Discussion.

Mr. Hayter. Mr. HARRISON HAYTER, President, said that the Author of the Paper was no longer with them. His life was lost about a year ago, in an unfortunate accident, when he was only about forty years of age, and in robust health. The Institution and the profession had thus been deprived of an able member, and the country of one who had already made his mark as a mechanician and a scientist. In 1885 the Author had given to the Institution a Paper on "The Electrical Regulation of the Speed of Steam-Engines;"[1] and in 1888, another Paper on "Trials of a Non-Condensing Steam-Engine."[2] The present Paper was related only in a small degree, if at all, to that of 1885; but it might be regarded as a continuation of the Paper of 1888. In the latter communication had been submitted the results of trials of a central-valve engine working non-condensing. The present Paper was devoted to a record of trials with a condensing-engine of the same type. The Paper of 1888, extending over three successive evenings, elicited an interesting discussion; and he hoped that the present Paper would lead to results equally valuable. It was full of information, the result of careful research; and the Tables appended to it were most elaborate. The numerous diagrams showed the pains that had been taken in the preparation of the Paper. If the Author had been present, he would without doubt have received a very cordial vote of thanks from the members. The President could now only express a confident belief, which would be shared by all, that this last effort of the Author would add to his posthumous reputation. Mr. Robinson would open the discussion by a few preliminary remarks.

Mr. Robinson. Mr. MARK H. ROBINSON said that, after the statement of the President, no words were needed from him to tell what the world had lost in the premature death of the Author. Before referring to any of the points raised in the Paper, he would say a few words in anticipatory answer to a question which some writings in the technical press led him to half expect—to what end these innumerable calculations and figures? Would they help the "practical man?" Could they teach him to make a better engine? To those

[1] Minutes of Proceedings Inst. C.E., vol. lxxxi. p. 166.
[2] *Ibid*, vol. xciii. p. 128.

Mr. Robinson. questions he answered emphatically, "Yes." Up to a certain point the practical man might ignore the present Paper and others like it; but if he aspired to design economical steam-engines, he might derive more good from the study of, say, Mr. Macfarlane Gray's $\theta\,\phi$ diagram than from many portfolios of working drawings. Practical use was the object of the Author's experiments. It was to help to perfect his own condensing-engines that they were undertaken, and that end had been largely attained; a wholly new series of central-valve condensing-engines had been designed by the light of the results given in the present Paper, though, unhappily, by other hands than those of the Author. The danger which, as many thought, now threatened English engineering lay in the more thorough education and the superior mathematical knowledge of so many foreign engineers. When there was a break-down to set right in a hurry, or a day's emergency work to be done in an hour, then might he find himself in the hands of an Englishman, but he dared not shut his eyes to the progress of scientific engineering abroad. Essentially a practical engineer, the Author began his work with a distinct prejudice against theory, and against the mathematical treatment of the steam-engine; but he ended by becoming one of the leading exponents of the scientific treatment of the subject, simply because, as a true engineer, he could not but recognize its necessity. Ten years ago, the Author was known as the designer of an ingenious engine, which, in spite of its high speed, was fairly economical and gave marvellously little trouble. When high speed was necessary, and coal was not very important, it was allowed to be just the thing. Five or six years later, by sheer force of scientific work and research, the Willans engine was in a position to challenge the very highest types of slow-running engines for economy, and the unlooked-for truth was established that the faster an engine ran the more economical it ought to be, other things being equal. There were few things in the Paper more interesting than the reasoning respecting the loss by the necessary cutting off of "the toe of the diagram," and the inevitably greater relative loss it produced in a condensing than in a non-condensing engine—a subject which had been fully treated by Prof. Cotterill in the latest edition of his book on the steam-engine.[1] The reasoning was admirably clear, but to those who saw the Paper for the first time, or had not read Prof. Cotterill's book, some aid might be given by a graphic comparison of the two cases. Down to the lower dotted line, *Fig. 47* (*i.e.*, down to atmo-

[1] Cotterill, "The Steam-Engine." London, 1890.

Mr. Robinson.

spheric pressure), was the ideal diagram which the Author took for the non-condensing engine. On the assumption that it was not worth while in practice to carry expansion below $4\frac{1}{2}$ lbs. above atmospheric pressure, *i.e.*, to an absolute back pressure of about 19·2 lbs., the smaller shaded triangle showed the necessary loss with a non-condensing engine. The same engine turned into a condensing engine (with its cylinder-capacity enlarged as necessary) might conceivably expand down to the Author's theoretical

Fig. 47.

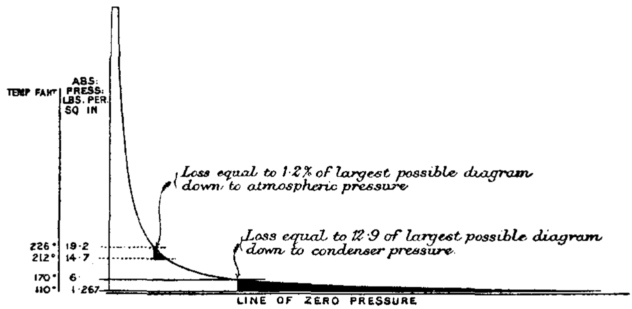
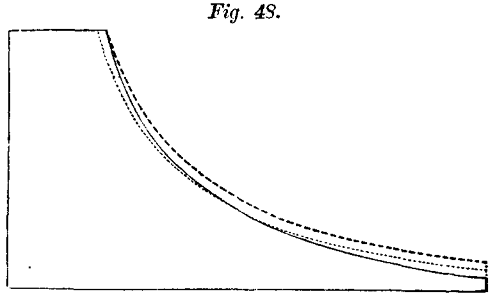


Fig. 48.



—— Engine with small initial condensation.
- - - Same engine, with same cut-off, but with larger initial condensation.
. . . . Same engine, with large initial condensation, but with cut-off altered to give the same power as in the first case.

back-pressure, viz., that corresponding with 110° F. For that reason, he took the whole diagram down to 1·127 lb. (absolute) as the ideal diagram for a condensing-engine. But he reasoned that, although one might hope to get a condenser which would condense down to 110° F., there was no use in carrying the expansion below 6 lbs. (absolute) at release—170° F.; and this left a relatively large triangle shaded as loss. Thus, whereas the inevitable loss in the non-condensing engine was only 1·2 per cent.

