XXIX. THE CALIBRATION, ACCURACY AND USE OF GAS METERS.

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GAS METERS are widely employed in physiological work for measuring continuous or interrupted currents of air, but they are not always employed correctly and their accuracy is generally underestimated. To this state of affairs it has doubtless contributed that a quantitative examination and calibration, especially of large gas meters, could not be made in the laboratories employing them but had to be left to the manufacturers.

When Professor Lindhard and I installed a Jaquet respiration chamber in the laboratory we were forced by circumstances to put in a meter for producing and measuring the ventilating current of air which was not, in the opinion of the firm, Dansk Maalerfabrik, by whom it had been made, large enough for the purpose, since it had to be used at a maximum rate of 180 revolutions per hour, while wet meters, especially when large, are not considered as accurate beyond 100 revolutions per hour. We had therefore to arrange calibrations at those rates at which we proposed to work it. The apparatus constructed for this purpose has proved very suitable for the examination and calibration of meters generally and some of the results hereby obtained may possibly be of service to other physiologists employing meters.

The Calibration Spirometer.

The calibration spirometer (Fig. 1) is an adaptation of a similar instrument employed by the Dansk Maalerfabrik, the chief improvement being that I have arranged an automatic record of the volume per revolution of the meter calibrated. The drum (1) which is as nearly as possible cylindrical is suspended by a band of soft steel and counterbalanced by the adjustable weight (2). It moves up and down with a minimum of friction. When the drum is in its highest position the weight can be held by an electromagnet (not shown in the figure) from which it can be released at any desired moment by breaking the current. Along the steel band a fine brass wire is arranged carrying a number of lead weights (3). These can be displaced along the wire and a complete equilibrium in all positions of the drum can thus be secured. When the weight (2) is reduced, any desired pressure up to 20 mm. water can be produced in

the spirometer. The revolving fan (4) which can be driven from outside by a motor is used for mixing purposes. In calibration work with air it is revolved for a few minutes when the spirometer has been filled, to secure a uniform temperature and perfect saturation of the air with water vapour.

The drum is painted inside and outside with a hydrophobe composition so that its volume will not be altered by water adsorbed to its wall. This detail is very important. When left in contact with water, ordinary paint will take up a considerable volume of moisture which cannot drain off. According to experiments a painted tinplate continued to gain in weight while immersed in water during a couple of months, ultimately to the extent of 2.5 g. per 100 sq. cm. Such an increase would in my spirometer diminish by 3.5 cc. the effective volume per cm.

The spirometer drum has been calibrated by measuring a large number of internal diameters (133) evenly distributed over the whole length and circumference of the drum. These measurements have given as the average diameter 450.135 ± 0.09 mm. or a volume of 1591.4 cc. per cm. height. When the drum is used in the spirometer a lowering of 1 cm. will drive out a little more air than the corresponding volume of the drum because the surface of the water in the reservoir will be raised when 1 cm. of the wall of the drum is lowered into it. The volume of 1 cm. of the wall of the drum is

9.4 cc. The rise in the water level will also, of course, correspond to 9.4 cc., but since only 19.0 % of the water surface is inside the drum the extra volume corresponding to 1 cm. will be $\frac{19}{100} \times 9.4 = 1.8$ cc. and the effective volume of 1 cm. therefore 1593.2 cc. A further correction for the volume of the hydro-

Fig. 1.

phobe paint and for water adhering to the inside reduces the volume to 1593.0 cc. This latter correction is of course a little arbitrary. When the drum has been rapidly raised the water must be allowed to drain off for about five minutes before a practically constant volume is attained. The water adhering to it at first may amount to a couple of cc. per cm. or more.

The spirometer is arranged to record electrically the revolutions of the meter which is being calibrated. Two electromagnets (5) are placed on the top of the spirometer drum. When the drum is lowered each of them will write a vertical line on a strip of paper stretched out on a detachable board (6). The meter is arranged to close a circuit through the magnets once during each revolution and the magnets will make corresponding notches (7, Fig. 2) on the lines drawn. When the distances between these notches are afterwards measured in cm. the volume per revolution is found by multiplication with 1593.0. As the measurements of diameters have shown that the sectional area of the spirometer drum is not quite uniform all measurements of vertical distances are made from the lowest position of the drum as a base line and a small table has been worked out giving the corrections which must be added to the distances as directly read off. The total working height of the drum is 95 cm. and the largest correction which must be applied between 51 and 68 cm. is — 0.5 mm.

Details of the arrangement of a recording magnet are shown in Fig. 2. The magnet is removed from the strip of paper while the drum is being raised and can be laid on by pulling the thread (8). Eight separate records can be made on a strip of paper 5 cm. broad.

Wet gas meters.

