}$ in. alcohol, which gives 95% of readings within $\pm 10\cdot 6 \times 10^{-5}$ in. w.g. This is a 95% accuracy of 0·4 dyn/cm² (±0·2 limits) which means that airspeeds of 6·6 ft/s may be measured to within ±0·5% if a sufficiently accurate Pitot-static tube is available.

POSSIBLE LIMITS OF ACCURACY

Preston used a similar instrument in which the meniscus was returned to zero by raising the reservoir, instead of increasing θ. The sensitivity was therefore the same at zeros as at readings; sensitivity control was less flexible than with the present instrument and no magnification was available. MacMillan[5] treated this type of instrument theoretically and gave the expected accuracy as $7\cdot 9 \times 10^{-5}$ in. w.g. (95% limits of $\pm 2\cdot 41 \times 10^{-5}$ in. where the theoretical accuracy is taken to be equal to the 99·8% limits). He pointed out that sensitivity is not the immediate problem in reducing this limit and indicated the micrometer screw, tilting the base and evaporation as sources of error when the temperature effect is eliminated. Preston's results confirm this, for he reported a "sensitivity of better than" $19\cdot 75 \times 10^{-5}$ in., but could only measure to $39\cdot 5 \times 10^{-5}$ in.[4] Ower[6] obtained an accuracy of $0\cdot 5 \times 10^{-5}$ in. using a narrow bore two-cup manometer with a high degree of temperature control and a magnification of ×10. Further, micrometer-heads calibrated directly to 10×10^{-4} in., and reading to 1×10^{-5} in. by vernier are available. The magnification of the present type of instrument could be increased to ×50 without making the tube too long; using the accurate micrometer mentioned above, 5×10^{-7} in. could then be measured, so that accuracy of measurement need not be a limiting factor. To do this the tube should be 0·5 m long, reading at 1·0 cm; it should be extended 4 to 5 cm below the pivot so that the meniscus is well away from the flexible joint.

Tilting of the base is no problem with a wall-fixing instrument; temperature control by MacMillan's method [equation (1)] could be obtained only by decreasing the tube bore, although increasing the reservoir diameter also contributes towards satisfying the equation. Using alcohol in an insulated reservoir 5 cm square and a tube 1 mm in diameter a high degree of temperature control should be obtained.

The ultimate limit of response is determined by the meniscus resistance which may be important with tubes of 1 mm diameter. The use of *iso*- or *n*-octane or *n*-hexane, which, in a tube of this diameter[7] has a Jamin-resistance of about a tenth that of alcohol in a tube 1·8 mm diameter,[8] reduces this limit considerably and a better meniscus is formed. But leakage from the surface may be expected to prevent the use of extremely high sensitivities, if these have any value. However, indices of *n*-hexane in a 1 mm tube and alcohol in a 0·1 in. tube, horizontal and open at one end to atmosphere, diminish at about the same rate, i.e. 0·1–0·2 mm/h, and a meniscus of *n*-hexane recedes at about 0·017 in./h in the present instrument (Fig. 4, Part 5). Thus there would be little more leakage with *n*-hexane than with alcohol, nor could evaporation be a much greater problem; even less so with *n*-octane and at higher sensitivities, for drift is proportional to tan θ. Also specific gravity is constant and lower than with alcohol, hence a higher magnification factor is obtained. Provided the coiled rubber connector is replaced by polyvinylchloride, *n*-octane or *n*-hexane could be used; with a wider reservoir, narrower tube and more accurate micrometer, the degree of accuracy would then depend almost entirely upon the temperature control achieved.

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