Mr. Robinson. of the best possible diagram in the condensing engine there was, perhaps, not an actual necessity, but good practical reason (in order to avoid worse disadvantages) for working with a loss as great as 12·9 per cent. In the diagrams undoubtedly the most noticeable feature was the straight-line law of the total steam-consumption, which his colleague Captain Sankey had asked him to suggest should be called the "Willans" law—a suggestion which he was sure all interested in steam-engine research would endorse. The idea of regarding the total steam used under all conditions, rather than the steam per HP., had proved to be most useful and suggestive. When ascertained facts were recorded by curves, there was usually too much conjecture in the attempt to extend them far in either direction. But when, instead of a curve, a straight line was being dealt with, there need be less hesitation in exploring that part of the field which lay outside the region of experimental knowledge. It might sound paradoxical, but he hoped to run the experimental engine at no mean pressure at all. It would be done by running the dynamo, to which the engine was coupled, as a motor. It would then be seen what steam it took to do nothing —that was, to make good the loss of heat through conduction along the metal, through radiation, and through initial condensation. One of the main objects of the experiments was to settle the best ratio of expansion under various circumstances, but the conclusion expressed was that it was hardly possible to define the best ratio, though it was easy to place a limit to it. In that connection, he would call attention to the fact that the better an engine was, the fewer expansions it required in order to develop a stated power, with a given steam-pressure and a given back-pressure. In *Fig. 48* the full line was intended to represent approximately the expansion curve of a good engine, in the sense of an engine working with small initial condensation and not much re-evaporation. If the engine had a good deal of initial condensation, and consequently larger re-evaporation, expansion might tend to follow the thick black dotted curve. That was what some would call a well-fattened diagram, and they rejoiced over it; but the fattening might cost too much. As only a given HP. was required, the cut-off gear would next make the cut-off earlier, and the expansion-curve would finally assume the position of the thin dotted line. The engine would now work with more expansions, and show less steam present at cut-off. But the total quantity of steam which entered the engine as steam and as water, was larger in that engine than in the one which gave the same power with fewer expansions. He was sure that the Author would, if he had been present, have expressed his obligations to Mr. Macfarlane Gray for that admirable instrument of research, the $\theta\ \phi$ diagram, and for the bent towards the scientific treatment of steam-engine problems which he had so largely derived from Mr. Gray's inspiring counsel and help; and he would have referred once more to the help and encouragement he had received from Mr. Crompton, Mr. Druitt Halpin, Prof. Kennedy, Mr. Mair-Rumley, Prof. Unwin, and many others who were never forgotten by him or by his colleagues. If he might be allowed once more to refer to *Fig. 47*, he thought that no one could doubt that, for a non-condensing-engine, the ideal diagram was rightly taken down to the line of atmospheric pressure—14·7 lbs.; but with regard to the condensing engine, to obtain a boundary line equally certain, he was afraid the bottom line of all must be taken—the line of zero pressure. It was impossible, however, to expand down to zero pressure without a cylinder of infinite capacity, and the Author had therefore cast about for some more reasonable boundary to his ideal diagram, and had fixed upon a pressure corresponding with 110° F., as something which might reasonably be obtained in the condenser. Of course, that was an arbitrary limit only; but he wanted to point out that, the line of zero pressure being ruled out, it was necessary to take an arbitrary line; there was no choice. Some might argue for 100°, and some for 105°; but he did not think that any one would argue for 0°. If all would agree to the Author's line, it would be a good thing. Another point had reference to the greater relative area of the shaded triangle representing the necessary loss in the condensing-engine compared with that for the non-condensing engine; he should have explained that this was common to all condensing-engines; it was not in any way peculiar to the Willans engine—Nature was responsible for it. Though the minimum percentage of loss out of the diagram which it was possible to obtain in a condensing-engine was, and must be, larger than the loss in a non-condensing engine, it was better to have a large diagram subject to a loss of 13 per cent., than a diagram only two-thirds as large, subject to no loss at all. In fact, the greater absolute economy of the condensing-engine was in no sense called in question. The loss was in practice inevitable, being imposed by considerations of practical convenience. With regard to the rate of expansion which was justifiable or advantageous, he would point to the results of two triple-expansion engine trials, one G_4, and the other L_4, with a steam-pressure of 184 lbs. per square inch in the steam chest, made at the same speed, 400 revolutions per minute. One was with 12·36 Mr. Robinson.

Mr. Robinson. intended expansions, and the other with 20·6 intended expansions, and the results were exactly the same—12·74 lbs. of steam was used per I.HP. His chief object in directing attention to the matter was to deprecate the conclusion that 20 expansions would necessarily be no better than 12 in such a case. It should be borne in mind that those two experiments were tried with the same engine; and that the engine which had cylinders rightly proportioned for a 12-expansion trial was not rightly proportioned for a 20-expansion trial. For instance, in the trial G_4, with 12 expansions, the range from mean admission to exhaust was less than 60° F., in each one of the four stages into which the expansion was divided. In the high-pressure cylinder it was only 57·2° F.; whereas, in the trial with 20 expansions, the range in the first cylinder was 83·5° F. Under those circumstances, of course, the 20-expansion trial had no chance at all; and there was little reason to doubt that if the engine were re-made and the cylinder proportioned for 20 expansions, a gain would be shown in working with that number rather than with twelve. It did not, however, follow that, although there might be a gain in I.HP. there would be a gain per brake HP. The additional piston-ring friction due to the larger cylinders might more than nullify the gain. In fact it might be said that if automatic expansion was to do its very best the governor would have to alter the size of the cylinders, as well as the point of cut-off.

Mr. Cowper. Mr. E. A. Cowper did not think he should have spoken if it had not been for the fact that the steam-engine was such an old friend of his. The experiments and calculations related in the Paper were most elaborate, and greater in number than was necessary; for he feared it would be only some of the younger members who would be industrious enough to master them all. He confessed that he had not had the time to do so. In one respect he thought the Paper might have been improved by making it perfectly clear to the meanest capacity, what was the quantity of water that had to be evaporated to produce a net horse-power clear of all friction. He did not mean to say that one could not get at it by studying the Paper and making some calculation; but to do that, a person must thoroughly understand a steam-engine to begin with. He did not say that the test of pumping water need be resorted to (and with such a quick-working engine it would be ridiculous to ask it), but if the engine were tried like the engines at the Royal Agricultural Society's Exhibitions—viz., with a good brake, and also driving its own feed-pump, air-pump and circulating-pump, and having all the credit of any condensation in the steam-pipe, loss at the safety-valve, &c.,—one could compare it commercially with numerous other trials of engines at once. But the experiments recorded in the Paper were directed distinctly to the behaviour of the steam under certain circumstances, one notably being the high speed of the engine. It was satisfactory to note that the "wire-drawing" of the steam was not great; that was owing to the passages being short and of large area, rendered possible by the central-valve arrangement. He understood that the engines had been proved again and again to develop power with great economy in driving dynamos direct at high velocity; and it would seem that they were well fitted for that kind of work, and for steam-launches and torpedo boats, as they ran very quickly and, owing to their being single-acting, kept one brass of the connecting-rod and of the plummer-blocks always in contact with the shaft. He would mention a point on which some disagreement existed. It was well known that he advocated the use of "steam-jackets," as he thought, with reason; for he had proved their value during more than forty years, and could not have made his "compound engine" without them. But in the present case it was argued that the condensation of steam in the cylinder, and its re-evaporation therein, was limited by time; and that at 400 revolutions or cylinder-fuls of steam in a minute, the percentage on the whole power could not be great. It was, however, admitted that steam-jackets might be of some use, though it must be borne in mind that their first cost was an item for consideration. Mr. Cowper.

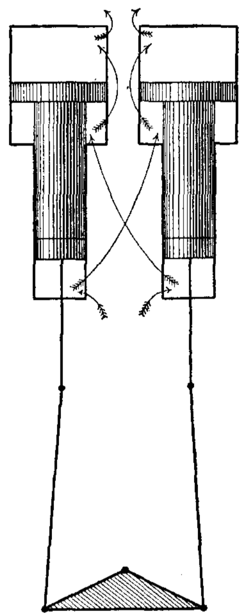
Mr. HENRY DAVEY considered that the chief value of the Paper would be found in the tabulated comparative results of a series of experiments under different conditions of working. It possessed a peculiar charm in the perfect way in which theory had been brought to the aid of practical investigation. Pure theory was often misleading in the absence of practical knowledge to guide its application; but here was theory brought powerfully to the aid of practice. It should not be lost sight of that the experiments, although representing the economic value of different modes of working the Willans engine, were more or less special experiments. It was necessary that the trials should be free from variable losses which would vitiate the results. Care was taken to avoid errors due to the circumstances and imperfections of every-day work. The same might also be said of many other carefully conducted engine-trials, made to ascertain the economy of an engine of any particular make. More uniform and accurate results were obtained by measuring the water from the condenser, than by measuring the feed into the boiler. For it must be noticed that the Mr. Davey.

Mr. Davey. experiments were directed to engine losses, and should not be mixed up with steam-pipe and boiler losses. That was recognized years ago by Messrs. Farey and Donkin; but since that time surface-condensing had become more general, and from the surface-condenser the condensed steam could be actually weighed; whereas, by the Farey and Donkin system, it was a matter of calculation from observed temperatures, and therefore it was not so certain in its results. In carefully conducted engine-trials with large engines, he thought it would be found that the difference between the measurement of the water entering the boiler, and the water coming out of the condenser would fall within 5 per cent.; although a greater difference would probably occur in every-day work. It should be observed that the engine did not drive its air-pump, but, as the results were all given in terms of I.HP., that did not matter. It would have been useful to have had a record of the actual work done by the engine to compare with the indicated power. In former times engineers took the duty of the boiler and engine together, and expressed it in lbs. of coal of known quality per I.HP., or, with pumping-engines, in units of work per cwt. of coal. The method was imperfect, because it did not make it appear whether the duty of the engine was good or bad, because of a good or bad boiler or engine, or because they were both good or bad; but the record for practical and commercial purposes was a useful one. Now with the aid of independent engine- and boiler-trials, and with sufficient reliable data, the best class of engine, and also the most suitable boiler could be selected; but the cost of the working establishment could not be neglected, and that, for various reasons, differed with all engines from calculations merely based on the results of engine- and boiler-trials. Turning to the Paper, he found that the Author had adopted in his engine the Cornish cycle. Mr. Davey had, in that room, spoken on the economical value of that cycle, not from a theoretical point of view, but because he had found from prolonged practical experience and observation that the Cornish engine did a very much higher duty for a given pressure of steam and a given range of expansion than any other engine he knew of, and he thought the Author was right in applying the Cornish cycle to his engine. It had been stated that, for pressures up to 150 lbs. per square inch, the compound engine with the Cornish cycle was likely to prove superior to the triple engine. He had long been under the impression that that would be so, and had made compound engines with the Cornish cycle, of the design illustrated in *Fig. 49.* In the Willans engine he observed

