of flow through the orifices. The real criterion of the nature of the flow was the value of $\frac{vd}{\nu}$. Dr. Stanton.

*** A single reply to the Discussion and to the Correspondence is given at the end of the article.

Correspondence.

Mr. A. A. BARNES observed, with regard to that portion of the Paper which dealt with the discharge through square-edged orifices, that careful attention should be paid to the footnote to Table III, and to the limits which this note placed upon the results given in Appendix III. It was true that the Paper purported to deal with the measurement of air, gas and steam only, but since in the two instances cited reference was made to the coefficients for the discharge of water through orifices, it was important that the differentiation should be observed between the two distinct cases in which an orifice was installed (*a*) in a parallel-sided pipe under pressure, and (*b*) in the side of a tank or at the end of a channel with free discharge into the air. For case (*a*) the Author's value, 0·608, for the coefficient was most useful, as constituting a standard by means of which the quantity of water flowing in a pipe might be ascertained by the insertion of a diaphragm of almost any convenient size, merely by noting the drop in pressure, provided that were taken at the orifice (Case IV., *Fig. 17*). Since it was stated that this value 0·608 was based upon the results of experiments on diameters ranging from $\frac{1}{16}$ inch up to 9 inches, Mr. Barnes would ask the Author to give a few more figures for the larger diameters, similar to those in Appendix III for the very small orifices. With regard to case (*b*) for orifices discharging water into the air, it was found that orifices of different diameters did not possess the same discharge coefficient. The discharge in this case still varied with the square root of the pressure or head, but it also varied with the diameter. Mr. Barnes had found that for circular orifices discharging water into the air, the power of the diameter with which the discharge varied was 1·985, and if H represented the head in feet from still-water level to the centre of the orifice, and D the diameter of the orifice in feet, then Q the discharge in cubic feet per second was given by the relation Mr. Barnes.

$$Q = 3\cdot73\ D^{1\cdot985}\sqrt{H}$$

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Mr. Barnes for all values of H above the critical head. This critical head had been found by Bilton not to exceed 2 feet for all diameters greater than $\frac{7}{16}$ inch.

Mr. Connet. Mr. W. N. CONNET, on behalf of the Builders Iron Foundry, of Providence, R.I., stated that since 1898 the Foundry had collaborated with several of the large steelworks and with others in carrying out tests to determine coefficients, and had developed a series of registering, indicating and recording instruments. In 1903 a 6-inch Venturi gas-meter for blast-furnace gas, and in 1904 a 6-inch Venturi steam-meter, were tested and used by the Illinois Steel Company. In 1904 the Solvay Process Company calibrated a Venturi meter-tube for the measurement of air by means of a 50-foot gasholder. The tests were made under the supervision of Mr. B. N. Bump.

The air was compressed by a positive blower, of Root type, to the outlet of which a regulating valve was attached. About 100 feet of straight 12-inch pipe connected with the Venturi meter-tube, which had an inside diameter of $11\frac{7}{8}$ inches at the inlet-end and a throat diameter of 6 inches. From the outlet-end of the meter tube about 50 feet of 12-inch pipe led to the gasholder which had an average inside diameter of 49·95 feet.

Twenty-one tests were made, in all but one of which the gasholder gave a displacement of about 21,650 cubic feet. The time of the tests ranged from about 6 to 44 minutes. The rate of flow ranged from about 4·7 cubic feet to 58·3 cubic feet per second, corresponding with throat velocities of 10·47 feet to 363·72 feet per second. The air pressure at the inlet of the meter tube varied from 3 inches of water at the lowest velocity to 17·2 inches at the highest velocity, but the pressure within the gasholder was maintained constant at 2·85 inches. The "Venturi Differential" ranged from 0·13 inch to 19·65 inches of water. In calculating the results complete temperature and pressure corrections were made. All tests were made with "running start" and "running finish."

Taking the general Venturi formula as

Throat Velocity $= V = C_F \times C_R \times \sqrt{2gh}$, in which C_R denotes ratio coefficient $= \sqrt{\frac{R^2}{R^2-1}}$, R* denotes the throat-ratio, it was found that the average value of C_F or the "friction coefficient" was 0·985.

In 1905 6-inch and 10-inch Venturi air-meters and a 16-inch

* n in the symbols used by the Author.

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Venturi gas-meter were tested and used by the Lackawanna Steel Company, Buffalo, N.Y. In 1911 a 60-inch meter with a 25-inch throat was furnished to the Bethlehem Steel Company, South Bethlehem, Pa., for measuring blast-furnace gas supplied to large gas-engines. The capacity of this meter was 3 million cubic feet per hour. In 1911 calibration tests were made at the Illinois Steel Company's works upon 24-inch, 36-inch, 48-inch and 60-inch Venturi meters measuring blast-furnace gas, and using a gasholder of 100,000 cubic feet capacity. In a test on the 36-inch size use was made of the Register-Indicator-Recorder furnished by the Builders Iron Foundry. This consisted of two oil-chambers 12 inches square connected together and connected with the vent holes of the Venturi tube. Large floats transmitted the differential pressure to a shaft whose partial rotation varied as the square of the velocity of the gas, and an indicator hand on this shaft traversed a graduated dial. A square root cam, also on this shaft, moved a vertical lever in proportion to the first power of the velocity of the gas, and this lever carried a recording chart pen and an integrating counter dial. With certain minor modifications that was the standard form of instrument in use throughout the United States for light-pressure gas and air, but for pressures above 25 lbs. per square inch, and for steam-meters, mercury instead of oil was used for operating the floats, and the float wells were much smaller in cross section. There were about 500 air-, gas- and steam-meters in use in the United States, and an important group of copper mines in Montana had an equipment of some fifteen Venturi meters, 8 inches and 10 inches in diameter, measuring compressed air at a pressure of 70 lbs. per square inch under conditions very similar to those described in the Paper. Mr. Connet.

