AIR-COMPRESSORS.*

NOTE ON TESTING.

BY WILLIAM REAVELL, OF IPSWICH, *Member of Council.*

With the rapidly growing use of compressed air for so many purposes, it is highly desirable that some standard form should be adopted by which the efficiency of compressors can be ascertained, alike for the protection of the user and for the development of the art. "Efficiency" is a term sometimes used loosely, and the technical press still occasionally contains examples of so-called "efficiency tests," which fail to correct the volume of delivered air for the high temperatures reached while compressing, or which ascertain the volume by calculation from the indicator card, or fail to give the figures for "overall efficiency."

No test should be regarded as complete which fails to give :—

- (a) The net horse-power applied at the compressor shaft.
- (b) The volume of air actually delivered, expressed in terms of free air, that is, air expanded down to the atmospheric pressure.
- (c) The corrected volume by reducing it to the equivalent volume when cooled down to the same temperature as that of the air aspired.

For small machines the "receiver" method of testing is frequently

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used, and the time taken to pump up an air-receiver of known capacity to the required delivery pressure is noted. Such a method is inaccurate, because the real conditions under which the compressor is subsequently to work are not reached until the instant when the final pressure is attained and the test stopped. A more correct way is to take "time" observations when the pressure has reached, say, one atmosphere below the required pressure and continued till the pressure has reached one atmosphere beyond this pressure.

To obtain really reliable results, however, an auxiliary receiver A should be placed between the receiver B of known volume, which is to be filled, and the compressor (as in Fig. 16). A regulating valve C is fitted between the two receivers, and the test receiver is fitted with a discharge-valve D of ample area. When the

FIG. 16.
*Receiver Tests. Arrangement of
Main and Auxiliary Receivers and Valves.*

compressor is started the valve C is regulated so as to maintain the full pressure in A while B is discharging freely to atmosphere through D, which is a rapid action lever type sluice-valve or cock. If, then, D is closed at the instant of commencing the test and the time taken to fill B to the same pressure as has been maintained in A, the compressor performance will have been at constant pressure. It only remains to correct the volume in the receiver B for the difference in temperature, as compared with the temperature of the aspired air.

Observations of the exact temperature in the receiver at the instant of completion of test are difficult to obtain, but if the valves C and D are tight when closed, the air in B should be allowed to remain while its pressure is gradually reduced as the temperature

falls. If, then, the pressure is noted when it has ceased falling, a calculation based on this lower pressure will give the correct volumetric efficiency of the compressor.

Receiver tests are not applicable to compressors of large volume, and diaphragm or nozzle tests must then be resorted to. Where the machine to be tested is of the reciprocating type, it is advisable to put at the end of the discharge-pipe from the compressor an air-receiver of sufficient capacity to damp out pulsations. The resistance against which the compressor works is effected by a control-valve placed between the compressor and receiver. A thin plate is fixed to the outlet of the receiver, and has a circular hole through which the air escapes to the atmosphere. A slight pressure difference will then be set up between the receiver and the atmosphere which will remain constant as soon as a state of equilibrium is reached. This pressure difference furnishes a means of calculating the volume of air delivered. The equation for the air flow should be based on the adiabatic expansion of air. This, however, as is well known, involves the use of exponential equations and complicates the work thrown on the staff in the average test-house. If, therefore, an orifice is adopted which is sufficiently large to give but a slight pressure difference, the ordinary hydraulic formula can be applied, seeing that the actual change in the density of the gas would be negligible. For example, a pressure drop of as much as 12 inches will only give an error of 1 per cent in velocity when applying this formula. It is the Author's practice to use orifices or nozzles of sufficient diameter to keep the pressure drop below this figure. In the hydraulic formula we have

$$V = C_1 A u.$$

Where

V = volume discharged in cubic feet per second.

C_1 = coefficient of contraction.

A = area of orifice in square feet.

u = actual velocity in the orifice in feet per second.

$$u \text{ is given by } C_2 \sqrt{\frac{2g(P_1 - P_2)}{\rho}}$$

Where

C_2 = coefficient of velocity.

g = gravitational constant = 32.2.

ρ = density of air or gas in lb. per cubic foot.

$P_1 - P_2$ = pressure difference in lb. per square foot = $5.18 \times h$, where h = head of water gauge in inches.

There are two drawbacks to this method ; in the first place it is difficult to ascertain accurately the temperature of the air in the receiver, which is necessary for determining the specific weight w ; secondly, the discharge coefficient is not constant, but varies with the pressure ratio $\frac{P_2}{P_1}$; it is also affected by the thickness of the orifice plate. A reference to text-books will reveal considerable divergence in the value of the coefficient C , and any results obtained by the adoption of a certain value may be ± 5 per cent, or even more, from the true value. Again, the readings are frequently affected by the existence of air currents across the face of the orifice. For these reasons it is better to make use of the pressure drop produced

FIG. 17.—Diaphragm.

FIG. 18.—Nozzle.

artificially in the pipe-line through which the air passes by the insertion of a definite resistance, such as a diaphragm or nozzle, and this recommendation holds good whether a receiver is used or not.

If the machine being tested is of the rotary or turbo type, obviously a receiver is not necessary. The diaphragm is usually a thin metal disk, held conveniently between flanges on this delivery pipe, as in Fig. 17. In place of this a rounded nozzle is favoured in modern practice, this being arranged as in Fig. 18.

Fig. 19 shows the arrangement for measuring the temperature

and pressure. Pressure connexions are arranged on the up- and down-stream side, which lead to the two legs of a U tube, usually filled with water. It is advisable to keep the pressure drop reasonably low, say below 20 inches w.g., in which case the specific weight at the restriction may be taken to be the same as on the up-stream side. Only three readings require to be taken, namely, the pressure drop h across the diaphragm or nozzle; the pressure p in front of the nozzle, and the temperature t . The two latter values are required to determine the density of the air immediately in front of the restriction.