Wet gas meters consist essentially of a measuring drum which can revolve with a minimum of friction in horizontal bearings. The drum is mounted in a box filled with water to a constant level. Meters for commercial purposes are provided with a system of cog-wheels driven by the drum and indicating on dials the gas volumes passing through either in litres or in cubic feet. Meters for scientific purposes (Bohr meters of Dansk Maalerfabrik) have only an electric contact arrangement for counting the revolutions and a subdivision of the volume per revolution generally in 100 parts. The experimental meters are more accurate, partly because they are not influenced by the variable resistance offered by the cog-wheels but also because the volume of one revolution is a constant quantity when the meter is properly handled while the gas volume delivered during a fraction of a revolution is not strictly proportional to the angle through which the drum has been turned. The error may amount in a well-made meter to 1–2 % of the volume of a revolution. In a Bohr meter the subdivisions of the revolution can be calibrated by means of a gas pipette delivering a constant volume, suitably $\frac{1}{10}$ or $\frac{1}{20}$ of the volume of the meter.

Experimental meters are provided with a levelling arrangement which

insures that the axis of the drum shall be horizontal. When they are correctly mounted the volume per revolution depends (1) upon the water level and (2) upon the rate of revolution. Bohr meters have a line marked on the front indicating the proper level of the water. The error which can be committed when the water level is carefully adjusted to this line may according to my experience produce errors of $\pm 0.1\%$ on the volume of the revolution.

Fig. 2. 1, one of the uprights of the spirometer stand. 2, part of the iron beam across the top of the spirometer drum. 3, steel wire along which the drum is sliding. 4, crosshead with guide for the rod carrying the magnet 5. 6, the detachable board and 7, part of the record with notches corresponding to the revolutions of a meter. 8, the thread for laying on the magnet.

Another arrangement is to have an overflow tube which can be opened and allow any surplus of water to flow off down to the constant level. This arrangement is extremely accurate if sufficient time is allowed to drain off the whole of the excess of water. In experiments with a meter of 14.50 l. per revolution I found that the addition of 100 cc. water, which raised the water level about 1.5 mm., diminished the volume per revolution to 14.40 l. or by 0.7 %. When the surplus of water was allowed to drain off during 12 hours 96 cc. were recovered and the attainable accuracy of the adjustment is therefore of the order $\pm 0.03\%$.

The volume per revolution of a properly adjusted wet meter is constant within less than 0.1 % at all rates below 1 revolution per minute and for small meters (10 l. per revolution or less) even at all rates below 100 per hour, but when the limit is exceeded there is a definite relation between the rate and the volume. This point has been specially investigated in the case of the 50 candle (4 cb. feet) meter employed for our Jaquet apparatus. This meter is driven by a motor and pumps air out of the respiration chamber. A constant water level is maintained in it irrespective of the rate by a slow current of water (1-2 l. per hour) passing constantly into it and out through the overflow tube. For calibration purposes it is connected by 60 mm. tubing¹ with the spirometer. A water seal which can be rapidly opened and closed is arranged on the tubing at such a distance from the meter that the resistance in the tubing between the seal and the meter corresponds as nearly as possible to the resistance offered by the chamber and tubing in respiration experiments. When the seal is opened the meter draws air from the atmosphere and when it is closed the meter is connected with the spirometer alone. The spirometer drum is loaded so that it will drive out air through the same opening at a rate similar to that at which the meter is pumping. The meter is kept working at a constant rate for a sufficient period to allow the perfect adjustment of the water level, the attainment of which is shown by the inflow and outflow of water being equal. The spirometer drum is raised and held in the highest position, and at a suitable moment shortly before the meter will close the electric circuit the spirometer drum is released and the water seal closed. When the drum approaches the lowest position the water seal is again opened. The meter is so large that only one revolution can be recorded during the sinking of the spirometer drum.

We have made a number of determinations at varying rates of the meter and found that at all rates below 1 revolution per minute the volume of air transported per revolution is constant, while at rates exceeding 1 revolution per minute the volume decreases with increasing rate.

The following numerical results have been obtained:

1 rev. in seconds	142	112	96	94	78	60	45
Vol. per rev. l.	113.98	114.02	114.07	113.96	114.00	114.00	113.55
1 rev. in seconds	33	31	29	24.5	22.5	20.6	18.6
Vol. per rev. l.	113.39	113.20	113.48	113.15	112.78	112.26	112.18

The determinations were made in the course of several days and slow and rapid speeds alternated irregularly. By graphic interpolation a table has been constructed from which the volume per revolution can be taken for all practicable rates of the meter.