Mr. G. J. Gibbs, of Preston, observed that the matter of leakage from extensive systems of mains carrying compressed air had occupied his attention from time to time, and no practicable arrangement of a fixed orifice was known capable of passing the working quantities, of air and still sufficiently sensitive to indicate the flow of such small quantities as usually escaped by leakage. The problem had been solved by calibrating stop-valves of the sliding-gate type, the observed variable being the amount of opening of the valve required to produce a definite small loss of pressure due to the throttling effect of the partially closed valve. The amount of opening was indicated on a scale, and the loss of pressure was shown either by a simple fluid manometer of the reservoir and single-leg type, similar in principle to that described in the Paper, or, since only a single value of the differential pressure needed to be indicated, the Mr. Gibbs.

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Mr. Gibbs. working member of the manometer might consist of a freely floating piston whose rise and fall could be observed in a gauge-glass. The valves as now arranged were usually calibrated with reference to such small pressure-drops as $1\frac{1}{2}$ inch of water for elastic fluids, or $1\frac{1}{2}$ inch of mercury when the flow of water was to be measured. Such an arrangement of valve and manometer provided a rate-of-flow indicator which afforded readings even when such rates approximated to zero. The calibrations were carried out at the works of Messrs. Alley and MacLellan, of Glasgow, by means of air supplied by a fan at pressures equivalent to about 20 inches of water, the rates of flow being measured by means of sharp-edged orifices placed in series with the valve. Calibrations were also made by means of water, in which case the rates of flow were measured by means of V-notch weirs, and also by weighing the quantities discharged in definite times.

It was interesting to find confirmation of the accuracy of the assumption that the coefficient of discharge through such complicated passages as existed in double-gate sluice-valves remained constant whether the fluid was air or water: it had also been confirmed with reference to steam and compressed air. As a natural sequence the calibrations were extended to the practical limit of the carrying-capacity of the pipes to which the valves were to be fitted, thus providing the user with a means of observing the rate of flow. Such meter valves had been applied in considerable numbers to pipe systems conveying compressed air, steam and water, and some very interesting results had been obtained in practice: for instance, a 3-inch diameter steam-pipe, which according to the estimate of the engineer in charge was delivering 800 lbs. of steam per hour to certain pieces of apparatus, was found, when the meter valve was fitted, to be passing 3,200 lbs. per hour. It was fortunately possible to find and apply an independent check which confirmed the latter quantity.

Mr. Harper. Mr. W. A. HARPER had perused the Paper with great interest on account of his close association with the Rand Power Supply Scheme, for which his firm had acted as Consulting Engineers. When the question of plant extensions to the group of mines amalgamated under Rand Mines, Ltd., was under discussion, it was found that the aggregate cost of so many extensions justified the establishment of a large central power-station. He had considered the matter very fully with Mr. A. M. Robeson, the Chief Engineer to Rand Mines, Ltd., who decided that as so much of the existing plant was pneumatic, it would cost too much to scrap it in favour of electric working, and that it would not pay to operate it

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alone. To avoid the cost of electrically-driven compressors every- Mr. Harper. where, they had looked into the possibilities of air-transmission and distribution, and although it was the first time it had been attempted on anything like this scale, they had determined to distribute high-pressure air in mains, in addition to the ordinary electric supply. It was not apposite to the Paper to detail the difficulties encountered in obtaining rotary compressors for the purpose, all of which had to be specially designed for higher pressures and greater outputs than any previously made, but certainly the metering of the air had been by no means the least of the obstacles to be overcome. Mr. Robeson required a meter that would measure air in units equivalent to kilowatts supplied to a hypothetical electric compressor with the same efficiency as the existing steam compressors. It was a new departure, and it was so important that the system of measuring should be unimpeachable that it was considered advisable to get the best possible advice on the matter. Dr. Unwin had very kindly taken an interest in the problem and had assisted in deciding upon the formulas on which the contract was based. By means of these formulas and a series of tests on six of the big steam compressors then in use, the weight of air at different pressures constituting the equivalent air units were obtained. The Author had ably completed the practical solution of the problem by evolving the meter described in the Paper. A long series of tests was made and the meters were found to be remarkably well fitted for the peculiar conditions under which they were required to work. As regards accuracy, when drawing up the terms of the contract a margin for error of $\pm$ 3 per cent. was asked for, although it had not been ascertained at the time that air-meters to register closer than this would be devised. The great advance made by Mr. Hodgson was shown by the fact, that when the final order to Messrs. Kent was drafted, the margin for error was cut down to 1·5 per cent. at full load, graduating to 2·5 per cent. at one-tenth load. The actual test results at the makers' works were almost invariably less than one-half of these figures. The satisfactory relations now existing between the Supply Company and the consumers were due in no small measure to the accuracy of the measurements of the power consumed, and the success of the Power Company, both from a technical and a financial point of view, was due to the care exercised at the start by all concerned in framing the agreements based on formulas which could not afterwards be disputed. In conclusion, he would remark that the air losses on the whole system represented only 5 per cent. on the average, and the power-factor

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Mr. Harper. of the whole system was considerably improved by the use of synchronous motors, for operating all the compressors which lay outside or were additional to those directly operated in the main station.

Mr. Herschel. Mr. CLEMENS HERSCHEL pointed out that the Paper, dealing with only one, though a very important, branch of the art of metering fluids and gases, in common with all the other Papers printed in the Proceedings that had mentioned the Venturi meter, contained nothing to support the belief that the members of The Institution were acquainted with the history of that method of metering fluids and gases, and with the uses to which it had been put. It might, therefore, be proper to supply to some extent that deficiency.

