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A METHOD OF CALIBRATING A SHARP-EDGED ORIFICE USED FOR DETERMINING THE FLOW OF AIR.

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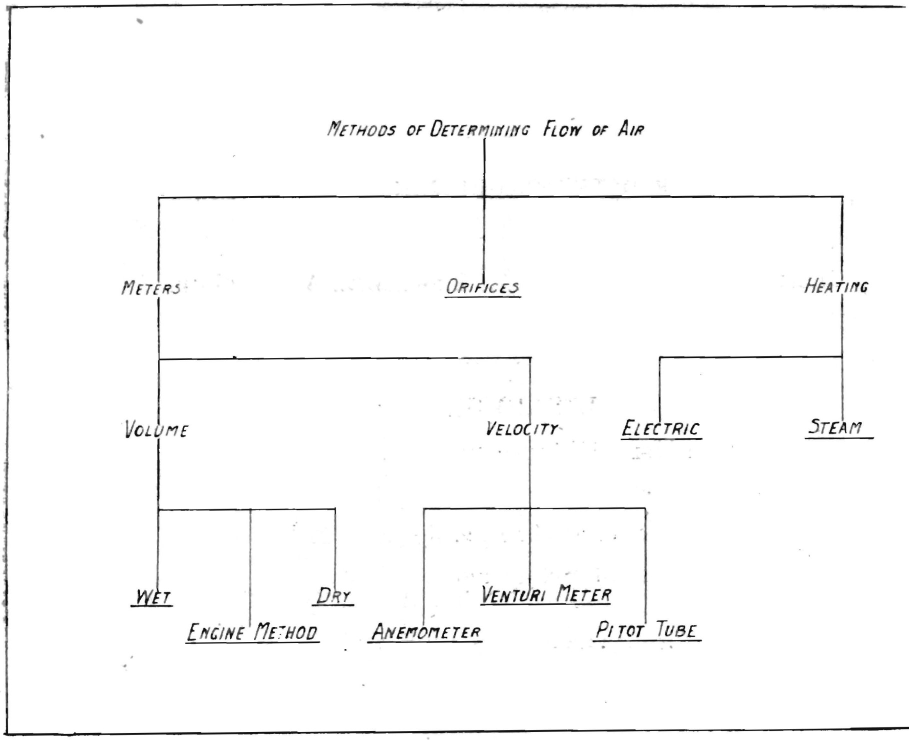
The methods available for the determination of the quantity of air supplied for any particular purpose may be summarised as follows:—(1) Meters, (2) Orifices, (3) Heaters. These methods may be further subdivided as shewn in Fig. I.

Volume Meters.—These are of two kinds, wet and dry. The former are generally restricted to small quantities, on account of their dimensions. Some forms of dry meters are very suitable for large volume measurements, and are made in sizes capable of dealing with 100,000 c. feet of air per hour. This type of dry meter consists of a short vertical tube in which an anemometer is fitted, and which drives a suitable set of dials or other recording gear.



—FIG. 1.—

Velocity meters are very suitable for continuous working, and may readily be arranged, with recording gear, to take either a continuous or intermittent record of the flow. The use of heater methods is quite possible; in fact, an electric gas meter has been designed. It consists of a series of resistance frames placed across the flow of the gas, and the variation of the resistance of these coils when a constant E.M.F. is maintained across the terminals gives a means of measuring the quantity of gas used.

Any heating method is open to the objection that the air in passing through the meter is appreciably heated, with a consequent increase in volume.

In any method for determining the quantity of air supplied, the following data is required:—(a) Temperature; (b) pressure, and (c) humidity.

The orifice method is a very simple one, and can be adapted to suit a very wide range of conditions and, provided it is carefully calibrated, will give results correct to about 1 per cent.

The information available on the calibration of orifices is confined principally to the experiments of Weisbach, 1859; Hirn, 1886; Fleigner, 1859; Durley, 1906; Watson, 1910; Müller, 1908.