If the water level of a meter is adjusted while the meter is at rest and the *quantity* of water remains constant while the rate is changed the volume per

¹ The tubing must be very wide to minimise the resistance which the meter has to overcome. The negative pressure in the drum of the meter should never exceed 5 mm. water. In the present case it is at the most rapid rate used about 2 mm. water.

revolution increases with increasing speed. A 14.5 l. meter was calibrated once by repeated fillings from a 1 l. glass bulb [described and figured by Krogh, 1915] and found to be 14.50 l. The rate in this case was extremely slow. Over a year later the meter was calibrated by means of the spirometer which was loaded so as to drive the air through at a rate of 1 revolution in 39 seconds. The pressure in the spirometer sufficient to produce this rate was 3.6 mm. water. The corrected readings of the record gave

Right mm.	Mean diff. mm.	Left mm.
875.6	—	876.9
784.0	91.55	785.4
692.8	91.2	694.2
601.9	91.0	603.1
510.7	91.15	512.0
419.7	91.15	420.7
328.8	91.0	329.6
237.9	90.8	238.9
147.0	90.9	148.0
56.2	90.9	57.0

The dispersion¹ of the single results is $\delta = 0.22$ mm. = 35 cc. and the average is 91.07 ± 0.07 mm. = 14.508 ± 0.018 l. measured in the spirometer at a pressure of 3.6 mm. water above that in the meter. The correction for excess pressure will increase the result by 5 cc. to 14.513 ± 0.018 l. When the rate is increased to 2 revolutions per m. the volume per revolution rises to 14.54 l. and at 3.4 revolutions it is 14.63 l. The corresponding pressures are 7 mm. and 9.5 mm. water.

When a meter is used at a constant rate the constant level arrangement with a current of water will generally be found to be the most suitable as no errors can arise from evaporation, but when the rate is inconstant or even discontinuous the constant quantity is the only possibility.

In respiration experiments, when a meter is used to measure the air expired from the lungs of man or an animal, the maximum rate during expiration can be taken to be approximately three times the total rate and care should be taken that the fastest rate does not exceed the capacity of the meter.

Dry gas meters.

Dry gas meters consist of two bellows which are alternately filled and emptied by the current of air passing through. They require no filling and will work equally well in any position. As the fractions of one revolution are often very incorrectly shown by a dry meter they should never for experimental purposes be divided in litres as commercial dry meters are but simply have a device for counting the revolutions.

¹ The term "dispersion" has been introduced by Charlier to take the place of "standard deviation."

A dry 10 candle meter (volume per revolution about 8 l.) arranged with one dial measuring 10 l. and divided in tenths of a litre was tested by passing air through it from the one litre bulb. The successive readings gave

Reading 1.	7.0	7.6	8.4	9.35	0.25	1.5	2.75	3.75	4.8	5.55	6.25	7.25
Diff. = 1 l.		0.6	0.8	0.95	0.9	1.25	1.25	1.0	1.05	0.75	0.7	1.0

The readings corresponding to 1 l. vary in this case between 0.6 and 1.25 l. but repeated tests starting from the same point gave very different results. When the meter was tested by the calibration spirometer it was found that successive revolutions of the hand indicating 10 l. per revolution showed similar variations, but since the volume of the drum was a submultiple of the volume corresponding to 50 l. the results were repeated with astounding regularity for each 50 l. The true volumes corresponding to successive readings of 10 l. were

0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
10.32	9.85	9.83	9.99	10.62	10.32	9.85	9.83	9.99	10.62

The volume corresponding to a reading of 100 l. is 101.2.

A 5 candle meter arranged to count the true revolutions and subdivided into $\frac{1}{100}$ parts of a revolution gave similar though smaller variations when tested by means of the 1 l. glass bulb but in this case a repeated test gave approximately the same errors at corresponding divisions. When tested by means of the calibration spirometer the volume per revolution proved constant so long as the rate remained constant.

The indications of a dry meter depend generally to a certain extent upon the rate, but the effect of the rate may differ in different meters. For the meters mentioned above I have found

			5 candle meter		
10 candle meter			L. per revolution		Pressure mm. water
100 l. in	300 seconds	100.9 l.	1 rev. in 45 seconds	5.10	3
	150	101.1		5.08	6
	145	101.2		5.04	15
	110	101.8			

The volume per revolution of a dry meter will not remain unchanged indefinitely, because the material from which the bellows are made will deteriorate. Within a year the change appears to be very slight but this of course depends upon the initial quality and age of the material. After nine months the calibration of the new 10 candle meter mentioned above has changed from 100.9 to 101.3 l. per 100 l. indicated.

SUMMARY.

A large recording spirometer for calibrating gas meters is described.

Wet gas meters properly handled are instruments of precision. Motor-driven wet meters acting as pumps and with a constant water level maintained by a slow current of water are accurate to less than 0.1 % at all rates below

1 revolution per minute. When they are calibrated for more rapid rates they can be used with almost the same accuracy at rates up to 3 revolutions per minute. The volume per revolution decreases with increasing rate.

In wet meters with a constant quantity of water the volume per revolution increases with increasing rate but can be determined with equal accuracy.

The subdivisions of the revolution of an experimental wet meter (Bohr meter) usually show slight errors which can be allowed for after calibration.

Dry gas meters are on the whole less accurate than wet, and when they are arranged to show the volumes directly in litres their indications are often very inaccurate and cannot be calibrated. They should be arranged to count revolutions.

Gas volumes representing fractions of a complete revolution are generally very inaccurately indicated but the volume corresponding to a whole revolution is a practically constant quantity. Varying rates may cause variations in the volume registered but at practicable rates usually within 1 %. The calibration of a dry meter changes with age.

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REFERENCE.

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