Charged from 1879 to 1889 with the duty of apportioning among some thirty users of water out of common canals, at Holyoke, Massachusetts, U.S.A., the amounts which each one might lawfully draw, to operate some thirty-five manufacturing corporations, many of them running night and day, Mr. Clemens Herschel was much troubled with the indeterminate quantities which these same manufacturers drew for wash-water in paper-mills, dye-works, and other large draughts of water out of the same canals; drawing in some cases out of 20-inch and 24-inch pipes. Some method of meeting that situation had to be devised, and after several years of struggling with the problem, Mr. Herschel experimented at the Holyoke Public Testing Flume (designed and used since 1881 for the mechanical testing of turbine water-wheels), with what he named the Venturi water-meter. This name came about by accident. Venturi was an Italian experimenter, who lived in Paris during the French Revolution, and published an account of his experiments on expanding ajutages, in Paris, in 1797. He had observed that during this method of discharge suction was produced at the throat of the ajutage, and proposed to use such suction as a pump to lift water. In course of time it became well known that these expanding ajutages increased the discharge otherwise obtaining, and they were used for various purposes, as for increasing the efficiency of hydraulic turbines.[1]

Mr. Herschel's invention consisted in producing such an expanding ajutage as part of a constriction in a pipe, and in imagining that, and then demonstrating by experiment how, the suction at the throat was a function of the velocity through the throat.

[1] Described, for example, in Francis's "Lowell Hydraulic Experiments," 2nd edition, 1868.

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When, during the experiments, it became necessary to speak of the head at the throat, it became easier to pronounce, and more euphonious, to speak of it and shout it as the "head on the Venturi," rather than "head at the throat"; and thus came into being the name "Venturi meter": Mr. Herschel.

> "One of the few, the immortal names
> That were not born to die."

Certainly ten thousand such meters were now in use the world over; about half of them in North America, the other half built in England for the rest of the world; even though 10 years of advocacy of it, illustrated, moreover, by its use on hydraulic works designed by Mr. Herschel, preceded its first use anywhere else.

Incidentally, be it said, engineers had many such sins of omission to account for. Twelve years after the date of an engineer's report, that the electric propulsion of trains on New York's "Elevated Railroad" was wholly unadvisable, trains began to run on it without the little "puffing Billies" that had up to that time hauled them. And other such cases could be cited.

The *Engineering Record* (New York), of 10th March, 1917, contained an advertisement showing photographs of Venturi meters in use to meter cold water, hot water, sewage, oil, ammonia, brine, air, gas, and steam; to which mercury might have been added. Cold water service alone was again subdivided into many uses, such as meters of all sizes, from the master meters on a 210-inch conduit, metering 500 million gallons daily on the New York new aqueduct, to those in $\frac{1}{4}$-inch pipe for experimental purposes; on the discharge pipe of pumps, to test them for efficiency, and thereafter to maintain their normal efficiency, by revealing when pump valves, or impellers, had become foul or otherwise out of order; on hydraulic turbine penstocks, for a use similar to that just named; to detect leaks in city water-supply distribution; in irrigation service, enabling the same water-supply to irrigate double the area of land and to produce three times the value of crop attainable under a more or less "go as you please" system of putting water on land; and many more.

Forty years ago the system (if it might so be termed) under which one municipality sold water to another, consisted in calling a board of arbitrators into being periodically, letting them examine all the accounts, and then determine what one town should pay to the other. Now the thing was done quarterly, on the basis of bills rendered for the quantity sold.

In 1895, when the Metropolitan Water Board of Massachusetts

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Mr. Herschel. came into being, there was devised, to regulate its accounts with some twenty adjoining municipalities which it supplied with water, a ponderous method of assessing these municipalities according to a mixed system based on their populations and valuations, instead of on quantities delivered to each of them, and on a price per million gallons delivered. The natural consequences could not fail to develop. Consumption per head, which was the sum of use and of waste, rapidly increased from year to year, as had been predicted in 1899; until the situation forced changes to be made in the laws governing the matter.

Recent reports of the Board gave the situation in 1915 as follows:—

	Million Gallons per Day.
"Estimated consumption, if measures to prevent waste had not been adopted"	172
Actual consumption	102

Had the consumption been allowed to aim at 172 million gallons daily in 1915, it would long before have necessitated a very large expenditure for extending the waterworks. Besides, buying by the million gallons, immediately brought about a desire on the part of the interested municipalities to sell by the thousand gallons, that is, by meter; and thus this great reform in the economical government and well-being of $1\frac{1}{2}$ million people could, by the aid of meters large and small, be speedily accomplished. The Author, though it was not so stated in the Paper, had in fact demonstrated that his work and meters had made possible a power distribution on the Rand, which otherwise would have been effected by isolated plants at the different mines, and at a much greater cost per unit of power used; another illustration of economies made possible and effected by the use of meters.

Mr. Hunt Mr. S. HUNT, of Johannesburg, who had been closely associated with the subject of the Paper for 5 years, contributed the following particulars of the behaviour of the Venturi and Gate meters installed on the Rand Mines Power Supply System under working conditions. The air was supplied by turbo-compressors running at a high speed and reached the consumer at an average pressure of 110 lbs. per square inch and a temperature of about 20° C. The flow measured by the meters was in all cases steady, and therefore complications due to pulsations were absent, the measurement taking place under ideal conditions. When the meters were first installed small difficulties were met with. Most of these troubles had now been removed, and although the two types of meter were based on widely differing fundamental principles, the aggregate

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registration at all points of delivery throughout the system as recorded by the two types of instrument agreed within 1 per cent. This satisfactory result had only been obtained by periodically adjusting and overhauling the meters. It would be realized how important it was that the agreement between the meters should be as close as possible when only 1 per cent. difference on the total registration meant nearly £3,000 annually. The Venturi recorders were inspected monthly, any necessary adjustments to the clock and pressure cam being made. A routine mechanism and bell test was made every 3 months, and the recorder was completely overhauled annually. These Venturi meters could be inspected and overhauled without interrupting the supply. There was no necessity to calibrate them against a master meter, because the coefficient of the Venturi tube was known, and it was therefore only necessary to calibrate the recorder against a standard manometer. Mr. Hunt.