The formula is the same as given above, but here again it is

FIG. 19.—Arrangement of Nozzle Testing Apparatus.

known that the coefficient of discharge of a diaphragm is a variable quantity, dependent on the conditions. It is important, therefore, in comparing different machines under test, to keep a fairly constant pressure drop. The coefficient depends also upon the ratio $\frac{d}{D}$ and upon $\frac{t}{D}$, t being the thickness of the diaphragm disk. For these reasons one cannot assume a value for the discharge coefficient which is applicable to all cases; a diaphragm of this type should be calibrated by careful laboratory methods under conditions similar to those for which it will be used.

Rounded Nozzle.—The rounded nozzle, Fig. 18, is more expensive

to produce, especially when required for large volumes, but it has the great advantage that its coefficient of discharge is practically constant, and is very close to unity; a well-designed nozzle has a coefficient between 0.98 and unity; indeed, the nozzle as recommended by the Verein Deutscher Ingenieure possesses a coefficient of about 0.99 to 0.997, which, for practical purposes, may be taken as unity. A sketch of this nozzle is given herewith, with the principal proportions indicated, Fig. 20.

For practical purposes the test shop must be provided with a simple formula which has all the various thermo-dynamical constants, discharge coefficients, conversion factors and nozzle particulars combined in one single figure. It is usual to demand the number

FIG. 20.
*German
Standard
Nozzle.*

of cubic feet of free air in terms of suction conditions which the compressor actually delivers, and in addition to the three readings, namely :—

The pressure drop H across the diaphragm.

The pressure p in front of the nozzle.

The temperature t .

the barometric pressure and temperature of the atmosphere at the time of the test must also be observed. These values are then to be inserted in the nozzle formula below, and the mathematical operation is thus reduced to a simple slide-rule problem.

Nozzle formula based on the hydraulic formula using the German standard nozzle :—

$$V_s = 15.8 \times A \times \frac{(t_s + 460)}{\text{Bar}} \times \sqrt{H \times \frac{(\text{Bar} + \text{Hg})}{(t + 460)}} \text{ (cub. ft. per sec.)}.$$

This formula will give results within + or - 1 per cent of the true value, if the pressure drop H is not more than 12 inches w.g., when discharging to atmosphere.

The steps by which this formula is arrived at are as follow :—

The discharge velocity, that is, the velocity at the throat of the nozzle is

$$u = \sqrt{2gh} \text{ (ft. per sec.)},$$

h being the head of the gas in feet corresponding to the pressure drop across the nozzle.

$$\text{Now } h = (P_1 - P_2) \times v.$$

Where

P_1 = Absolute pressure before nozzle.

P_2 = Absolute pressure behind nozzle. Both expressed in lb. per sq. ft.

v = Specific volume of air in front of nozzle, cub. ft. per lb.

v can be calculated from the general gas equation, $Pv = RT$, in which

P = Absolute pressure before nozzle = P_1 .

T = Absolute temperature before nozzle = $(t + 460^\circ)$ degrees Fahrenheit.

R = the gas constant = 53.2 for air.

Hence

$$v = \frac{RT}{P_1} \text{ and by substitution we get}$$

$$u = \sqrt{2g(P_1 - P_2) \frac{RT}{P_1}} \text{ (ft. per sec.)}$$

The discharged volume in terms of the entrance conditions P_1 and T is—

$$V_o = C \times u \times A \text{ (cub. ft. per sec.)}$$

where A = area of nozzle throat in sq. ft.

C = a discharge coefficient which for this type of nozzle may be taken as unity.

Usually it is desirable to express the discharge volume in terms of free air, that is, suction conditions, the corresponding absolute pressure being P_s and temperature T_s . Thus

$$\begin{aligned} V_s &= V_o \times \frac{P_1}{P_s} \times \frac{T_s}{T} \\ &= A \times \sqrt{2g(P_1 - P_2)} \times \frac{RT}{P_1} \times \frac{P_1}{P_s} \times \frac{T_s}{T} \\ &= A \times \frac{T_s}{P_s} \times \sqrt{2g \frac{RP_1}{T} (P_1 - P_2)} \text{ (cub. ft. per sec.)}. \end{aligned}$$

Actually the pressure drop $(P_1 - P_2)$ is measured by means of a water gauge, the reading H (see Fig. 19) being expressed in inches. This value must be converted into lb. per sq. ft. thus

$$P_1 - P_2 = H \times 0.036 \times 144 = 5.18 H.$$

Again the absolute pressure P_1 is the sum of the barometric pressure (Bar) plus the pressure (Hg) as read off the mercury gauge in inches, which involves the following conversion

$$P_1 = (\text{Bar} + \text{Hg}) \times 0.49 \times 144 = 70.5 (\text{Bar} + \text{Hg}).$$

Similarly $P_s = 70.5 \times (\text{Bar})$, 0.036 and 0.49 being the weight of 1 cub. in. of water and mercury respectively.

By substitution we get an expression for the volume of air discharged in terms of free air (suction) conditions thus

$$\begin{aligned} V_s &= A \times \frac{t_s + 460}{70.5 \times (\text{Bar})} \times \\ &\quad \sqrt{2 \times 32.2 \times 53.2 \times 70.5 \times (\text{Bar} + \text{Hg}) \times 5.18 H} \\ &\quad (t + 460) \\ &= 15.8 \times A \times \frac{(t_s + 460)}{\text{Bar}} \times \sqrt{H \times \frac{(\text{Bar} + \text{Hg})}{(t + 460)}} \text{ (cub. ft. per sec.)} \end{aligned}$$

If it is accepted that the risks of error, due to assumptions from the published Tables of the coefficient of contraction and coefficient of velocity, are less with the rounded nozzle than with the diaphragm, and still less with the German standard nozzle than with the rounded nozzle, the same general objection can be raised to all of them, namely, that any results based on them depend on the accuracy of the assumed coefficients. It was for this reason that in Germany, just prior to the War, attempts were made to determine a form of

nozzle contour which would have a sensibly constant discharge coefficient in the neighbourhood of unity, and which, with reasonable accuracy, remained of the same value for all geometrically similar nozzles. The nozzle shown in Fig. 20 is the outcome of these experiments.