Mr. Davey.

that the Cornish cycle was employed in all three cylinders. There was a receiver between each, and one between the low-pressure cylinder and the condenser. Under such circumstances, he would anticipate considerable advantage from steam-jackets, especially for the bottoms of the receivers, which formed covers for the cylinders below them. If water lodged anywhere, it would do so in the bottoms of the receivers. There need be no jacket on the last receiver. The necessity for steam-jackets was apparent from the fact that in all the results there appeared to be a large percentage of water in the steam at all stages of expansion up to the low-pressure release. The graphic methods used by the Author were valuable and instructive, especially the straight-line diagrams; which did not, like some of the others, relate to an ideal engine, but to the actual engine experimented on. The percentage of water in the steam was high in all the trials. Comparing C_4 with D_4 in the triple series, it would be seen that with steam at 55 lbs. per square inch and 14 expansions, there was 32 per cent. of water at low-pressure release, and with steam at 130 lbs. per square inch and 14 expansions, there was 26 per cent. of water. With the greater range of temperature there was less condensation, the thermal efficiencies being the same in both cases; whilst there was only one-seventh less feed-water used per I.HP. as the result of increasing the initial pressure from 55 lbs. to 130 lbs. per square inch, the expansions in both cases being the same. In the compound series (E_3) with steam at 130 lbs. per square inch and 11 expansions, the feed-water was 15·18 lbs. per I.HP., against 13·39 lbs. in the case of the triple (D_4) with 130 lbs. per square inch initial pressure and 14 expansions. It was reasonable to suppose that the mechanical efficiency of the compound would be somewhat higher than that of the triple engine, and that the small saving in feed-water might be scarcely worth the cost of obtaining it. As to the most useful ratio of expansion for a given initial pressure, it would be seen that *Fig. 7* showed 6·5 expansions as the limit for 50 lbs. pressure per square inch; but the experiments (C_4)

Fig. 49.



Mr. Davey. showed that with steam at 55 lbs. per square inch and 14 expansions, the feed per I.HP. was 15·41 lbs., and (L_2) showed that with steam at 60 lbs. per square inch and 6 expansions, the feed-water was 18 lbs. per I.HP. That indicated that the limit of useful expansion was higher than that shown on the diagram, but it was conflicting to find in experiment (L_3) that with steam at 60 lbs. per square inch and 11 expansions, the feed-water per I.HP. was 18·25 lbs. Assuming the results to be correct, the only apparent reason for the great economy of the 14 expansions over the 6 and the 11 expansions, was afforded by the fact that in the first case the engine was worked triple, whilst in the other cases it was compound. In regard to the use of automatic variable expansion-gears, he was glad the Author had given consideration to them, and had made experiments in that direction. With steam-engines fashion exercised great influence. At one time there was such a rage for a true horizontal line on the indicator diagram up to the point of cut-off, that it was considered to be of most vital importance; and it was the only part of the diagram that some people could appreciate. The value of automatic expansion had been greatly over-rated, and in numerous instances complicated gears had been used where a simple throttle would have been just as effective. Referring again to the Tables, it would be seen that what was called "plant efficiency" was expressed by the ratio which the theoretical mean pressure bore to the mean pressure without clearance; and not, as he thought it should be, to the real mean pressure of the diagrams. As the efficiency was calculated by the Author, it led in one case to an anomalous result of 102 per cent. He did not think that "plant efficiency" was quite the proper term to use. "Plant efficiency" sounded as if it meant the actual compared with the calculated, which it did not mean in that case. In the Tables thermal efficiency was expressed in terms of available energy, and almost the highest thermal efficiency was obtained with steam at 55 lbs. per square inch expanded 14 times—producing of course a very low mean pressure, only 10·8 lbs. The consumption of steam was 15·4 lbs. per I.HP. against 13·4 lbs. with 130 lbs. per square inch initial pressure, 25 lbs. per square inch mean pressure and a lower thermal efficiency. He did not point out this because of its wanting explanation, but to make it clear that the various efficiencies did not run in parallel lines, and that a high thermal efficiency might be coupled with a low real efficiency.

Dr. Hopkinson. Dr. JOHN HOPKINSON observed that it might be useful to point out how the terms in a formula used in the Paper arose. Consider

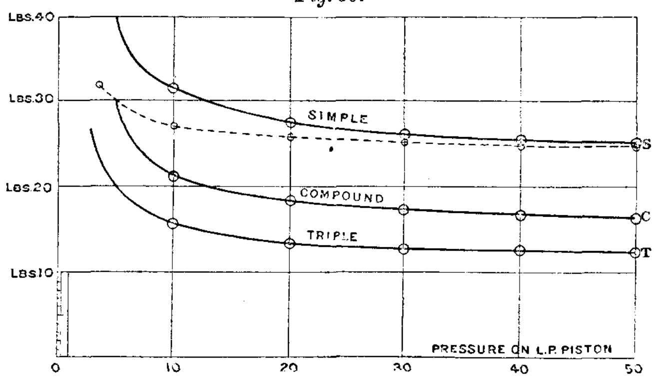
Dr. Hopkinson.

an indicator diagram of an engine, without the extension due to the release being at a lower temperature than the steam had attained at the completion of the expansion. Heat was absorbed at constant temperature during the time at which the pressure was constant; there was next adiabatic expansion, then rejection of heat at a lower temperature, and a gradual increase of heat and a rise of temperature. The heat was absorbed at the maximum temperature, and was rejected again at the lower temperature. But heat was also absorbed as the water was heated from the lower to the higher temperature. Instead of the normal diagram, it might be supposed that the steam was condensed to such a point that, on compressing it further adiabatically, the diagram might be brought back to the point from which it started; that is to say, the steam would be reduced to water at the boiler-temperature and pressure. If that were so, the duty of the steam would be the first term in the formula $\left(1{,}438 - 0 \cdot 7\right) \frac{T_1 - T_0}{T_1}$; but, in addition to that, there was, in fact, the heat absorbed during the gradual heating of the water, from the lower temperature to the higher, before it was converted into steam. The work to be obtained from this heat was expressed by the other terms of the formula, viz., $\left(T_1 - T_0\right) - T_0 \log_e \frac{T_1}{T_0}$; so that the first portion of the formula was due to the heat absorbed at the upper temperature alone, and the other portion of the formula was due to the heat absorbed in heating water from the lower temperature to the higher. There were one or two other points to which he desired to refer, particularly with regard to the use of the steam-jacket. The Author had stated that steam-jacketing was useful in all cases, but it was much less useful when the reciprocations were many than when they were few. He thought that position was incontrovertible. No one, he thought, would doubt the enormous use of steam-jacketing when the reciprocations were few, and when the surface of the cylinder would be cooled to the full extent due to the expansion of the steam. On the other hand, if the reciprocations were many, the condensation and evaporation would be less affected by heating the outside of the cylinder. There would not be time for the heat to be conducted through the cylinder to the outside, or from the heated exterior to the interior of the cylinder. Therefore, when the rate of reciprocation was high enough, the advantage of steam-jacketing was materially reduced. That, of course, did not affect the position taken by Mr. Cowper,—that the advantage of steam-

Dr. Hopkinson. jacketing when the reciprocations were few, and the cooling would be complete, was very great indeed. With reference to the advantage of increased expansion in producing increasing efficiency, he gathered from what Mr. Davey had said, that he viewed it as a question of indicated horse-power. It was abundantly clear that increased expansion would give, with regard to indicated horse-power, increased efficiency; for it simply meant that, having expanded the steam to a certain extent, by expanding that same steam further increased work could be got from it; and, if that were done, clearly there must be increased efficiency. But, if he understood the matter, the Author had considered that, when steam was expanded beyond a certain point, it was necessary to increase the size of the engine, and, therefore, to increase the frictional losses in it; and when a certain point was exceeded, the increase of those frictional losses became greater than the increased amount of power which the indicator diagram showed.