The Gate meters were calibrated against the master meter before being put into commission and every care was taken to ensure that the mechanism was correctly adjusted after it had been installed on the mine. When the meter had been in commission for a few days its agreement with the Venturi meter was noted. Once in commission, the Gate meters were inspected monthly, but it was not possible to make routine mechanism tests owing to the fact that a complete shut down was necessary to readjust the zero. Mechanism tests were made when found to be necessary by a variation from the original agreement with the Venturi meter. If the Gate mechanism was found to be correct, a test was made on the Venturi recorder to verify its accuracy, and if after these tests had been made the disagreement continued, the complete Gate meter was brought in and tested against the master meter. Owing to its construction the Gate meter was liable to be put out of adjustment by a sudden stoppage, such as that produced by the operation of the cut-out valve, or by a sharp increase in the flow; and if it were not possible to make a daily comparison with the Venturi meter it was doubtful whether the Gate meters could be considered reliable instruments. At any rate the frequency of calibration would have to be much increased.

Daily readings were taken on all meters, so that any discrepancy thus shown could be immediately investigated with the help of the hourly log kept at each mine. These hourly readings had proved to be of the greatest use. Any corrections necessary for clock and temperature errors were obtained from the daily returns and from the charts of a recording thermometer.

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Mr. Hunt. Recent experience had shown that the length of pipe both upstream and downstream of both meters should be as great as possible, and special importance should be paid to the downstream conditions of the Gate meter, nothing likely to induce a wire-drawing action being allowed. It would probably have been better for the cut-out valve, etc., to have been placed at a greater distance from the Gate meter, for with a high velocity considerable error might be caused, due to the violent interruption of stream-lines. The Gate meters were very sensitive to small changes of load and had a large range. The Venturi meters were comparatively slow in responding to quick changes of load, and tended to under-register with very small flows. The latter type of meter was well suited to steady flows, its slow action tending to decrease the wear of working parts, whereas the gearing of the Gate meters from the "Gate" to the "Recorder" had to be carefully watched. The cost of maintenance was a point which must be considered, but no figures were available that would give a fair idea of the comparative maintenance cost of the Gate and Venturi meters on the Rand scheme. It was probable that the maintenance cost of the Venturi meters was higher than that of the Gate meters.

The cut-out valves were very sudden in action, in fact rather too sudden, giving one quite a shock when they acted. Mr. Hunt had noticed a rise in pipe-line pressure of as much as 15 lbs. per square inch, but as a general rule it was about 8 lbs. per square inch. This shock could be considerably reduced with advantage. The cut-out valves had proved very efficient in keeping consumers within their limits, and, in the case of a burst main underground, in avoiding overload and an excessive waste of air.

The method of measuring fluid flow by square-edged orifices was used on the Rand with success, and numerous tests agreed very closely with the figures given in the Paper. The chief advantages of this method were cheapness combined with reasonable accuracy, and the ease and quickness with which the apparatus could be installed. The single-leg manometers designed by the Author of the Paper were excellent instruments for use in conjunction with orifice plates.

For meters where the differential pressure method was used the system of calibration by air and water would probably be successful, but in Mr. Hunt's opinion meters of the Gate type should be calibrated with the fluid to be measured, and actual working conditions should be reproduced as nearly as possible. Special care should be taken to ensure good upstream and downstream conditions for both types of meter. The information given as to the

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measurement of pulsating flows was extremely valuable, comparatively little investigation having been carried out or data published in connection with such flows. At one station on the Rand where the air was supplied by three reciprocating compressors and one turbo-compressor, an attempt was made to measure the output with a standard Venturi bell-type recorder, the working range being about 1 to 15, and the conditions of running ranging from all machines on full load to one reciprocating machine just turning over. The meter was installed in exactly the same way as on the Rand Power Supply system, but the results given by the meter were very erratic and varied at all loads. This erratic result could only be attributed to the pulsating flow. Various experiments were made with the object of getting a mean pressure to act on the bell by placing orifice disks in the connection pipes, and by placing receivers between the Venturi tube and the recorder. It was possible in this way to make the recorder read correctly at some loads, but at other loads the meter would be very erratic. The same meter was able to measure the air from the turbo-compressor alone correctly. The conclusion reached was that the large variations in the amplitude of the pulsation and the wave form of the air prevented the use of the standard type of Venturi recorder. Unfortunately the outbreak of war prevented trial of a new type of meter, and it might be some time before this problem could be solved. Mr. Hunt.

The fan proportional meter was of recent design, and its behaviour was not known in South Africa. It was quite a new departure to put the mechanism in the pipe-line, and it would be interesting to see whether that plan proved satisfactory. A by-pass would have to be installed to allow the meter to be inspected, but a by-pass was an advantage in any metering installation. It would be interesting to hear of the behaviour and capability of this meter, as it should be extremely useful for underground work, and there was a large field for a meter of that description.

Mr. J. Newell Reeson noticed that the Author had confined his remarks to the employment of apparatus involving the Venturi principle for measurement, and although that principle was of great use in the measurement of liquids, Mr. Reeson was unaware that it was sufficiently accurate for application to air, gas and steam. The description of the different apparatus designed for the purpose of measuring compressed air was exceedingly interesting, and especially the details given in the Appendixes. As regards the application of the principle to the measurement of gas, which was touched upon in the Paper, Mr. Reeson was unable to speak from experience, Mr. Reeson.