Another investigator, Dr.-Eng. J. Brandis, of Aachen, examined the hydraulic formula for use with diaphragms and established certain rules for the design of suitable diaphragms which, in conjunction with his formulæ, gave very reliable results. For any one interested, full particulars will be found in his book on "Messung Von Gasmengen," published by M. Krayn, Berlin, 1913.

Reference should also be made to the most recent investigations on this subject by the Physikalisch Technische Reichsanstalt in Berlin, an institution equivalent to the National Physical Laboratory. These investigations are based upon Reynolds' Law of Similarity and its application to the pressure drop in a smooth tube by means of which it is sought to establish an accurate method for measuring the volume of the fluid passing through the tube. A summary of these investigations has been published recently in the *Zeitschrift des Vereines Deutscher Ingenieure* (25th Feb. 1922), and the accuracy of the results obtained, both with air and water, appears highly satisfactory, the mean error between the measured and the calculated values being about $\frac{3}{10}$ per cent.

This problem of more accurately determining the measurement of volume of air and other gases under varying conditions is receiving the attention of scientists in other countries, and it is hoped that the time is not far distant when investigations will be made by the National Physical Laboratory, or some equally reliable Institution, which will place the British Engineer in the same position as that arrived at by German users as a result of the tests made in that country.

The Author desires to thank the various firms who have been good enough to supply him with information for the purpose of this Paper; also the members of his staff for assistance rendered in the preparation of the diagrams and papers.

The Paper is illustrated by 5 Figs. (Nos. 16 to 20).

Discussion in London, on Friday, 24th November 1922.

The CHAIRMAN (Mr. Richard W. Allen, C.B.E., (Member of Council) said that Mr. Reavell's Paper was in two parts, the first of which had been read at the Paris Meeting; but so interesting was it, that the Council had thought it would be a pity if the members of the Institution generally did not have the benefit of the opportunity of discussing it in London. Therefore, Mr. Reavell had once more read the Paper, but it had been greatly strengthened—and it had been, in his own opinion, made very much more valuable—by the second portion.

He thought the Paper could be looked upon as an historical one, because he did not think many Papers on air-compressors had been read before the Institution; and to-day high-pressure air was used very much more largely than had hitherto been the practice. For instance, the production of the Diesel engine had necessitated high air-pressures, and therefore it was very desirable that those who knew very little about the subject could turn to the Proceedings and read Mr. Reavell's Paper, which very clearly showed the history of the design, from what he might term, the ordinary, reciprocating type of compressor, then to the opposed piston type of compressor, and ultimately, as the Author had shown, to a compressor of the turbo type. How curious fashion was in engineering! At the present time one hardly ever saw an ordinary reciprocating steam-engine being built. It was all steam-turbines, and it was the same with the air-compressor. The air-compressor was probably a thing of the past, and engineers had now to look to the turbo air-blower: he believed that was the technical term, although he did not know why it was called a blower in one case and a compressor in another. The Author had shown him one or two examples of the rotary air-compressor, and it was a very remarkable apparatus. That was probably due more or less to the great advancement which had been made in the last two years in materials. He believed compressors of that kind could hardly have been constructed before the War. It was only the experience which had been gained in the War of the progress in steel—nickel-chrome steel and similar kinds of steel—that had enabled those compressors to be designed.

With regard to measuring, he had spent many years in measuring low-pressure air, up to 6 inches or thereabouts, and he had always found a very great difficulty. Air was so very different

from water. From his point of view he did not very much mind what the method of measuring was so long as everybody agreed on the method, because the object of having an apparatus for measuring was to compare, from day to day, the various designs, so that progress was able to be made by means of comparison. With regard to water, it was recognized, not only in the British Empire but throughout the world, that the Venturi meter was the only means of measuring water up to certain quantities. He thought the Author was to be congratulated on his suggestion—he would put it in that way—of a method, which it was to be hoped might be adopted or improved by the National Physical Laboratory, so that all those who were engaged in the use of high-pressure air could have some standard means of measurement.

With those few remarks he congratulated the Author upon the Paper, and proposed to the members that they should give Mr. Reavell a very hearty vote of thanks.

The vote of thanks was then put and carried with acclamation.

Mr. A. BAILEY (National Physical Laboratory) remarked that not being connected in any way with the compressor trade or with the manufacture of compressors, he would confine himself to the Note on Testing. The Author suggested that the National Physical Laboratory should carry out some investigations on methods of measuring flow of air. The National Physical Laboratory had been doing that for the last twenty years. The standard method which was used was the Pitot tube. The Laboratory had done a very considerable amount of work, using the Pitot tube as a means of measuring flow of air, and they considered that that was practically an absolute standard. The Pitot tube was a very adaptable instrument. One could get a piece of hypodermic tubing, of something like three-hundredths or four-hundredths of an inch diameter, simply bend it and place it facing the steam, and by means of a sensitive manometer one could measure the total head at any point in the stream. In 1912* they had proved that the difference between the total head measured by means of a Pitot tube and the static pressure of the air at the same point was $\frac{1}{2}\rho v^2$. So that, knowing the density of the air, one could calculate very accurately the velocity. That was the means always adopted at the National Physical Laboratory for measuring flow of air.

* See Advisory Committee for Aeronautics: Reports and Memoranda, No. 71.

Dr. Stanton in 1913 had read a Paper* before the Royal Society, in which he showed that if a fluid of any kind was flowing through a pipe, the flow would always be similar, that was to say, the coefficient of discharge would be the same, provided the value of the velocity into the diameter of the tube, divided by the kinematical coefficient of viscosity of the fluid, were the same in the various tests; that was to say one could determine the flow through a pipe by one measurement with a combined Pitot and static pressure tube, where water or air or any other fluid was being used. By adapting the results of that Paper, it would only be necessary to place a Pitot tube at the axis of a pipe, and make sure that the velocities were sufficient to predict the actual quantity of fluid flowing through by means of one manometer measurement.