Mr. Rigg. Mr. ARTHUR RIGG was inclined to think that the experiments described in the Paper would show that the ideas referred to by Mr. Davey as to expansion, and the rates of expansion, would require modification before they could be entirely received. One point to be remembered was,—scientific experiments of that character ought not to be accepted as applicable to all engines. Indeed, he did not think that the Author would have claimed for them general application. They were, however, valuable as applied to this particular engine; and it was a curious thing that the result of all such experiments as these tended to make engines simpler and simpler. With regard to the Author's straight-line diagram, the scheme was an admirable one; and many engineers had used it for various purposes. If, for example, they wanted to make a table of prices—say of engines—they put the HP. along a horizontal line, and the prices on a vertical scale, fixing two or three prices at different positions, and drawing a straight line between the points so calculated. Then, to find the proper cost of intermediate or larger or smaller sizes, it was only necessary to measure the height of vertical lines to their intersection with the oblique line. Of course, in applying a straight-line diagram to prices, the same class of engine would have to be taken throughout, or the result would be incorrect. The Author's returns had been made by an engine where the rate of expansion had been fixed, and the average pressure had been produced by the action of a throttle-valve. *Fig. 50* was reproduced from the Author's diagrams. It gave the weight of steam used per I.HP. per hour with a simple engine on the top line, with a compound engine on the second line, and a triple-expansion engine on the third line. It would be observed that, from 50 lbs. per square inch, the quantity of water slightly increased, and then increased with greater rapidity as the rate of expansion advanced. There was another line where super-heating took place, as shown by a dotted curve underneath the simple engine diagram in the *Fig.* This dotted curve exhibited the gain effected by slightly wire-drawing, and thereby drying the steam. It was interesting to see what effect a diagram of that character would have, by comparing it with that of another engine. There was only one engine that he knew of, with regard to which returns were available for such a diagram—namely, the Westinghouse engine. Those returns had been plotted on two diagrams, one at 80 lbs. per square inch and the other at 120 lbs., *Figs. 51* and Mr. Rigg.

Fig. 50.



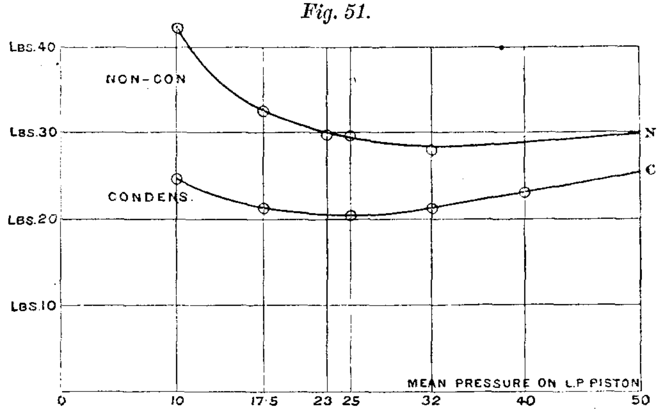
Condensing (Throttle-Valve.)

WILLANS ENGINE.—POUNDS OF WATER PER I.HP.-HOUR.

52. Beginning from the right-hand side, it would be observed how the line curved down, indicating that the rate of water-consumption decreased as the rate of expansion increased; and showing the difference which the Author had shown on Fig. 38, Plate 2, comparing the effects of varying rates of expansion and the action of the throttle-valve. It also showed that there was not much good in all the mechanism required to vary the rate of expansion. The dots shown on the lines were wonderfully close, and a curve had been drawn through them, making slight corrections. The experiments with the Westinghouse engines had been conducted with remarkable accuracy. The difference between the sizes of these engines was a point to be noticed. The Westinghouse engines

Mr. Rigg. included engines from 200 HP. to 40 HP. There was not much difference in the piston-speeds, the Willans being 200 feet and the Westinghouse 290 feet per minute. But the law governing the effects of variable expansion and the use of throttle-valves held good, however large the engine. The Westinghouse engine alluded

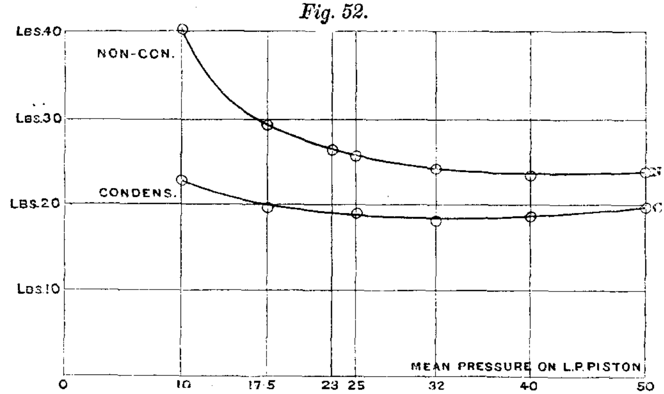
Fig. 51.



Compound.—Variable expansion.—80 lbs. pressure.

WESTINGHOUSE ENGINE.—POUNDS OF WATER PER BRAKE-HP.-HOUR.

Fig. 52.



Compound.—Variable expansion.—120 lbs. pressure.

WESTINGHOUSE ENGINE.—POUNDS OF WATER PER BRAKE-HP.-HOUR.

to had 14-inch and 24-inch cylinders, the stroke being 14 inches for both. The cranks were opposite, and the pistons were practically balanced. The next point to which he wished to refer was the importance of avoiding wet steam. Most engines in the country were fed with wet steam. Nothing could be more pernicious. According to the practice of engineers at the present day, or of the architects who made designs for mills, the engine was generally put in a low situation, so that the water from the steam in the boiler, and that which collected in the pipes, got into the engine and had to be discharged. The old engineers knew better, and when they put in a beam-engine they set the engine high, so that waste or condensed water might run down towards the boiler. That had the effect of clearing the cylinders of the water. In the case of one of Mr. Rigg's high-speed engines, at the Crystal Palace, at the Mining Exhibition in 1890, all the steam-pipes were underground—there were some traps that were supposed to carry off the water, but they did not do so. When about a dozen engines were running, the water got away fairly well; but directly the engines stopped, about 8 o'clock, when the electric light required to be worked, all the water had to go through this high-speed engine, and adversely affected its efficiency. Steam- or hydraulic-engines could be made to run at 500 revolutions per minute, but he defied any man to get an engine to work at that speed by water and steam mixed. Mr. Rigg.

WESTINGHOUSE ENGINE—WATER RATES PER BRAKE HORSE-POWER.

1	2	3	4	5	6
Brake H.P.	Average Pressure. Lbs. per Square Inch.	Boiler-Pressure, Lbs. per Square Inch.			
		120	100	80	60
		CONDENSING.			
		Lbs.	Lbs.	Lbs.	Lbs.
200	50·0	19·62	*22·53*	..	..
160	40·0	18·86	*20·02*	23·17	..
130	32·0	18·38	*19·56*	21·32	*24·30*
100	25·0	19·14	*19·44*	20·34	*20·10*
70	17·5	19·80	*20·05*	21·43	*22·57*
40	10·0	22·90	*23·12*	24·75	*22·55*
		NON-CONDENSING.			
200	50·0	23·94	..	..	..
160	40·0	23·50	*25·20*	..	..
130	32·0	24·32	*26·42*	27·70	..
100	25·0	25·57	*27·75*	29·80	..
90	23·0	26·51	*28·30*	29·80	*31·70*
70	17·5	29·40	*30·77*	32·48	*36·00*
40	10·0	40·05	*39·30*	42·75	*45·82*