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Mr. Reeson. although he was aware that Venturi meters had been used on an extensive scale at Sydney, New South Wales, in addition to the places mentioned by the Author. The principal difficulty encountered was the correction for variations of gravity, which, in the case of a mixed gas, i.e., a mixture of coal gas and carburetted water-gas, such as was employed in many gasworks, rendered this system of measurement somewhat troublesome. In measuring gas it was essential that the works measurement should be as accurate a record as possible, and an error of 1 per cent. was far too great. Such an error was equivalent to 100 to 130 cubic feet per ton of coal. In normal working the gas measured was corrected to standard temperature and pressure, viz. 60° F. and 30 inches of mercury, after allowing for the gas-pressure on the meter itself. He regretted that the Author had not mentioned other means of measurement, such as dry and so called rotary meters for gas and air. The former was an extremely accurate method of measurement, and one commonly employed in metering consumers' supplies, while the latter was much used for approximately measuring large quantities on works. This apparatus was probably more accurate than the Venturi tube.

Mr. Scott. Mr. E. KILBURN SCOTT had read the Paper with especial interest because the Author had some years ago got him out of a difficulty in some experimental work. It was necessary to measure the air delivered to an electric furnace for fixation of atmospheric nitrogen, and a large tank-type gas-meter was installed. It was, however, found to be too unwieldy and so was replaced by an orifice and a manometer which was supplied by the Author. The apparatus occupied about as many cubic inches as the other meter required cubic feet. For experimental purposes the ease with which the apparatus could be placed anywhere in a pipe system was especially convenient. Also the apparatus showed the rate of flow at a glance. It was therefore not necessary to pass a considerable quantity of gas or air before a reading could be made, as was the case when a meter which recorded by counter was used.

Now that compressed air for coal-mines was finding so much favour it was desirable to measure the air taken by various types of machines. For example, when such machines as coal-cutters were driven by electric motors there was never any doubt as to the amount of energy absorbed. Ammeters were a guide to the men working such motors and to those in charge. Compressed-air machinery required meters which occupied as little space, and which were as cheap as the ordinary ammeter. The Hodgson meters in their various forms approached nearest to this ideal.

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The AUTHOR, in reply to the Discussion and Correspondence, stated, with reference to Dr. Brightmore's question, that all of the equations Nos. (12), (14) and (16) were exact. The approximate equation (11) was only introduced in order to express equation (8) in terms of the pressure difference, and to make it more easily evaluated. That was stated in Appendix II of the Paper. In this connection it was interesting to note that in the case of square-edged orifices, such as that shown at IV, *Fig. 17*, the product $\Omega\phi$ in equation (24) was very nearly constant for the higher values of P_2/P_1 and n (say, when P_2/P_1 was greater than 0·88 and n was greater than 6); so that, for these higher values, the discharge through such orifices could be calculated within $\pm \frac{1}{2}$ per cent. by means of the simple formula— The Author.

$$Q = 0\cdot665\,N\left[(p_1 - p_2)\frac{p_1}{T_1}\right]^{\frac{1}{2}} \text{ lbs. per second} \quad . \quad . \quad (55)$$

which involved neither Ω nor ϕ.

With regard to Dr. Unwin's question, the meter shown in *Fig. 21* was designed to indicate the weight of steam passing under steady pressure conditions. In those cases where the pressure varied considerably, the meters were fitted with a device which automatically corrected for variations in pressure.

With reference to the remarks of Mr. H. E. Jones as to the difficulty of evolving a gas meter on the Venturi principle which took account of the varying specific gravity of the gas, Appendix XI dealt with the theory of such a meter, and meters designed on the lines there laid down had proved to be very accurate in actual use.

In answer to Captain Sankey's question about the Gate meter, whose theory was given in Appendix IX, if the pulsations were extremely rapid and of large amplitude, it was not possible to obtain very accurate measurements of the flow by means of meters of this type. In most cases, however, the pulsations, if rapid, were of small amplitude, and if of large amplitude, usually had a frequency of less than 200 per minute; so that it was possible to make the oscillating parts of the meters sufficiently light to enable such flows as were most frequently met with in actual practice to be measured with commercial accuracy. As to the accuracy of the Venturi air meters on the Rand, Mr. Hadley, the Managing Director of the Victoria Falls and Transvaal Power Company, in a Paper read before the Institution of Electrical Engineers in

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The Author. 1912, after the meters had been in use for about a year, had said that they had well fulfilled their guarantee of accuracy.[1]

The Author wished to thank Dr. Stanton for his remarks, and to express his agreement with the suggestion that in the case of orifices or nozzles for which the pressure difference varied as the square of the velocity of flow "the limits of speed of flow between which the coefficient of discharge was constant in value should be clearly defined for different fluids." It was also essential that when small nozzles were calibrated in order to determine the discharge of the same fluid through exactly similar nozzles of very much larger size which could not be so calibrated (as was sometimes done in the case of very large Venturi tubes for measuring water flows) to carry out the calibration of the smaller nozzles at "corresponding speeds." These were in the case of water flows quite correctly determined by means of the $\frac{V\,d\,W}{\mu}$ criterion[2], *provided that the nozzles were also geometrically similar with respect to their smoothness.*

The Author had found it to be preferable, when employing metering devices which depended upon a measurement of the differential pressure across a nozzle or orifice, to use, where possible, only those types of nozzle or orifice for which it had been established that the flow, within narrow limits, was proportional to the square root of the differential pressure over the whole range of flow to be measured. This simplified the calibration, and enabled the recording mechanism for various meters to be standardized.

Dr. Stanton's statement "that he could not agree with the Author's practice of taking the values of the pressure ratio P_2/P_1 as the criterion of the condition of flow," raised a point of some interest; namely, that the $\frac{VdW}{\mu}$ criterion only held for elastic fluids in these cases where the velocity was such that there was no appreciable difference of density between the upstream and the throat of the measuring nozzle or orifice, i.e., in these cases where the elastic fluid behaved as an incompressible fluid. A reference to equation (24), and to the values of ϕ plotted in *Fig. 24*, would show that, for air flows, the deviation in the value of ϕ, due to the elastic properties of the air, was greater than 1 per cent. when the value of the ratio P_2/P_1 was as nearly unity as $0 \cdot 98$.