The National Physical Laboratory had had no experience at all with the nozzles described in the Paper. They had not, at any rate, carried out any tests on nozzles, as such. They had tested flow meters which were operated by means of a nozzle, but the tests had really been on the meter and not on the nozzle. Therefore, he could not speak from any experience with nozzles. As far as he understood, there were various troubles in those nozzles. He did not know really that it was definitely decided as to where the pressure points should be placed. In several of the diagrams they were apparently on the face of the plate, one facing upstream and one facing downstream. In another diagram they were some little distance away from the flange, in the side of the pipe; and as far as he could gather from reading results of experiments which had been carried out, there still seemed some little divergence as to which was the best place for putting those points if the drop of pressure across the nozzle was to be determined.

Then again, there was the question of the variation of the coefficient. That, he took it, as Mr. Reavell mentioned, depended on the thickness of the plate, and he thought it would also depend, judging by Dr. Stanton's Paper of 1913, upon the velocity with which the air passed through the plate; that was to say, to get a similar coefficient of discharge for a plate like that, one would require to have $V.D.$ over the kinematical coefficient of viscosity constant, the kinematical coefficient of viscosity being the ordinary coefficient of viscosity divided by the density.

Mr. E. R. DOLBY asked Mr. Bailey to give the Meeting one or two notes about the most ingenious hot-wire instrument of

* Phil. Trans. Roy. Soc., Series A, vol. ccxiv.

Mr. Bailey's invention, which he had seen him using at the Laboratory. It was an extremely interesting piece of apparatus for measuring air.

Mr. A. BAILEY said he did not think the particular piece of apparatus to which Mr. Dolby referred was quite germane to the Paper. It was a hot wire anemometer for measuring low rates of flow of air. He did not want to take the credit for having designed it. All he had done was to adapt one for measuring direction of flow of air. The hot wire anemometer had been designed some years ago mainly by King, and by others, amongst them being Professor Morris of the East London College. The principle was as follows:—

A piece of fine platinum wire was heated by means of an electric current and its resistance, in still air, was measured by means of a Wheatstone Bridge. If, then, a stream of air were allowed to flow over the wire, heat was carried away and the wire was cooled, and there was a change in the resistance; this change of resistance formed a measure of the rate of flow of air over the wire. It was an extremely delicate instrument and rates of flow down to about half a foot per second could be measured fairly accurately.

The principle of the instrument which he himself had adapted was as follows: The "hot wire" consisted of a piece of platinum wire about $1\frac{1}{4}$ inches long and 0.004 inch in diameter, and one end of this was attached by means of silver solder to one end of a piece of manganin wire, about $\frac{1}{8}$ inch diameter; the end of the manganin wire was bent round so that the two wires were parallel and at a distance of $\frac{1}{8}$ inch apart. The two free ends were connected to copper leads which passed through an insulated cap on the end of a piece of brass tube, and an electric current was passed through these leads to the hot wire from terminals at the other end of the tube. The hot wire was in line with the axis of the tube, so that when the tube was rotated, the manganin wire described a cylindrical surface with the hot wire as axis. So long as the plane of the two wires was inclined at 20° or more to the direction of flow of the air, the proximity of the manganin wire had no effect and the instrument acted as a hot wire anemometer for determining speed, but as the manganin wire came in front of the hot wire, it shielded the latter from the flow, and the temperature (and, therefore, the resistance), increased; if the galvanometer readings were plotted against angular positions a very definite peak was obtained in the curve at the point where the plane of the wires was parallel to the direction of flow.

[For a more full description see Aeronautical Research Committee,

Reports and Memoranda No. 777 ; published by H.M. Stationery Office.]

Mr. R. L. QUERTIER said he would confine himself to the question of compressor valves. It was very interesting to compare the compressor with the steam-engine. The working cycle in one was reversed in the other. In the compressor one was building up pressure, and in the steam-engine one was letting pressure down, and when it was looked into it was found that mechanically operated admission and exhaust valves had to be used in the steam-engine, whereas in the compressor automatic valves could be adopted. As far as air delivery from the cylinder was concerned one naturally used a spring-loaded valve, but ten years ago there were a great number of firms who used either piston-valves or some form of mechanically operated valve to admit air into the cylinder, and they were thus able to save the drop in pressure of perhaps $1\frac{1}{2}$ lb. due to attenuation in the case of a double-acting compressor and perhaps 4 or 5 lb. in the case of a single-acting single cylinder compressor ; in the latter case, not only had the resistance of the valve to be overcome, but the actual inertia in the suction main. But these had all been dropped, and he thought he might say that practically every compressor maker to-day, with one or two exceptions, used a plate valve or some form of automatically operated valve for suction. He thought it was quite reasonable they should do so, because there was another side to the question. A piston-valve had to be driven by some form of mechanism, and that absorbed power, and it had been found, he thought, that the amount of power used to drive the piston-valve was practically equal to the amount of loss which would result in using an automatic valve to admit air. Consequently such firms said " We will cheapen our design and simplify it, and get rid of the piston-valve." Of course, what they gained in one direction they lost in the other. He thought that the machine which had been shown with the mechanically operated gudgeon suction-valve was the only one which had persisted right through, and was in use to-day, the reason being simply that with the gudgeon-valve a part of the actual mechanism of the compressor was used to control the suction, and so a mechanically operated valve could be employed to fill the cylinder without attenuation and thus save power and increase efficiency ; and, because it did not introduce any further working parts, there was no added friction and no added complication, so that what was gained in one way was not lost in the other.

Mr. H. HAERLE said he would confine his remarks to the

penultimate paragraph of the Note on Testing, in which the Author foreshadowed some form of standard nozzle and standard formula whereby air and other gases could be measured quantitatively.