Mr. Beaumont. Mr. W. Worby Beaumont desired to refer, in the first place, to the measurement of the pressure and the temperature of the steam, which had been taken in the experiments as that of the steam-chest, and not that of the mean temperature of admission. Judging from a remark in the Paper, that would not appear to have made much difference; but it certainly seemed that it must be much more nearly correct to take the temperatnre of the steam as it was delivered to the engine, rather than to take the temperature after it had partly gone through the engine. With regard to the efficiency obtained as the result of the experiments under consideration, in comparison with that obtained from the trials of the non-condensing engine, the condensing-engine was said to have an efficiency of 63 per cent., while the non-condensing engine had an efficiency of 78 per cent. That meant that the condensing-engine had not made quite as good a use of what had been given to it as the high-pressure or non-condensing engine; but for all that, it was, of course, to be understood that in almost all cases, the advantage was greatly on the side of the non-condensing engine. It appeared to him clear that some further term was wanted with regard to efficiency; because the statement that the non-condensing had a higher efficiency than the condensing-engine might be misunderstood—in fact, something of the nature of what might be called commercial efficiency, taking into consideration the actual cost of I.HP. in steam, rather than simply the relation between the heat-units ideally utilized in one engine and in the other. He supposed every one agreed as to the value of the θ ϕ diagram with which the Author had worked; but he did not think that all would agree with Mr. Robinson's apologetic statement with regard to what he had termed the ordinary limits which had been assumed. One of the good things done by the Author was to show that it was absurd to talk about the efficiency of the real steam-engine with reference to a thing that was, and could only be, a purely ideal engine. Mr. Robinson took a limit for the non-condensing engine, say, 120° F., as the lowest temperature to which it was desirable to go. He had taken an arbitrary limit, but everything in connection with the steam-engine became arbitrary at one point or another; and it was much better that it should be understood that the figures related to what one might call a possible engine rather than to an ideal engine. It would be interesting to know by brake-experiments where the limit was reached at which triple-expansion advantages were lost in the disadvantages connected with that form of engine. In the North of England, among the builders of the large engines used for

Mr. Beaumont.

driving cotton-mills, the opinion was generally held that the compound engine had arrived at as high a state of efficiency as could be obtained with any greater number of divisions of the expansion range; and that the possible gain by adopting further cylinders, valve-gear and other things, might be more than lost in the friction, maintenance and interest upon greater first cost. He thought that higher pressures than those now used would be productive of greater efficiency and economy; and possibly it might be necessary to use three or four stages of expansion in order to secure those advantages. Valuable as the Paper was, its value would be greatly increased by brake experiments, or experiments giving electrical output. He would ask whether any note was made of the power that was taken to work the air-pump? It was shown on the diagram, *Fig. 8*, as though it were worked by a belt from shafting. For comparison with some other engine-results, it was desirable to know whether or not the engine was to be debited with the power taken to work that pump.

With reference to a remark that had been made respecting the Cornish engine, it might be perfectly true that few people realized the cause of its great economy; but it had been pointed out as long ago as 1865. He would like to quote a few lines showing that it was thoroughly understood at that time, and perhaps earlier.

"A remarkable instance of the advantages following on the suppression of the cooling influence of the condenser is afforded in the economy of the Cornish pumping-engine. In this form of steam-machinery, a portion of the cylinder, the lid and one face of the piston, must always remain unaffected by the condenser; because, at the termination of the in-door stroke, only the equilibrium-valve is opened, and, while the piston is going out, a pressure equal to that present at the end of the stroke is kept up in the cylinder; evaporation is therefore arrested and the temperature is fully maintained. Before the exhaust opens, the equilibrium-valve is closed, so that no direct communication ever exists between the steam-side of the piston and the condenser. The entering steam has in consequence only to raise the temperature from that due to the terminal to that due to the initial pressure."[1]

That would be especially interesting if taken in connection with other things stated in the same Journal, with regard to condenser-effects. The only other point to which he wished to refer, was the statement made by Mr. Robinson at the commencement of the discussion, to the effect that attention should be paid to what was being done on the Continent, and that the great scientific advances

[1] *The Engineer*, vol. xix. p. 163.

Mr. Beaumont. there made should be estimated at their proper value. The suggestion implied seemed to be that English engine-builders ought to go to school on the Continent, and that if they lost their trade, it would be because they had not learnt all they might learn there in regard to the application of certain scientific investigations. No doubt it was sometimes necessary to eat humble pie, and recognize that there were certain reasons for estimating at a high value a great deal of what was taught on the Continent. He believed, however, that the Author had left matter to occupy the minds of Continental engineers for a long time. They would find enough in the Paper to exercise their analytical studies for many years to come, and to show them that English people, if they had not done so much in study of the work of others, might still be at the head in practical research and its application. He believed it was true that a Continental firm had taken a licence from Messrs. Willans and Robinson to make English high-speed engines. It could be safely maintained that, vast as was the value of a great deal of the quiet study prosecuted on the other side of the Channel, English engineers might still hope to maintain their position as leaders in those great branches that had kept them in the first rank amongst engine-builders, locomotive-builders, and marine engineers. For the production of rank and file, the Continental system was excellent; but English methods produced men, who, like the Author, were originators of practice, theories and industries.

Mr. Gray. Mr. J. MACFARLANE GRAY added to the formula written by Dr. John Hopkinson, the equivalents of the three terms in the letters used in *Fig. 3*, thus:—

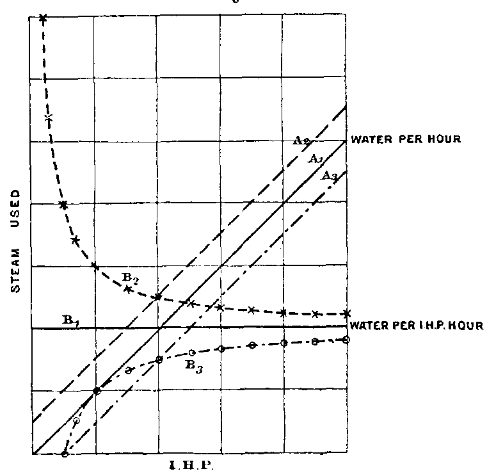
$$L + (K + M) - M = L + K,$$

so that the $p\ v$ diagram might be also read on the $\theta\ \phi$ diagram, to which the mathematical expressions in the formula directly related. The memory of the Author, and the fact that he had the honour of his friendship, would always be an agreeable recollection. Of course, the peculiar representation of the thermo-dynamic features of the engine were partly due to the Author's association with him. Their connection was accidental, but by this means the subject had been more rapidly brought into public notice than it otherwise would have been. He desired to say a few words on the meaning of "plant efficiency." Working with dry saturated steam in an adiabatic engine, for which the admission-pressure, the terminal-pressure, and the final back-pressure were all specified, and for which the feed was of the temperature of the exhaust, there was a certain calculable duty, the realization of which would be perfection; and this would be a reasonable standard of comparison for the performance of any engine. The percentage of that duty actually obtained was what he would call engine-efficiency. Line 28, Table III, Appendix III (not here reproduced), gave that ratio, but in the standard the steam apparent at high cut-off was employed. Reducing the numbers in line 28 by the percentage of missing steam given in line 50, the resulting engine-efficiency came out 70·3, 70·37, 68·5, 61·6, 63·2, 69·24, 64·1. The thermal efficiency, line 35, was based upon the actual steam used; but it ignored the terminal pressure, and included in the standard of comparison the excluded toe of the diagram, which would be a miracle in the work output. The numbers given, properly understood were, however, also significant. He urged the adoption of the 70·3, 70·37, &c., as engine-efficiency, instead of 56·84, 57·41 as thermal efficiency. In the Author's opinion, however, that course would have been read as making the result appear better, and he preferred to sacrifice some advantage, rather than be thought to be studying effect in the choice of methods of representation. The name "plant-efficiency," was not sufficiently explanatory. Given an engine for which the cut-off, the ratio of expansion, and the final back-pressure were fixed, there was theoretically a certain calculable mean effective pressure for an adiabatic engine. The man who thought to buy such a plant might wish to know what portion of that pressure would be obtained in practice. That affected the torque only, not the economy. Line 28 referred to, answered the question in reference to that engine under certain varying conditions described. To obtain that result, it might be necessary to more than fill the admission-space with steam, for the initial condensation was not reckoned in the standard; although its re-evaporation counted in the result, in some cases, making the plant-efficiency apparently greater than that due to the steam according to its measurement. Mr. Gray.

Professor ALEX. B. W. KENNEDY proposed to show his sense of the value of the Paper by saying a few words arising out of a point which Mr. Willans had made peculiarly his own—the matter of the way in which steam-consumption represented itself graphically, which he was glad to hear Captain Sankey proposed to call the "Willans law." It was astonishing, if not even humiliating, to think how long this thing had been lying straight under one's eyes, and yet had not been seen. It had been customary to plot curves per I.HP.-hour without taking the trouble to plot the Prof. Kennedy.