The work of Durley, Watson and Müller is the most recent, but unfortunately in each case a different type of orifice was used, and consequently the results are not comparable. The orifices used by Prof. Durley consisted of parallel holes bored through brass plates, having a constant thickness of 0.0571 in. just near the orifice. Such orifices are, strictly speaking, short tubes of constant length 0.0571 in., and with a varying ratio of diameter to length, and therefore the results of one orifice are not comparable with another one, for in order to get similar stream line flow it is essential that there should be geometric similarity between the various orifices, e.g., take 5-16 orifice length is 0.0571 in.; 4½ orifice length is 0.0571 in.; i.e., ratio of length to diameter is in one case over 14 times what it is in the other.

The orifices used by Dr. Watson were parallel holes in thin plates; whilst those by Müller were champhered at an angle of 45 deg., but had a small portion parallel for a length of .004 in.

From these particulars it is clear that there is not geometric similarity between these various orifices. One reason why such orifices have been made is on account of the supposed ease of reproduction. Prof. Durley stated that, as the diameter of the orifice is increased the coefficient is decreased. It will be remembered in the case of orifices for water that with parallel holes there is a tendency to wet the front edge of the orifice, and if this does happen the coefficient is much higher. A somewhat similar effect occurs in the case of air, and is the cause of the higher coefficients with the smaller diameter orifices designed by Durley.

The use of sharp-edged orifices removes the objection due to geometric dissimilarity, provided the angle of champhering is constant. They are fairly easy to make, and may be made of ample thickness to avoid any breathing action. The angle of champhering is usually 45 degrees.

Some time ago I had occasion to determine the velocity of the air supplied to a piece of apparatus, and decided to use a sharp-edged type. I was unable to get any information concerning their calibration, and finally decided it would be desirable to undertake the work.

There are several methods that were possible, e.g., a boiler could have been filled with air under known conditions of pressure and temperature, and then allowed to expand in suitable pipes, etc., with provision for maintaining a constant temperature, and finally escape through the orifice. The pressure and temperature readings would give a measure of the volume discharged, and the pressure and temperature readings near the orifice would give the conditions existing there, from which the necessary data could be determined.

The method I adopted was as follows:—A known quantity of CO_2 gas was mixed with the stream of air, and at some convenient position an average sample of the mixed gas and air was taken and analysed. The actual volume of air flowing could be determined from the quantity of CO_2 admitted to the stream, and the amount obtained in the analysis.

This method gave fairly good results, and I have called it the Gas Shunt method of calibration. The idea occurred to me after reading an account of a method of gauging a river, which was as follows:—A known quantity of a salt was mixed with the river water, at some selected position up stream, and at the required position for gauging, a sample of water was taken and analysed. From this analysis, and the total quantity of the salt added, the volume of the stream was readily obtained. This is rather a crude system compared with the refined methods now adopted, but I understand they gave fairly good results.

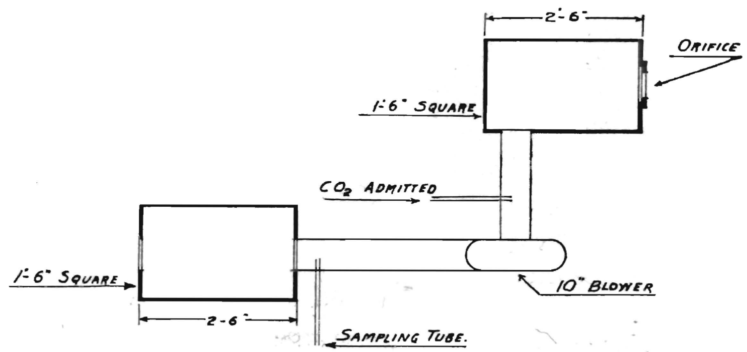
The apparatus for this investigation was as follows:—

A 10 in. Sturtevant blower, driven by a 2 H.P. electric motor, was provided on its suction side with a wooden box, 1ft. 6in. square by 2ft. 6in. long, in the end of which the orifices could be fitted. On the delivery side of the blower the air was passed through a length of piping, and then to another wooden box of similar dimensions, and then to the atmosphere. The pressure on either side of the orifice was determined by an ordinary water manometer, which proved quite satisfactory owing to the steady condition of the flow during the experiments.