It had been his lot to have had a great deal to do with the design of various types of air-compressors, and with the testing of them, and it had gradually dawned upon him that people, especially customers of air-compressors, were very gullible people when they accepted a certain output of air on the basis of a test which was far from accurate. Taking weights and measures, there were standard weights against which weights would be checked at any time; the same applied to measurements of length or area or volume; there were well-defined standards as a basis. But when it came to the measurement of that illusive quantity, to which the Chairman had already referred, namely, air or gas, it seemed very difficult to get at the truth.

The Author had dealt with two types of measurement—static and dynamic; the static, in which a receiver with a known volume was required and which was pumped up, and the dynamic, where the air flowed through a restriction, preferably in a pipe. As to the former, it was amazing how long the test by receiver had persisted—amazing, because it was so difficult to get at an accurate result. For instance, it was almost impossible, unless great precautions were taken, to ascertain the exact volume of the receiver. The reply might be: “Oh, that is easy. You simply fill it up with water.” But the receiver changed in temperature, and therefore its dimensions changed. Further, air was compressed into it, and owing to the internal pressure, the receiver expanded and its volume increased, and the error might amount easily to 1 or 2 per cent. Then there was the possibility of leakages on the way from the compressor to the receiver, and finally one never knew what was the actual temperature of the air in the receiver. He was glad, therefore, to find that the Author had not put very much emphasis on the receiver method, but had proceeded to the nozzle method, which was more scientific and more accurate.

He had been very much interested in the remarks of Mr. Bailey. He knew, of course, that the Pitot tube did give a very accurate reading for ascertaining the velocity, but he was afraid that for practical purposes it was not quite the thing. In a pipe the velocity of the air or gas was not uniform across the whole section. Therefore, if the Pitot tube was put into the axis, the maximum velocity was being measured there, and one must know what correction factor to apply in a circular pipe in order to obtain from that maximum reading the true mean. He had found that this country was behind

the Germans in that we had not got standard regulations and rules for making tests. Inspectors went all over the country, representing firms which purchased compressors amounting to large sums of money. He had seen an inspector who had once had to test a compressor for high-pressure work and he would not have the nozzle test. He insisted on the receiver test, and he had been smart enough to bring with him a calibrated thermometer; he (the inspector) would not trust the ordinary commercial article which was used, though it was remarkably accurate. That inspector had checked the firm's thermometer against his own. There was a difference of a fraction of a degree. Five degrees on the Fahrenheit scale only meant an error of 1 per cent; the discrepancy of a fraction of a degree therefore constituted a negligible error. Yet, after taking that precaution, the inspector had quietly accepted the statement that the contents of the bottle were 16 cubic feet. He dared say that that inspector in his report had given the capacity of the receiver as 16·000 cubic feet and had thought he was very accurate. Many gentlemen present would know that the receiver method could be juggled with. He would mention the following fact, knowing that the Author would not take advantage of it! If one compressed air and made a charge test and then quickly blew down the bottle and charged again, the compressor somehow had improved in the meantime and gave 3 or 5 per cent more air. That could not be done with a nozzle or a diaphragm.

What was really required—and he hoped his few remarks would contribute towards that end—was some authoritative body in this country which would set up some form of standard nozzle and the formula to be used therewith, which would be recognized as an engineering standard. It would have to be a nozzle test or a diaphragm test, but the rules would have to lay down the exact proportions—bore of orifice to the diameter of a pipe; length of straight pipe in front and behind; particulars of the manometer to be used; limits of pressure drop within which the apparatus was allowed to be worked; type of connexions to the manometer, etc. He wondered if the members knew that if one blew through a rubber tube just to clear it, the discharge of carbon dioxide from the lungs would increase the specific gravity of the air in that connexion, which might affect the result as much as $\frac{1}{2}$ per cent. So that it was wise to make the connexions short. Therefore rules and regulations drawn up for the purpose of making standard tests should also specify the length of the connexions and the thickness of the rubber tubes. Then a Table should be set up giving exactly the proportions to which any compressor maker or customer could make a nozzle and know

that, with that nozzle, which was an exact replica of a standard nozzle tested by, say, the National Physical Laboratory, he would obtain results within 1 per cent—or, at any rate, within 2 per cent of the true value.

Captain H. RIAL SANKEY, C.B., C.B.E., R.E., ret. (Past-President), was pleased to hear that the last speaker did not approve of the Pitot tube method for the purposes under discussion. Why should not the Institution of Mechanical Engineers be the Authority to determine the standard method of measuring the discharge from compressors. He would propose that to the Council.

Mr. G. T. GILLESPIE said the portion of the Paper he wished to refer to was that which dealt with receiver tests. He would not for a moment detract from the value of accurate scientific tests with all the necessary laboratory appliances, but there was a wide field which could be covered with advantage by the simple receiver test, using only the instruments to be found on the plant, or which could be cheaply provided, such instruments being a pressure-gauge, revolutions counter, and stop-watch.

There were many air-compressors in use by industrial concerns which were working very inefficiently from the volumetric point of view. If these could be tested with reasonable accuracy under normal working conditions, useful information would be obtained from which improvements in the working of the machine could be planned. The absence of observations of temperature was in favour of the compressor, and therefore if a low volumetric efficiency was proved by the receiver test, it merely meant that a more scientific test would show a lower efficiency still.

Some designers seemed to be under the impression that, provided they gave plenty of area in the suction valve, the delivery could take care of itself, on the plea that all the air drawn into the cylinder must be pushed out. It certainly would be pushed out, but if the effective area of the delivery valve were too small, a rise of pressure in the cylinder well above the receiver pressure would result, some of the air would pass out through the suction valve, and another portion would leak past the piston.

The curve connecting the rise of pressure in a receiver being filled by an air-compressor and the number of strokes from starting of the compressor (or time in seconds if the revolutions per minute were uniform) was a straight line if the volumetric efficiency of the compressor was unity or some other constant value, and assuming isothermal conditions in the receiver, Fig. 21 (page 1102). The

efficiency, however, of a compressor invariably decreased as the delivery pressure rose. The theoretical fall in efficiency, if the cylinder had clearance, followed a certain law, but whether there were clearance or not, there would in practice be a fall in efficiency and the rise in pressure in the receiver would be along a curve as shown in Fig. 21.