Prof. Kennedy. actually observed quantity—the weight of water used per hour. Thus many things had escaped notice that would have been otherwise revealed. He might first point out what this law of the Author's meant. If on one axis were taken any scale of power—I.HP. or E.HP.—and on the other a scale of steam used in a given time, the law showed that the curves co-ordinating the steam and the power would be straight lines. The straight line might lie in three different ways, as shown in *Fig. 53.* It might, first of all, lie so as to pass through the origin, as the line A_1, which would mean that the engine used no steam at all when it was doing no work. It had been stated by Mr. Robinson that he proposed to find out by experiment how much steam an engine did use when it was doing no work; for that purpose he presumed he would open

Fig. 53.

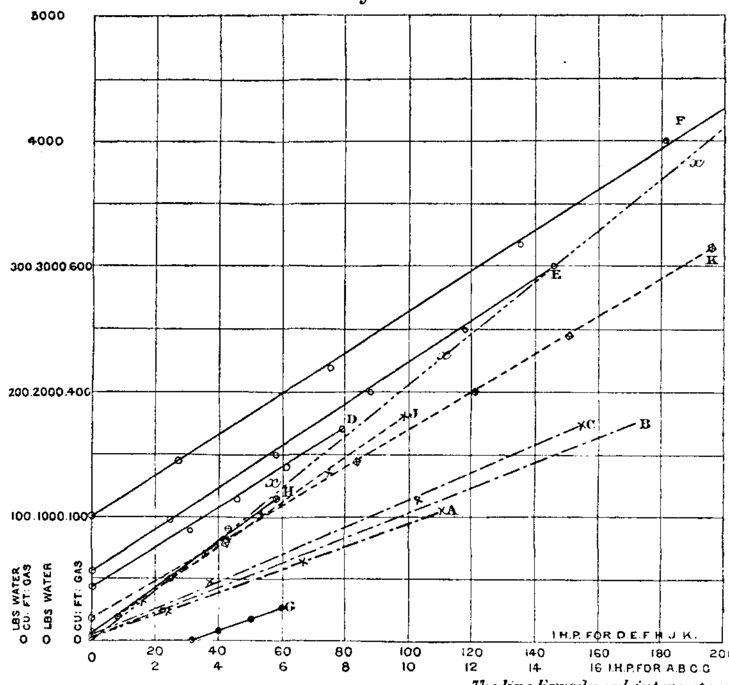


the stop-valve, shut the exhaust-valve, open the drains to a steam-trap, and drive the engine by a dynamo as a motor, simply letting the steam do just as it liked. No doubt this would show that the engine would use steam—mainly, of course, by condensation and radiation—although it did no work. In this case the diagram would cross the axis above the origin (as A_2), showing that the engine used a certain amount of steam when it was doing no work, and all the diagrams hitherto had been of that kind. Or, lastly, it might cross the axis to the right of the origin (as A_3), and he had been puzzling his brain to see what that would mean, and, in fact, put it down as absurd, until that morning Mr. Legros pointed out to him that it had a perfectly definite meaning; it meant that the engine worked backwards thermodynamically. Prof. Kennedy. An engine might do work in refrigerating by continually taking the pressure off the surface of water which was to be cooled, and so evaporating it. The engine, that is, might convert the water into steam. The engine would be working the boiler instead of the boiler working the engine; and in this case, of course, power had to be expended before steam was obtained. The three lines, A_1, A_2 and A_3, *Fig. 53*, represented three different curves, if their results were plotted as water used per HP.-hour. These curves were shown in the lines B_1, B_2 and B_3, of which B_2 was the usual case. He wished, however, to draw particular attention, for certain reasons, to B_1, which was a horizontal line. If the curve of total water per hour was a line passing through the origin (as A_1)—no steam being used at no power—then the steam used per HP.-hour was the same at all powers from zero upwards. It followed that, in any diagram of the nature of *Fig. 53*, any line whatever drawn (like A_1) through the origin corresponded at all points to an equal consumption of steam per HP.-hour,—a fact from which very interesting results would be found to follow.

He exhibited a few curves (*Figs. 54* to *57*), which showed how widely applicable the Willans law proved itself to be. *Fig. 54* was comparable with those given in the Paper, the base being on a scale of I.HP. The lines A, B and C represented tests of three gas-engines. Here the working-fluid was one with which no losses occurred from initial condensation, and with which, therefore, the lines might be expected to pass very nearly through the origin; it would be noticed that they actually did so. This corresponded with the fact that, in a gas-engine, the consumption of gas per I.HP. was much more uniform than was usually found in steam-engines, although the difference practically disappeared when the gas was measured per E.HP. The three lines, D, E, F, represented three Willans engines of different sizes. They were all non-condensing. They were, he believed, not strictly comparable, because they had not all exactly the same expansion, but they were nearly so. This matter of the comparison of different-sized engines was not mentioned in the Paper, but was of great importance, and the use of the Willans diagram threw much light upon it. It would be noticed that any line through the origin, such as x, cut the three curves in three different points. Any such line, however, represented the same consumption of steam per I.HP.-hour, as he had just pointed out. In this case, it was apparent that each of the three engines, at nearly its own full power, was using the same amount of steam per HP.-hour;

Prof. Kennedy. and that therefore it was, so far, most economical to use the smallest possible engine. The three lines H, J, K showed the results of three Willans engines of different powers worked condensing. The most obvious point was that they all passed very much more nearly through the origin than the former lines. This had surprised him somewhat at first, but after all it was merely a matter of common sense. If a condensing-engine were used it might be expected to use less steam per HP.-hour at all

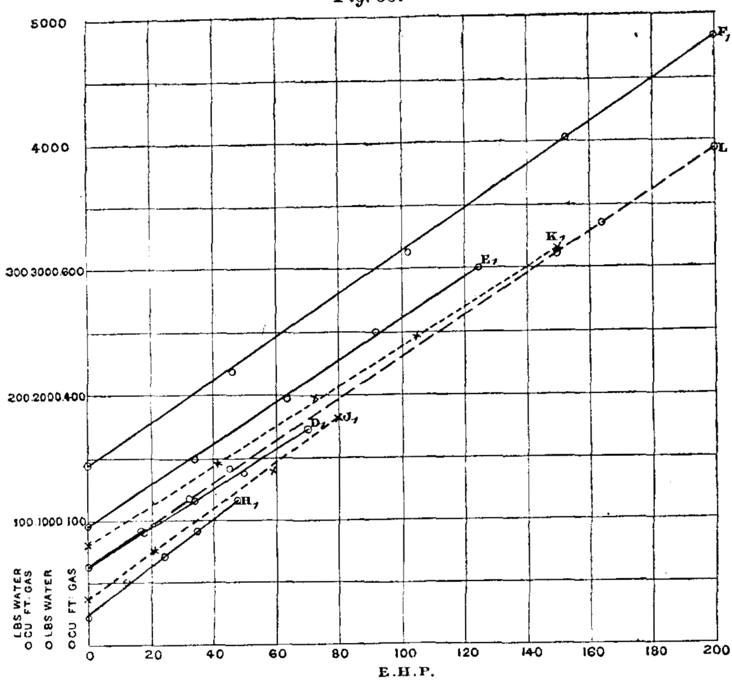
Fig. 54.



The line F produced intersects a final experiment at 242 I.H.P.

powers than a non-condensing engine. But if the Willans law was true, the amount used per hour should still be represented by a straight line. There was no reason why the slope of this line should be very different from that of the former. It was therefore obvious that what was to be expected was simply a bodily shifting of the line downwards, and this was exactly what occurred. The initial waste, therefore, was bound to come very much less. A second point brought out by the diagram, and by no means an obvious one, was that the lines were no longer even approximately parallel, but the larger engines had water-lines sloping at a smaller angle. The larger-sized engines of this type, used with condensation, were decidedly more economical than the smaller-sized ones. It would be noticed that all three sizes used nearly the same amount of water per hour between 30 I.HP. and 50 I.HP.; and that, above this, each size of engine was more economical than the next smaller size. He had no similar experiments with Messrs. Willans and Robinson's new Prof. Kennedy.