It is most important in using the water manometer that the inlet pipe should be flush with the inside of the box.

The CO_2 was stored in a carefully calibrated gasometer. The sampling vessel consisted of a set of 4 glass gas tubes, having a combined volume of 958.32 cubic centimetres at a pressure of 760 m/m and at 0°C. This sampling vessel was exhausted by means of a vacuum pump, which reduced the pressure to from 1.5 to 2 m/m of mercury. The volume of the contents of the sampling vessel after sampling was determined by means of pressure and temperature reading, both before and after sampling. The contents were slowly displaced by means of mercury through weighed potash and soda lime tubes. The increase of mass of these tubes gave a measure of the volume of the CO_2 in the sample, which was checked by measuring the amount of air left in the sample.

The rate of admission of the CO_2 from the gasometer was determined by means of a stop watch, and a definite interval of time was allowed after admission of the CO_2 before taking the sample, to ensure a true mixture. The pipe for obtaining the sample extended across the full width of the 6in. pipe, and was provided with a number of small holes along its length.



—FIG. 2.—

In these experiments the greatest difficulty I met was to devise a means of making the wooden boxes airtight, and keeping them in such condition. I finally decided to provide all joints with a tongue, and, after screwing up tight, run in a quantity of marine glue. This gave satisfactory results for some time, but I would recommend anyone requiring an airtight vessel of wooden construction to line it with sheet metal, and solder all joints.

The orifices were made of gunmetal 7in. diameter x 3-16 in. thick, and ranged in size as follows:—2, 3, 4.5, 6, and 8.5 centimetres, with angles champhered at 45 degrees.

In all the experiments the results were reduced to dry air at 0°C and 760 m/m. It was found that coefficient of velocity was practically unity, so that the coefficient of contraction is also the same as the coefficient of discharge.

The value of the coefficient of discharge was obtained by the method over a range of .5in. water up to 5in., and it was found to have a constant value over this range.

The values are given in Table 1.

The following is a set of readings taken from one experiment:—

Barometer, 755 m/m/ at 19.3°C.
Diam. of orifice, 6 c/m=2.362in.
R.P.M. of blower, 3300.
Water pressure, 6.3in. water.
Temp. of sample, 21.8°C.
Mercury column before sampling, 753 m/m.
Mercury column after sampling, 2 m/m/.
Mass of CO_2 in sample, 0.0586 grs.
Rate of passing CO_2 into air, 4 cubic feet in 35.5 seconds.
Theoretical velocity, 161 ft. per second.
Quantity of dry air at 760 m/m and 0°C., 181 cub. feet per min.
Coefficient = .615.

The theoretical velocity of the gas is calculated from equation 4 in the Appendix.

The value of the coefficients for the various orifices is given in Table I. These values were determined over a range of 1in. up to 6.3in. of water, and over this range the coefficient is constant.

TABLE I.

Diameter of Orifice.		Coefficient.
Centimeters.	Inches	
2	·787	·617
3	1·181	·617
4·5	1·771	·615
6	2·362	·615
8·5	3·346	·614

In order to check this method of calibration I arranged the apparatus as shewn in Fig. (3) so that two orifices could be placed in series.