In conducting a receiver test, observations were made of the

Fig. 21.

strokes from starting and the corresponding pressure in the receiver. These were plotted as abscissæ and ordinates respectively. The test was stopped when the maximum safe pressure in the receiver was reached. Ordinarily, the efficiency of the compressor was calculated from the quantity of free air forced into the receiver throughout the period from atmospheric pressure to the final pressure. As this efficiency was the average over the whole range of pressure and not the efficiency at any particular pressure, it was valueless as an

indication of the performance of a compressor at the normal or working pressure. This information could, however, be obtained from the curve. If it were required to know the efficiency of the compressor at any pressure p , it might be obtained from the formula :—

$$E = \frac{Q}{p_o q} \times \frac{dp}{dn},$$

where E = volumetric efficiency of the compressor.

Q = capacity of receiver.

p_o = atmospheric pressure.

q = swept volume of cylinder.

p = pressure in the receiver at any instant.

n = number of strokes from starting.

If the tangent were drawn to the curve at the point p , making an angle θ with the zero pressure line, $\frac{dp}{dn} = \tan \theta$.

Therefore to find the Volumetric Efficiency of the compressor at any specified delivery pressure the rule was : Draw a tangent to the curve at the desired point to cut the zero pressure line, find the tangent of the angle it made with this line (that is, perpendicular $\div$ base in their respective units). Multiply this quantity by the capacity of the receiver and divide by the product of the swept volume of the cylinder and the atmospheric pressure.

If the receiver were tight, some correction might be made for rise in temperature of the air in it by allowing the pressure to fall, by cooling of the air on the final pressure being reached, till the reduced pressure was approximately steady; plot this point immediately below the highest point of the curve, and then draw another curve by swinging the template about the lowest point till it cut the new point (see dotted curve on Figure). The new curve should be used for the calculation of Volumetric Efficiency. Cooling, however, was very slow, and the results of this correction might be vitiated by leakage.

The derivation of the above formula was as follows :—

For a rise of pressure in the receiver of Δp corresponding to an increment of strokes Δn , the volume of free air forced in would be $\frac{Q \times \Delta p}{p_o}$ (assuming isothermal conditions). The displacement of the piston would be $q \times \Delta n$.

Therefore, mean Volumetric Efficiency = $\frac{Q \Delta p}{p_o} \div q \Delta n$ during rise of pressure Δp

$$= \frac{Q}{p_o q} \times \frac{\Delta p}{\Delta n}.$$

Therefore in the limit Volumetric Efficiency at the point p

$$E = \frac{Q}{p_o q} \times \frac{dp}{dn} = \frac{Q}{p_o q} \tan \theta.$$

Mr. E. R. DOLBY said he would like to refer to the cooling of the air. The Author had very rightly laid great stress upon the necessity for cooling the compressed air, as nearly as possible down to the temperature of the free air, if the best efficiency was to be attained. The Author had described a cooler which he (Mr. Dolby) understood consisted of air-pipes in a container, and those pipes were surrounded with what he might term "solid" water. He ventured to suggest that a type of evaporative condenser might give very good results. The type he had in mind was a casing in which would be fixed the air-pipes and spray nozzles, the casing being open to the air. The spray nozzles would be merely the ordinary kind used for spray baths, for treating fruit trees with insecticide, for humidifying air, and so on. Those nozzles created an impalpable mist. The mist settled upon the tubes in a thin film, which would be vaporized by the heat of the air. In vaporizing, not only the sensible heat would be lost, but also the latent heat. He would like to inquire if the Author had ever used such a method or known of it being adopted, and if so, with what results.

Mr. G. L. COPPING said that in view of the interest shown that evening in the subject of air testing, he would like to mention that since last May a Committee had been sitting consisting of representatives of several prominent fan-makers, of the Admiralty and of H.M. Office of Works to consider the standardization of methods of testing and the appropriate curves and capacities for publication in connexion with fans, both low-pressure and high-pressure, and he felt that the present moment was an opportune one for suggesting that it might be possible to make that Committee of more importance by the addition to it of gentlemen concerned with air-compressors so that the results could be adopted throughout the country for all apparatus for the movement of air. If that could be done, it would be of great importance to the whole trade, and especially to those who had started the particular investigation. The Institution of Heating and Ventilating Engineers had originated the investigation, and if any further particulars were required he was sure they would be only too pleased to give them and to know that interest was being shown in the matter by a senior institution, such as the Institution of Mechanical Engineers.

Mr. HERMAN OXLIN remarked that, with regard to the testing and measuring of air, it had struck him, in relation to what the previous speaker had stated about the efforts now being made to measure air in connexion with low-pressure fans, it ought to be pointed out that low-pressure fans or blowers no doubt would always call for a different method of testing than did blowers and compressors which compressed air to a higher pressure. It seemed almost impossible to apply the method of nozzle testing to large fans which moved quantities of air up to 100,000 or 200,000 cubic feet per minute. It would require such a large plant that probably firms would not find it possible to accommodate it. Other methods, no doubt, would have to be adopted for measuring quantities of such magnitude. If such large quantities were measured, say, by measuring the speed by means of the Pitot tube, it would be found that the disturbance which was created in the discharged air by the runner was so great that reliable readings would not be obtained. It appeared to him that if measurements of air were to be adopted on the lines of measuring the speed of flow, it would probably have to be done on the inlet side where a much more steady flow would be obtained.

Mr. E. T. VINCENT said that being only a Graduate he felt hardly competent to discuss the Paper, but there were one or two points principally connected with the design of air-compressors in which he was interested, and on which he would like to give an opinion. He was confining his remarks to the type of compressor used for injection purposes in Diesel engines. The engine proper, he thought, had outstripped the air-compressor from the point of view of reliability. A great number of breakdowns were due to the air-compressor, and the majority of them could be attributed to the excessive temperatures reached during compression. If one examined the descriptions of various motor ships which appeared in the Press, it would be found that the air-compressor on each engine was capable of supplying sufficient air to operate both engines at full power. That was claimed as an advantage, as it provided against any eventuality, but, at the same time, made an accident almost inevitable.