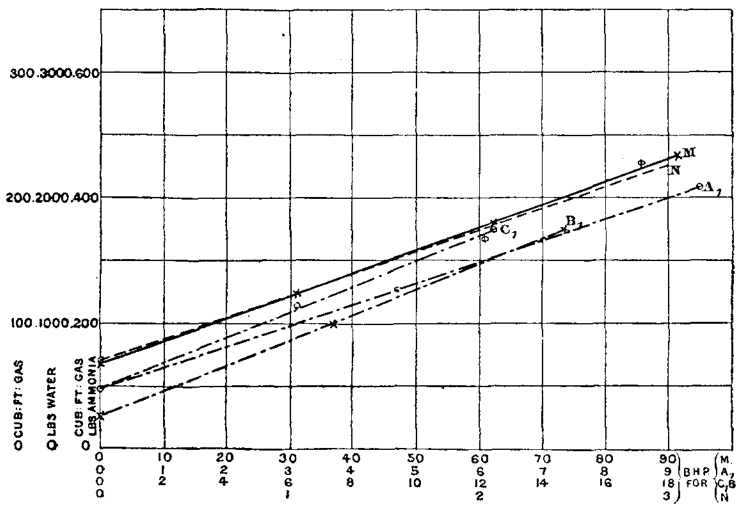
Fig. 55.



type of condensing-engines (those whose proportions were based on the results given in the Paper under discussion); and he was therefore unable to say into which category they would place themselves. Possibly Captain Sankey could say something on this point. The line G (*Fig. 54*) was obtained from experiments on a refrigerating-engine working exactly in the manner he had mentioned. It was given in the figure more as a curiosity than for any other reason. Instead of plotting out the results on the basis of the I.HP., it was as easy to draw them on the basis of

Prof. Kennedy. E.HP. or B.HP. *Figs. 55* and *56* showed some of his former results plotted in this way. The results from the same engines were given in similarly lettered lines in the different figures. D_1, E_1, and F_1 were three non-condensing Willans engines, and H_1, J_1, K_1, were three condensing Willans engines. As to these last, it was only fair to say again that none were of the latest type of condensing-engine made by the firm, and discussed in the Paper—these latter having given considerably better results. L was a line taken from tests of the Parsons turbo-motor, which lay most extraordinarily within the general limits, and the observed points of which lay most closely in a straight line, although it was, of course, a motor of an entirely different type from that of an ordinary steam-engine.

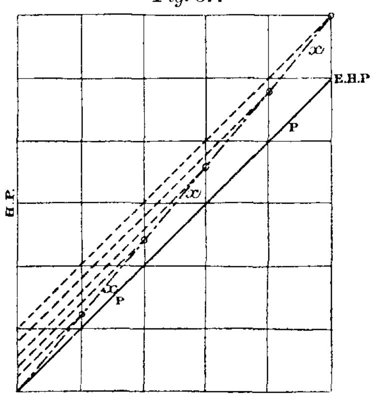
Fig. 56.



In *Fig. 56* the base of the diagram was brake-HP. The lines A_1, B_1 and C_1 represented again the three gas-engines of *Fig. 54.* It was obvious that, neither with these nor any of the other machines could the lines pass so nearly through the origin as in *Fig. 53*; for in all cases the zero of brake HP. was accompanied by some considerable I.HP.—the power, namely, which was necessary to drive the engine itself at full speed, running light. Line M belonged to an ordinary horizontal Corliss engine, and line N to a small motor driven by anhydrous ammonia, but in the last-named case the points were indifferent. It was a remarkable thing that Willans' law appeared to apply equally well to machines so extremely different from his own engine. He wished to refer briefly to *Fig. 57*, as it represented, he thought, a direct extension of the use of the instrument which the Author had placed within reach when he gave this law. Taking a base, not of indicated, but of useful HP., and taking the same scale for power (not now for water) on the vertical axis, a line at an angle of 45° as P P, might represent useful HP. Above that was plotted a line representing the corresponding I.HP., and this line he had found to be almost always a straight line. Any vertical line would cut the two oblique lines, the one in the useful HP., and the other in the corresponding I.HP., and the distance between the two would be the I.HP. for the engine—the amount of power taken to drive the engine itself. Very often the two power lines were sensibly parallel. In an average of thirty or forty Willans-engine tests, the power taken to drive the engine at full power was about fifteen per cent. more than the power taken to drive it empty. Whether that was a true average or not for other types of engine he did not know, but in ordinary engines he had often found the difference to be much greater; he gave the figure, however, for what it was worth. It was clear that with a type of engine which was as economical in small as in large sizes it was always most economical to use the smallest possible. He was not speaking of economy in wages, but simply of the one point of economy in steam. In fact the Author's dictum was absolutely justified, that all engines ought to be worked as hard as possible, and boilers as lightly as possible. In *Fig. 57* he had drawn representative curves for four engines, each one larger than the one before it, and had assumed in each case that the power necessary to drive the engine was constant, and was equal to 10 per cent. of the maximum power of the engine. He had further assumed that the small engines were as economical as the large ones. He had then drawn the line $x\,x$ passing through the origin, simply to indicate how in such engines the consumption of steam per I.HP.-hour at the full power was absolutely the same in each case. The same line would show how much was

Prof. Kennedy.

Fig. 57.



Prof. Kennedy. wasted if engines too big for their work were used. Of course where the larger engines had curves not parallel to the smaller ones, but having a less slope, the case would be altered, as he had pointed out in connection with *Fig. 54*. But that would simply mean that the engine was of a type in which the smaller were less economical than the larger sizes. That might be so in many cases, but in the case of Willans engines it was only so to a limited extent. There was an extraordinary resemblance between the results obtained in very large and in very small engines. There was a point raised in the Paper as to whether the steam ought to be measured going into or out of an engine. He had had doubts about it for a long time, but the Author's experiments had led him to believe that the most accurate result was to be obtained by measuring it passing out of the engine. Of course it was often impossible so to measure it, but wherever it could be done it was the best course to follow, where pains could be taken to get as accurate results as those obtained by the Author. It might be interesting for members to know how far results in practice bore out the figures given in the trials of Willans engines. He had frequently, during eight, nine or ten consecutive hours of ordinary work in an electric-lighting station, measured all the water, and noted all the power, and the points on the curve at which the work of each engine was done; and had then compared the water actually used with that which ought to have been used; and he had found that it came within about 5 per cent. —a difference not more than might be expected from the feed-pumps and the general waste. For results over a whole week, where the nights came in, and when also the starting and stopping was included, it was not within 5 per cent., but was more like 10 per cent., and often considerably more. There were losses between the boiler and the engine due to the leakage of valves, to open drains, to condensation in pipes, and to several other causes which he feared had not yet been explained. Taken altogether those losses were considerable and gave a good deal of trouble.

Mr. Crompton. Mr. R. E. CROMPTON felt that a few words on the subject of the trustworthy nature of the results which could be obtained from the trials described, might add to the value of the Paper. It was well known that electrical engineers who were designers of central-station plant had to consider the fact that the proportion borne by the cost of the power employed by them to the total cost was much larger than in any other manufacturing process, except, perhaps, the driving of ships at sea. For that purpose they had to devote much attention to questions of economy connected with the production of power. It was well known that he, for one, had pinned his faith to a great extent in past years to the Willans engine; and he felt that he was justified in that course by the excellent and concordant results that he had obtained. Moreover Prof. Kennedy, who was unsurpassed in the care with which he made tests, had also obtained corroborative testimony to that effect. The point to which he wished to direct attention was that there were peculiarities of construction in the Willans engine which made it peculiarly a steam-meter, and a far more absolute measure of the steam passing through it than any other engine with which he was acquainted. This fact had been of enormous use to him in locating the losses that existed between the consumption of coal and the development of power. Over and over again it had been found that the monthly fuel-account did not agree with what it should be, when calculated from the estimated value of the boilers and engines as power-producers; but in every case, after due allowance had been made for ascertained losses, the Willans engine had been cleared from blame, and had given results varying not more than $2\frac{1}{2}$ per cent. from the results claimed for it by the makers when they sent it out. As Mr. Robinson and Captain Sankey knew, he had on several occasions written pointing out certain curious facts that appeared to require explanation; but in every case he had been eventually able to furnish his own explanation. In the works directed by him, which were in the Eastern Counties, coal was extremely dear—Welsh coal costing 24*s.*, which forced them to use nothing but the most economical plant. The town was lighted by them, and as their own power required was considerable, they had organized a power-department supplying power for the public lighting and also for their own works. Each department was debited with the amount of power used. They had accurate means of checking by meters part of the power used, but up to the present they had not very accurate means of checking the power used on that part of the plant which was on the alternating system. For that reason it had been necessary to take complete sets of indicator diagrams at regular intervals of 15 minutes, for 24 hours consecutively. Every Wednesday for some months past he had conducted such trials, the results of which were at first disappointing. It came to this, that with three Willans engines of about 135 to 150 HP. they appeared to be actually using about 29 lbs. of steam per I.HP., whereas they ought only to have used about 20 lbs. during hours when the engines were fully loaded, and 26 lbs. during hours of partial load; and it became necessary to find out where the balance was going. By separating the Mr. Crompton.