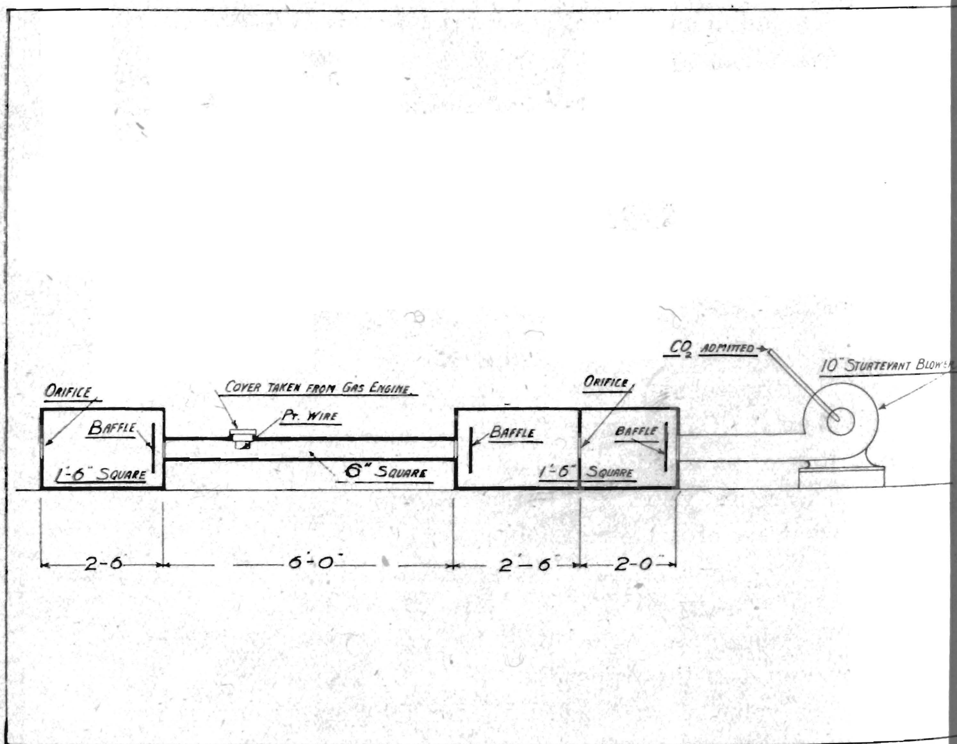


FIG. 3.

After the air had passed through one orifice it went through a square pipe of constant section, and finally issued from the second orifice. To make these comparisons I made some orifices according to Prof. Durley's design. The results from this comparison were very good indeed, and gave the same value, .615, for sharp-edged orifices, 4.5 and 6 c/m and also .615 for orifices 2, 3 and 8.5. The coefficients for Prof. Durley's Design of orifice are given in Table II.

Diameter of Orifice.	WATER PRESSURE.				
	1 inch.	2 inch.	3 inch.	4 inch.	5 inch.
5 16	·603	·606	·610	·613	·616
½	·602	·605	·608	·610	·613
1	·601	·603	·605	·606	·607
1½	·601	·601	·602	·603	·603
2	·600	·600	·600	·600	·600
2½	·599	·599	·599	·598	·598
3	·599	·598	·597	·596	·596
3½	·599	·597	·596	·595	·594
4	·598	·597	·595	·594	·593
4½	·598	·596	·594	·593	·592

As a further check, one of these orifices was used to measure the air supply to a gas engine. The engine was arranged to be driven by a motor at its normal working speed, and its air supply was taken from a large box fitted with the orifice. In order to get fairly steady readings at the pressure gauge it was necessary to make the volume of the suction box between 700 and 800 times the volume of the cylinder.

The position in the stroke at which the air was at atmospheric pressure was determined both by means of light spring indicator cards and also by a diaphragm indicator and detector. The temperature corresponding to the atmospheric pressure was also measured.

From the piston displacement and its volumetric efficiency, also the pressure and corresponding temperature, the quantity of air per minute could easily be obtained, and the coefficient for a 3 c/m orifice was .615 at 5in. water pressure.

Finally a photographic method was tried to see if it were possible to measure the vena contracta as the jet appeared so well defined. Some smoke particles were introduced into apparatus, and a beam of light from an arc lamp was directed to the emergent jet.

The photographs which I have made into slides shew very clearly the type of jet, and, in the case of the 4.5 c/m orifice, coefficient, obtained by measuring the photograph, was of the order .62, which is, I consider, a very fair check measurement.

APPENDIX.

THE FLOW OF A PERFECT GAS THROUGH AN ORIFICE.

The flow is assumed adiabatic, i.e., the gas neither receives or rejects any heat, and further, that the flow is free from eddies.