The compressors were designed to distribute, more or less equally, the work between the stages when working at full capacity. Under normal running conditions, the compressors were throttled down to about half capacity, the result being that excessive work was thrown on the h.p. stage producing excessive temperatures as shown by the following figures, which were calculated for compression according to $PV^{1.32} = C$.

The air was assumed to be cooled to the initial temperature of 70° F. between the stages. The high temperature reached in the h.p. stage would heat the incoming air resulting in a still higher

	Full Output.			Three-Quarter Output.		
	L.P.	I.P.	H.P.	L.P.	I.P.	H.P.
Clearance Volume per cent	4	5	10	4	5	10
Compression Ratio . .	4.1	4.1	4.1	3.96	4.1	6.23
Delivery Temp. °F. . .	340	340	340	338	340	442

delivery temperature. The final delivery temperature would go on increasing as the compressor was still further throttled.

The figures showed that it would be much better to design compressors to work at that load at which they would operate in practice, instead of that load at which it might, or might not, be called upon to operate; a very much more reliable engine would then be obtained.

There was another point. All writers on compressors agreed that the clearance volume of the cylinders had very little effect upon the b.h.p. per cubic foot of air delivered, but the speaker had yet to see a compressor which had anything but approximately the minimum figure. He desired to retain the minimum clearance in the l.p. cylinder in order to keep the size of that cylinder as small as possible, but was convinced that if the clearance volume of the i.p. and h.p. cylinders was greater, the reliability would be increased.

The following figures illustrated this case :—

	Full Output.			Three-Quarter Output.		
	L.P.	I.P.	H.P.	L.P.	I.P.	H.P.
Clearance Volume per cent	4	15	30	4	15	30
Compression Ratio . .	4.1	4.1	4.1	4.3	5.1	4.93
Delivery Temp. °F. . .	340	340	340	351	390	381

Comparing this Table with the previous one it was seen that the extra compression ratio was now split up between the i.p. and h.p. cylinders, instead of being only in the h.p., with the result that the final temperatures were much lower.

If anything but a minimum of lubricating oil were used, the high temperatures of the normal design of compressor caused carbonization, if not explosions. The carbonization of the oil destroyed the valve-seats, and might cause the valves to stick up, thus destroying the efficient working of the compressor.

The conclusions to be drawn from these remarks were : (a) that the compressors should be designed for the duty for which they were intended, namely, to supply injection air only ; (b) that at the same time the clearance volumes of the i.p. and h.p. cylinders should be increased so as to provide against breakdown if, for any reason, the engine had to operate for long periods at reduced output.

A motor ship was always provided with auxiliary compressors for the supply of starting air, which was compressed up to anything between 300 and 500 lb. per square inch. To provide against accidents, why not provide a single stage motor-driven compressor which would take air from the starting bottles and compress it to the blast-pressure. This would effect a saving in space and weight of the main machinery and, at the same time, increase the reliability and efficiency.

The CHAIRMAN thought the sense of the Meeting was that there was a decided want of some testing apparatus for high pressure air.

Mr. WILLIAM REAVELL, in reply, said that some of the succeeding speakers had been kind enough to answer for him the remarks of earlier speakers. It was for that reason that Mr. Bailey would understand why he would not refer to his remarks respecting the Pitot tube measurements.

With regard to Mr. Gillespy's method of testing the efficiency, he (the Author) had never seen such a method as that proposed. It was one which required thinking over, and when Mr. Gillespy's remarks, accompanied by his diagrams, appeared in the Proceedings, no doubt all the members would find food for thought in them. He thought, however, that with the compressors having efficiencies at normal pressures of only 60 per cent, there was one other very obvious remedy which should at once be adopted by the user.

With regard to Mr. Dolby's remarks on evaporative coolers, that was quite a new line of thought. It was not one which he had ever heard of or tried, but he (the Author) would certainly think it

over. There was only one point which occurred to him, and that was he did not quite see how by spraying the water on to the tubes one could get the full advantage in a cooler than one obtained by carefully designing it on the counter current principle so as to get the air finally leaving practically at the temperature of the inlet water. He was much obliged for what Mr. Copping had said regarding the method of testing fans, but he thought Mr. Oxlin had fully answered that point.

With regard to Mr. Vincent's remarks, he had been very delighted to hear what he had had to say, because he himself had been fighting that battle for years. He had read a Paper before the North-East Coast Institution last winter, in which he had dealt very fully with the same question in regard to compressors for Diesel-engined ships. There was no question that Mr. Vincent's theories were absolutely correct. The proportions which were adopted for compressors for Diesel ships, he agreed, were wrong. They were selected so as to give what was called an ample margin of safety, and Mr. Vincent was quite correct in saying that on the contrary it had the opposite effect. The question of rearrangement of clearances, of course, as Mr. Vincent said, was one way. The proper way, it seemed to him (the Author), was to make the main compressor of the proper size to do the work when the ship was in blue water. When one was dealing with navigation in narrow waters (which was an extremely small percentage of the total time which the ship was in service), one should use the auxiliary compressors to assist the main compressors. That was one of the reasons why it was there. Mr. Vincent was quite correct in saying that with such an alteration most of the troubles which lead to carbonization were got rid of. All those troubles were due to too high temperatures, which, in turn, were due to too many stages of compression which were erroneously thrown upon the high-pressure cylinder, when wire-drawing the suction air to the low-pressure cylinder, as was necessary when the compressors were too large.

Finally, he would like to associate himself with Captain Sankey's most timely intervention. If, as the result of it, proper calibrated nozzles were tested, standardized, and adopted, and manufacturers could then use a simplified formula which did not involve difficult calculations, they would then be able to test compressors by measuring the flow of air in a simple way and feel quite sure that they were arriving at almost exact correctitude.

Communications.