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[1] Viz.: $\pm$ 1·5 per cent. from full load to three quarters full load.
$\pm$ 2 per cent. at one-third of full load.
$\pm$ 2·5 per cent. at one-tenth of full load.

[2] μ is the "coefficient of viscosity," the kinematical viscosity, ν, being $\frac{\mu}{W}$.

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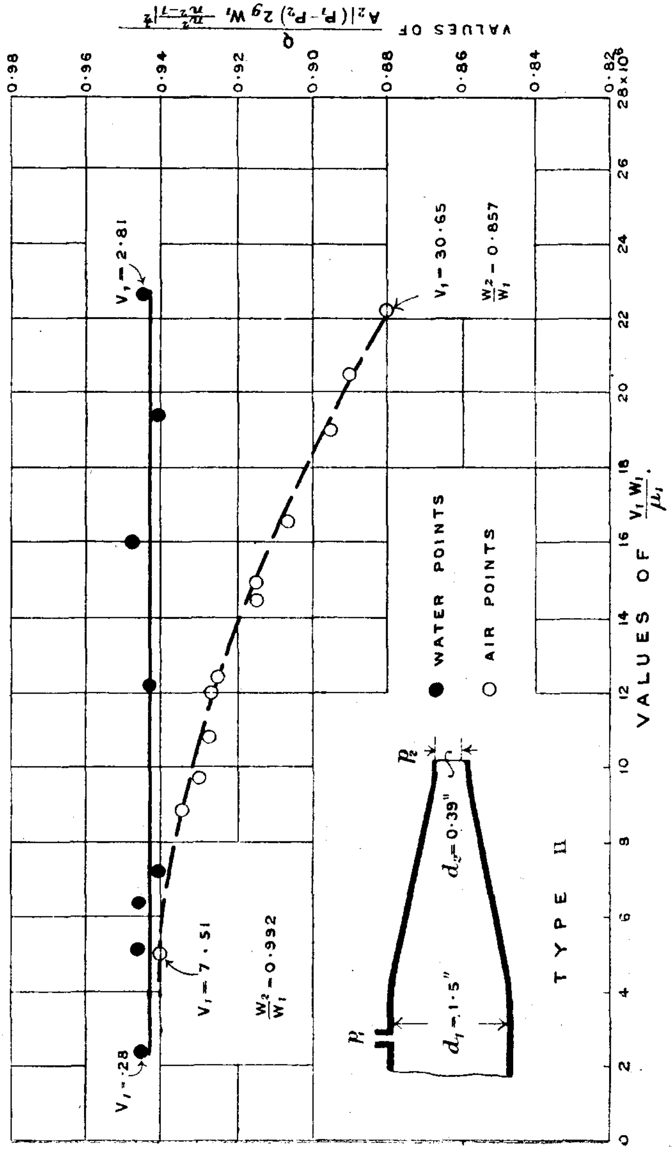
The Author.

Fig. 32.



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The Author. This point was also clearly brought out in *Figs. 32* and *33*, in which values of $\dfrac{Q}{A_2\left[(P_1 - P_2)\,2gW_1\,\dfrac{n^2}{n^2-1}\right]^{\frac{1}{2}}}$ *, (which corresponded to Dr. Stanton's $\dfrac{p_1 - p_2}{\rho v^2}$) had been plotted against $\dfrac{V_1 W_1}{\mu_1}$ for

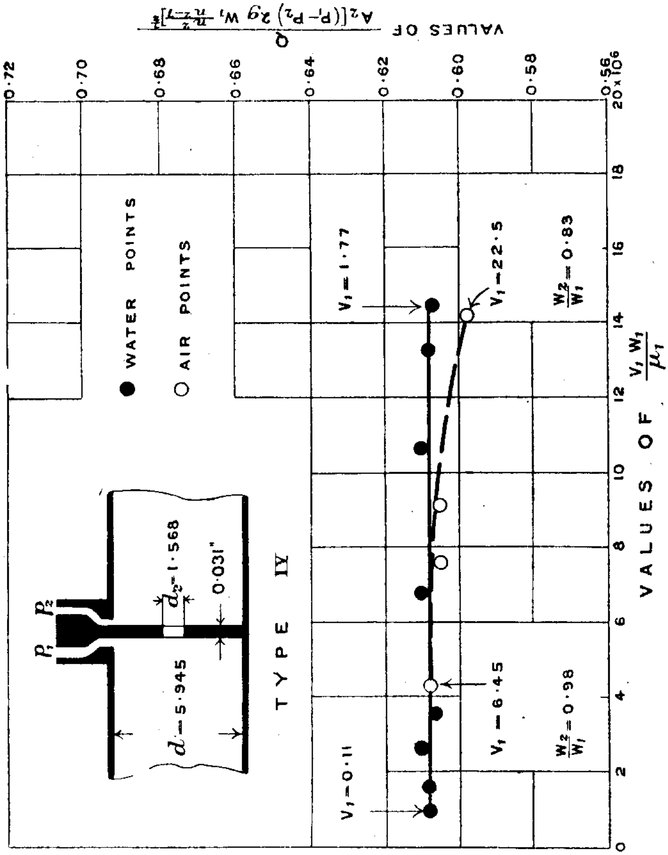

Fig. 33.

water and air flows through a nozzle and an orifice. These figures showed that the values of $\dfrac{Q}{A_2\left[(P_1 - P_2)\,2gW_1\,\dfrac{n^2}{n^2-1}\right]^{\frac{1}{2}}}$ for water and air flows deviated from one another at the higher velocities,

* See equation (11).

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i.e., when the value of the ratio of the densities at the throat and the upstream of the nozzle or orifice (W_2/W_1) deviated appreciably from unity. The Author.