The fundamental gas equation is:—

Heat supplied = Work done + Charge in internal energy *i.e.*,

$dH = Pdv + Cv\,dT$

for an adiabatic change $dH = 0 \therefore Pdv + Cv\,dT = 0.$

In passing through the orifice the gas does work on itself in generating kinetic energy at the expense of its internal energy.

say small adiabatic flow

then $$dk + Cv\,dT + d\,(Pv) = 0$$

$$dk + Cv\,dT + Pdv + vdP = 0$$

but $$Pdv = -\,Cv.dT$$

$$\therefore dk + vdP = 0$$

In going from conditions $P_1\ v_1$ **to** $P_2 v_2$

$$\int_{v_1}^{v_2} dk = \int_{P_2}^{P^1} vdP$$

$$\therefore \frac{V_2^2 - V_1^2}{2g} = \frac{\gamma}{\gamma - 1}(P_1 v_1 - P_2 v_2)$$

Assuming we start at zero Velocity

$$\frac{V^2}{2g} = \frac{\gamma}{\gamma - 1}(P_1 v_1 - P_2 v_2)$$

$$V = \sqrt{2g \frac{\gamma}{\gamma - 1}(P_1 v_1 - P_2 v_2)} \qquad (1)$$

from the adiabatic law $P_2 v_2 = P_1 v_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}$

$$\therefore V = \sqrt{2g \frac{\gamma}{\gamma - 1} P_1 v_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}\right]} \qquad (2)$$

Quantity of air discharged in lbs. per sec.:—

$W = \frac{V \times A}{v_2}$ $\quad V$ = velocity in feet per second

A = area in square feet

$v_2 = v_1 \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}}$ $\quad v_2$ = specific volume of 1 lb of air at pressure P_2

$$\therefore W = \frac{A}{V_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}}} \sqrt{2g \frac{\gamma}{\gamma - 1} P_1 v_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}\right]}$$

$$\therefore W = A \sqrt{2g \frac{\gamma}{\gamma - 1} \frac{P_1}{v_1} \left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma + 1}{\gamma}}\right]} \quad \ldots(3)$$

The condition for maximum discharge is when the expression in the square bracket is a max., i.e., when

$$\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma + 1}{\gamma}} \text{ is a max.}$$

i.e. when $\frac{d}{dM}\left(M^{\frac{2}{\gamma}} - M^{\frac{\gamma + 1}{\gamma}}\right) = 0$ when $M = \frac{P_2}{P_1}$

$$\frac{2}{\gamma} M^{\frac{2}{\gamma} - 1} - \left(\frac{\gamma + 1}{\gamma}\right) M^{\frac{1}{\gamma}} = 0$$

$$\therefore M = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}}$$

γ for air is 1·404.

This gives a value to M of .53.

i.e., when the ratio of the pressure in either side of the orifice is .53, we have the condition of maximum discharge.

Equation (2) may be used to determine the theoretical velocity

$$V = \sqrt{2g \frac{\gamma}{\gamma - 1} P V_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$PV = RT$$

$$\therefore V = \sqrt{2g \frac{\gamma}{\gamma - 1} R T_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

This reduces to

$$V = 109{\cdot}1 \sqrt{T_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]} \qquad (4)$$

V = Velocity in feet per sec.
g = 32·2
γ = gamma = $\frac{CP}{Cv}$ = 1·404 for air.
P = Pressure in lbs per square foot.
A = Area in square feet.
R = Gas Const. = 53·2 foot lbs per lb of air.
T = Absolute Temp. Fah.
v = Volume of air in cubic feet per pound.
k = Kinetic Energy.

Discussion.

Mr. A. W. Tournay-Hinde said that it gave him pleasure to propose a vote of thanks to the author of the extremely interesting paper that had been presented to them that evening.

The paper was particularly lucid as to the methods used by the author for calibrating a sharp-edged orifice, when used for determining the flow of air. It interested the speaker very much, and he also felt sure that those present could not fail to be impressed with the simplicity and with the accuracy of the methods employed by Mr. Swain. The paper was not one that per-