Professor P. M. BAKER wrote that the Paper was a most useful and practical contribution to the Proceedings, especially at the present time, when the extended use of steam-turbine or electric drives called for such development of the air-compressor as would enable it to operate efficiently at high speeds. An outstanding feature of the Paper was that it emphasized the importance of constant experimental investigation, a direction in which the Author's work was so well known, if our air-compressors, or indeed, appliances of any sort were to be kept in the front rank of the world's products.

The importance of accurate and scientifically conducted tests could not be too strongly emphasized ; such tests guided the designer, indicated the path of progress, and enabled the user to tell whether his plant was operating as satisfactorily as it should.

Mr. Reavell had dealt with the output end of the tests—the other end was equally important. The net horse-power input could be readily determined by the use of rated electric motors, by assuming an efficiency of a prime mover, by a cradle method for small units, or by a transmission dynamometer. He had used the last-named with considerable convenience, particularly in cases in which he was considering the plant from the user's point of view, when the power transmitted through the main coupling must be known if the two parts of the plant—the driver and the driven—were to be debited with and examined for their respective losses.

The shaft dynamometer which he had used measured the power transmitted by a long shaft or a spring coupling, by utilizing the twist which resulted from the torque. Each end of the appliance carried the inductor type rotor of a tiny multipole alternator, so that the twist of the shaft produced a phase difference between the two resulting currents. It was possible to adopt such electrical arrangements that a wattmeter could be made to read the transmitted power directly with considerable precision.

Mr. Reavell had referred to the "diaphragm" and "nozzle" methods of measuring air delivered. Such tests were excellent for *works* purposes, but it was impossible to overstate the importance of *standardizing* the form and dimensions of the nozzles to be used, and the position of the pressure-gauge connexions. Tests lost a great part of their value when output coefficients varied so greatly that A's results for any test could not be compared with reasonable confidence with those of B, an equally capable observer. The Institution should, in his opinion, take an important part in the deliberations on the standardization of such tests, as it would thus

support true progress in one branch of engineering. He had himself a liking for the Pitot tube, which he had used extensively in air and gas flow measurement. There seemed to be an impression abroad that the Pitot tube or, indeed, any method which determined the velocity of the gas by observation at one point, was unreliable owing to possibilities of erratic velocity distribution. That was not so, provided that the appliance was fixed in the middle of a long, straight run of pipe of constant diameter, so that the flow was free from disturbance due to variations of direction or speed of the gas. The apparatus was difficult to use, on account of the small pressure differences to be read, but a careful observer could get reliable results for any but low velocities.

He would much like to see experiments tried with the neat appliance devised by Professor Morris, as he was convinced that an *ad hoc* apparatus suitable for commercial test on air-compressor lines could be made with the smallest possible modification of the existing apparatus, and that such an apparatus would enable an engineer to keep in constant touch with the state of his plant.

There were two small points in the main Paper which called for comment :—

(a) The “rotary” type of compressor, like the rotary steam engine, seemed to have a fascination for inventors. He had only recently to advise a young man not to waste £3 on applying for a patent for a steam-engine which was virtually represented by Fig. 12 (page 848). The high ratio of $\frac{\text{surface}}{\text{volume}}$ for the crescent type of machine was of no disadvantage to the compressor, where heat had to be squandered, but *fatal* to a steam-engine.

(b) It grieved an engineer to think that the energy represented by the temperature rises shown in Fig. 14 *had* to be wasted. The low temperature of heat abstraction would render recovery very difficult, but it occurred to him that, in a large plant, the high temperature end of the cooler might heat feed-water or an air-heater for the furnaces. It would be interesting to know whether anything was done in this direction. Presumably the interstage coolers did not lower the air temperature to inlet conditions (which in some circumstances would need an infinite supply of cooling water), and a combination of feed-heating and air-cooling might indicate an optimum temperature of inlet for the second and succeeding stages for any particular cases.

Professor A. RATEAU, LL.D., wrote that Mr. Reavell, at the end of his Paper, had stated that turbo-compressors with few wheels or

fans and intermediate coolers were, from the point of view of efficiency, better than compressors with a large number of wheels cooled by means of the casing and of the diaphragms first introduced by himself. His own experience did not agree with Mr. Reavell's conclusions. He (Professor Rateau) had no personal interest in the question as he was a maker of both types, the one with few wheels and intermediate coolers and the other type without these, but with casing cooling.

He would refer to an excerpt, "Les Compresseurs Centrifuges," printed from a very complete investigation on the subject by Mr. Huguenin, one of the writer's engineers, which had been published in the journal *La Technique Moderne* for June, 1922. This gave a clear comparison of the two systems and in particular the results obtained from very complete trials of a 1,000 h.p. compressor, which had been installed at the Orange-Nassau Mines. The efficiency of this compressor, as compared with isothermic compression, was as much as 65 per cent; the compressor was cooled only by the casing and had no intermediate coolers. With the other type of compressors on the other hand, as generally arranged with two intermediate coolers, an efficiency of only 60 per cent could be attained. He (Professor Rateau) would have wished to make this statement if he had been present.

Mr. WILLIAM REAVELL wrote that he had read with much interest the contribution which Professor Rateau had made to the discussion on that portion of the Paper dealing with Turbo-Compressors, and systems of cooling for such machines. Any expression of opinion from such an eminent constructor as Professor Rateau deserved most careful attention, and the information he gave was very interesting. The question of the relative efficiency of cooling by coolers, or cooling in the casing only, obviously turned, to a great extent, on the design of the turbo itself. The greater the number of disks or runners which were used—involving a smaller pressure difference per disk—the easier it was to cool efficiently by jacketing the casing only.

Professor Rateau, however, would be the first to agree that the present practice of some of the largest Continental turbine constructors was to increase the peripheral speed of the runners or disks, and to reduce their number, thereby having an increased pressure ratio per disk, and under these conditions they appeared to find an advantage, taking first cost and efficiency together, in favour of the system referred to in the Paper, of cooling by means of independent intercoolers.