On consideration, it would be apparent that when the differences of density on the upstream and downstream sides of the orifice were considerable, and the elastic properties as well as the viscosity of the fluid had to be taken into account, it was not possible to obtain any simple and exact general criterion of flow which covered the case of both liquid and gaseous discharges, or even the discharge of different gases through the same nozzle. It was, however, possible, in the case of any *one* fluid, such as air, to plot the results of a complete set of tests taken on one size of orifice, so that the discharge coefficients obtained for this one size could be used for any geometrically similar orifice of any upstream diameter (d_1) when discharging at any upstream density (W_1). The form which the results took in the case of a square-edged orifice such as that shown at IV, *Fig. 17*, when so plotted, was indicated in *Fig. 34*, p. 190.

The reasoning on which this figure was based was as follows:—If viscosity alone had to be taken into account, the discharge coefficient, Ω, should be constant when $\dfrac{V_1 d_1 W_1}{\mu_1}$ was constant. If, on the other hand, elasticity alone had to be considered, it was obvious that, for a given compressible fluid which followed Boyle's law, the flow conditions were similar when the ratio P_2/P_1 was constant.

Both these conditions were fulfilled in the case of such a fluid $\left(\text{for which } V_1 \text{ was proportional to } (T_1)^{\frac{1}{2}} f\left(\dfrac{P_2}{P_1}\right);\text{ this followed from equations (4}a\text{) and (8)}\right)$, when the ratios P_2/P_1 and $\dfrac{(T_1)^{\frac{1}{2}} f\left(\frac{P_2}{P_1}\right) d_1 W_1}{\mu_1}$ were constant, that is, when P_2/P_1 and $\dfrac{d_1 P_1}{(T_1)^{\frac{1}{2}} \mu_1}$ were constant. If, therefore, curves were plotted connecting Ω and P_2/P_1 for a given orifice and a given elastic fluid for various values of $\dfrac{d_1 P_1}{(T_1)^{\frac{1}{2}} \mu_1}$, the value of Ω could be obtained for any similar orifice for the same fluid for any values of P_2/P_1, d_1, P_1, and T_1. If elasticity alone were taken into account—and this was usually all that was necessary for the velocities and sizes of orifices that occurred in commercial metering—the whole group of curves shown

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The Author. in *Fig. 34* reduced to the single line AB. It was because the variations in the discharge coefficient which were most usually met with under the conditions of the commercial metering of gases were due to elasticity rather than to viscosity that the

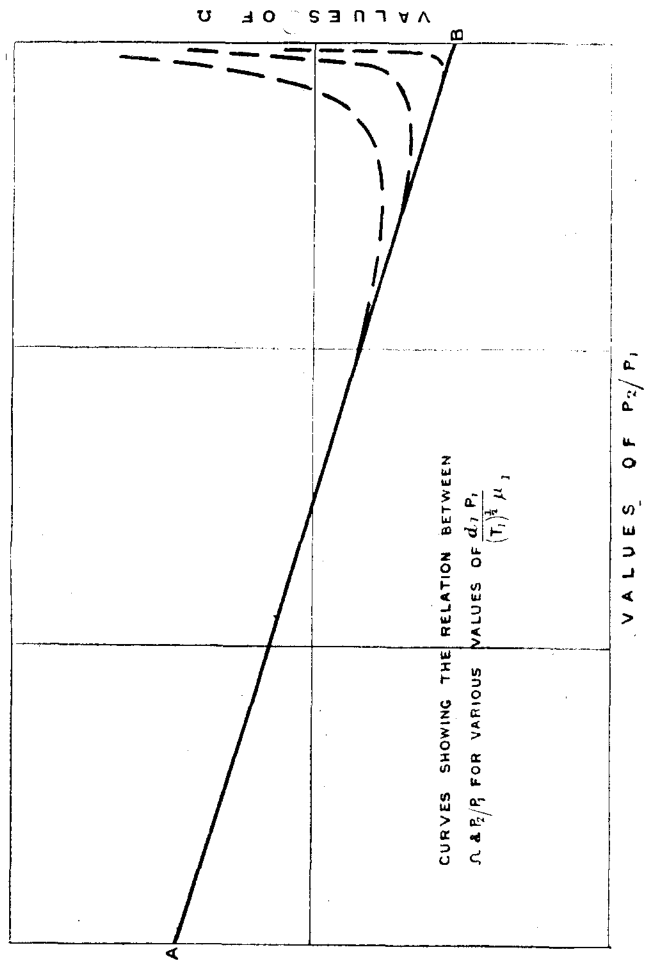

Fig. 34.

Author had taken P_2/P_1 and not $\dfrac{VdW}{\mu}$ as the criterion of flow throughout the Paper. When it was realized that, except in the case of small orifices (say $\frac{1}{4}$ inch or $\frac{1}{16}$ inch in diameter), the dotted portions of the curves shown in *Fig. 34* occurred only at

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values of P_2/P_1 which were very nearly unity; it would be seen that the P_2/P_1 criterion was the correct criterion to use under the given conditions. The Author.

Fig. 35 showed values of $\dfrac{Q}{A_2\left[(P_1 - P_2)\, 2\, g W_1 \dfrac{n^2}{n^2-1}\right]^{\frac{1}{2}}}$ for water and air flows through a square-edged orifice plotted against $\dfrac{V_1 W_1}{\mu_1}$ when the ratio W_2/W_1 was very nearly unity in the case of the air flows, i.e., when the rate of flow was such as to cause no appreciable expansion of the air. It would be seen that under these conditions the values of $\dfrac{Q}{A_2\left[(P_1 - P_2)\, 2\, g W_1 \dfrac{n^2}{n^2-1}\right]^{\frac{1}{2}}}$ for water and air flows plotted very well together.

In reply to Mr. Barnes, the Author stated that he had carried out very few experiments on the discharge of water into air through circular orifices. It was therefore impossible for him to criticise on experimental grounds the formula put forward by Mr. Barnes. Mr. Barnes' formula was, however, contrary to the law that for geometrically similar orifices discharging the same incompressible fluid at the same temperature, the discharge coefficient, calculated on the basis that the velocity varied as the square root of the head, was constant for the same values of V *d*. For, obviously, if the value of the discharge coefficient was constant for any particular value of the product V *d*, and did not vary with V, it could not vary with *d*. It seemed probable to the Author that the apparent deviation from the law of flow through similar orifices shown by Mr. Barnes' formula was due to the orifices tested by him not being geometrically similar.

In the case of square-edged orifices placed in the pipe-line there was no very definitely marked critical velocity. The discharge coefficient gradually approached a limiting value, as shown in *Fig. 35*. This variation in the coefficient was usually only noticeable in the case of small orifices, as, in the case of the larger orifices it occurred at very low heads. These low heads were difficult to measure accurately with ordinary apparatus. If it were ever found necessary to determine the value of the discharge coefficient for moderate and large size orifices and nozzles when discharging at very low velocities, special apparatus would need to be devised. If, however, it was assumed that the values of the discharge coefficient varied with the values of the ratio $\dfrac{VdW}{\mu}$, one could forecast with

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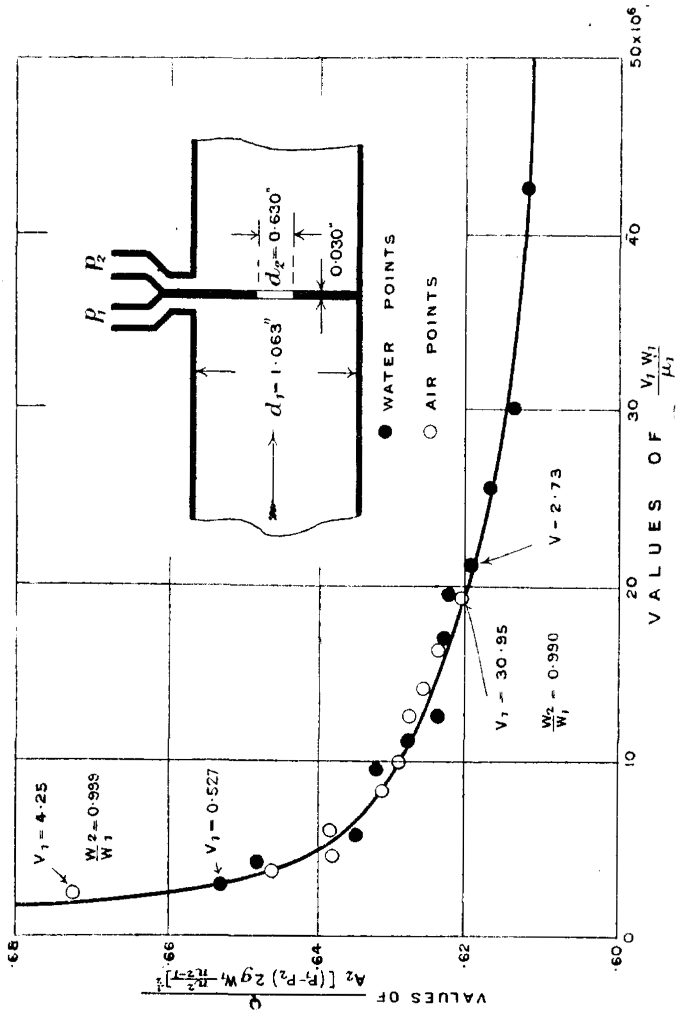
The Author. considerable accuracy what happened in the case of the larger orifices by means of tests carried out on small orifices at fairly high velocities.[1] A good deal of the information asked for by

Fig. 35.



[1] If it was assumed that V was proportional to $(P_1 - P_2)^{\frac{1}{2}}$; and in this assumption there was a slight error if Ω was not constant; it followed that, for geometrically similar orifices, the value of Ω depended upon the ratio $\frac{(P_1 - P_2) W}{\mu^2}$; provided that there was no appreciable change in the density of the fluid as it passed the orifice.

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Mr. Barnes could therefore be deduced from the data given in *Fig. 35.* The Author.

In connection with Mr. Harper's remarks, the Author wished to state that the ease with which successful meters were produced was, in a great measure, due to the fact that the Engineers who were responsible for the air side of the power scheme were able to give what proved to be a very accurate forecast of the conditions under which the meters had to work.

In reply to Mr. J. Newell Reeson, the Venturi gas meters supplied to Sydney did not correct for density, as, at the time they were supplied, the density correcting meters were not sufficiently developed to warrant their being sent so far afield as Sydney.

With regard to the use of the rotary meters for the measurement of large volumes of gas, these had an advantage over meters on the Venturi principle in that they measured directly in volume units. It was, however, difficult to make them reasonably accurate over a greater range than 1 to 10, if a pressure drop of 1 or 2 inches was not exceeded. This was all that the gas companies were usually prepared to allow. Their accuracy was easily impaired when measuring dirty gas by the clogging of the jets, and in such cases it was not possible to say whether a meter was registering accurately or not without first dismantling it. Further, it was necessary to calibrate each meter over the whole range of flow to ensure that the speed of the impulse wheel was proportional to the volume passing at all rates of flow to be measured. The Author had done a great deal of work on meters of this type, and had designed and tested a new type of rotary meter in which an endeavour had been made to minimize the above faults.

In conclusion, the Author wished to thank all those who had taken part in the Discussion, and to emphasize the remark made by Mr. Clemens Herschel—whose contribution to the discussion he had read with peculiar pleasure—that each development in the art of metering paved the way for new possibilities and wider usefulness in industrial processes.

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