Mr. Crompton. apparatus, the losses were located and the consumption of the engines had been found week after week to vary only between 20·8 and 21·5 lbs. of water when fully loaded, or within 2½ per cent. of what they were supposed to use. This small variation might be due to errors in measurement. The effect of this had been to direct attention to losses which engineers ought to know of, but which all engineers did not appreciate at their full value, viz., losses in steam-pipes from condensation, losses in the pumps and other apparatus connected with the water-supply to the boilers. These were found to be greatly in excess of anything that would be believed, but which had now been accurately traced. The fact that when every loss had been debited to its proper source, the steam-consumption of the engines was shown to be 20·8 lbs. when fully loaded, and 24·8 lbs. when partially loaded, was enough to point his remarks. Some of his remarks on what all were beginning to call the Willans law had been anticipated by Prof. Kennedy, a law which he was proud to say was first promulgated at a discussion on a Paper read by himself. He would add his voice to those who would strongly wish that engineers should call it the Willans law; it was a law which, although possibly known before that date, was brought forward prominently by the Author for the first time.

Mr. Wingfield. Mr. C. H. Wingfield mentioned that among the objects of the Author's trials, one was of special interest to designers, viz., "To ascertain with a given steam-pressure and ratio of expansion the percentage of the theoretical mean pressure which is in this type of engine actually obtained in practice." This percentage, when known, would enable a designer (when the I.HP. revolutions per minute, steam-pressure, number of expansions and back-pressure were given) to predict the actual mean effective pressure, and from it to determine the proper dimensions of a cylinder to develop the required power. Unfortunately, the back-pressure was a quantity which usually varied with the speed of engine, the boiler-pressure, and the expansion-ratio; and the "plant efficiency" was also variable. At 400 revolutions per minute, for instance, it varied in these trials with a compound engine, from 75·03 to 102·0. In calculating line 27, Appendix III, for the purpose of this comparison of actual with theoretical results, the Author had regarded the adiabatic as the ideal mode of expansion. That, no doubt, was more correct than the hyperbolic law; but as the mean-pressure was more easily calculated by the latter, he thought it would be preferred if results at least as consistent could be obtained by its use. It must be borne in mind that the object under discussion was not, what law did the expansion-curve follow? but, what was the simplest way of estimating the probable mean effective pressure in a proposed engine? Mr. Wingfield.

It was frequently assumed that the actual mean effective pressure would be a fixed fraction of that obtained by deducting the expected back-pressure from the mean absolute pressure—the latter being estimated by multiplying the initial absolute pressure p_1, by $\frac{1 + \text{hyp. log. E}}{\text{E}}$; and Tables had been published purporting to give the value of this fraction. This had been happily called by Professor Unwin the "diagram-factor" for different classes of engines.[1] This rule would be expressed algebraically thus—

$$m.e.p. = \left\{p_1 \frac{1 + \text{hyp. log. E}}{\text{E}} - b\right\} \times \epsilon,$$

where $m.e.p.$ = actual mean effective pressure reduced to l.-p. piston (line 25 in Appendix).

p_1 = absolute pressure in the steam-chest (line 4 in Appendix).

E = nominal ratio of expansion as given under the reference letters in the Tables.

$= \frac{\text{volume of l.-p. cylinder}}{\text{volume of h.-p. cylinder} \times \text{cut-off in h.-p. cylinder}}.$

$\left.\begin{array}{l} b = \text{back-pressure} \\ \epsilon = \text{diagram-factor} \end{array}\right\}$ have to be estimated.

If more steam was passed through an engine by increasing the pressure or the number of revolutions, the back-pressure would usually rise, and the value of the diagram-factor, like the "plant efficiency" (line 28), would also be affected.

He had found, however, that if b, instead of representing the actual unknown absolute back-pressure, were made to stand for a quantity which he called a "virtual back-pressure," found from trials of similar engines, this virtual back-pressure was not only independent of the revolutions and expansions; but the diagram-factor ϵ was less affected by the expansions, and scarcely at all by the revolutions.

On pages 7 and 8 of the Paper there were foot-notes, stating that the Author limited his standard back-pressure to 1·267 lb. per square inch, on the ground that a lower vacuum could only be obtained at a cost exceeding the gain. He thought it was Mr. Weir

[1] *The Practical Engineer*, June 17, 1892.

Mr. Wingfield. who just called his attention to this source of loss. Although an important point, he thought it had not been generally noticed. People were proud of a considerable vacuum in condensers; but he wished to point out that, under certain conditions, an improved vacuum did not give any increase of power, but only resulted in a waste of heat. The laws of the efflux of steam were not yet finally determined,[1] but Napier's experiments, as expressed in a formula adopted by Rankine,[2] were sufficiently accurate.[3] These indicated that the weight of steam which would pass through an opening 1 square inch in area in 70 seconds was nearly equal to the absolute pressure of the steam; provided the absolute pressure on the side of the opening towards which the steam was flowing was less than about three-fifths of the absolute pressure on the high-pressure side. That meant that if there was a constant pressure of steam, and, therefore, a constant density, the velocity would be constant provided the vacuum was not more than three-fifths of the steam-pressure. If the indicator-card of an engine showed a certain back-pressure, and the condenser-pressure was three-fifths of that, or less, if the law was rigidly true the bottom of the diagram would not be lowered by further reducing the condenser-pressure, as there would be no increase in the velocity of the steam. The condenser would be cooler, because more heat would pass off in the circulating-water. Heat would also be wasted in providing power for the extra quantity of circulating-water; and all the heat wasted from the first of these two causes might have been left in the feed-water, and so have saved fuel. Although this was not strictly true, there was an undoubted tendency towards it. A good indicator-card might be got with 20 inches vacuum, and, perhaps, with 28 inches there was no further gain. Where this was so, it showed an improvement would result from larger ports. It was stated in the Paper that the Author was not aware whether it was generally known that much of the economy of the Cornish engine was due to the range of temperature being practically halved by the plan of letting the steam pass from one end to the other without further expansion before being exhausted. He thought there was possibly another reason for this device. He did not know what the original inventor had in his mind; but he had heard of a Cornish engine in which the

[1] "Experiments on the Efflux of Elastic Fluids," by Mr. George Wilson, *Engineering*, vol. xiii.

[2] *The Engineer*, vol. xxvii. p. 359.

[3] An analysis of these experiments and of Rankine's formula by Mr. Macfarlane Gray is given in *Engineering*, vol. xiii.

Mr. Wingfield.

difference of temperature at the two ends was so large, and the engine worked so slowly, that the piston became so big at one end of its stroke that it stuck fast at the other end. Of course the method of reducing the range of temperature would also prevent that trouble. It was said (page 20 of the Paper) that the diagrams from each cylinder had been measured collectively. If Mr. Robinson would explain how this was done, he was sure it would be of interest. On page 24, the short distance called *w* in the *Figs.* was defined as the water required by a frictionless engine doing no work at the revolutions specified. On page 25, radiation, conduction and cylinder-condensation were enumerated as the causes of this water-consumption, when the frictionless engine was developing no power. He thought there was another loss which had to be made up by part of this water mentioned previously by the Author,[1] the steam used in overcoming the back-pressure, pushing the atmosphere out of the way; in the present instance pushing the steam in the condenser out of the way. If the mean-pressure on the steam-side of the piston in a frictionless engine was not sufficient to balance the mean back-pressure, the engine would run backwards. The cylinder must, therefore, be filled at each stroke with sufficient steam to balance the back-pressure. The engine would not be moved by this steam, and no power would be indicated, the indicator-card being similar to that of *Fig. 25.* If the engine were started at say 400 revolutions per minute, being frictionless, it would not stop but would keep on measuring out cylinder-ful after cylinder-ful of steam at this pressure like a water-meter; and this amount of steam must be used at zero power, besides what was required to supply initial condensation, &c. There was an interesting point in Figs. 27 to 30, Plate 2, to which attention had not been drawn; but he thought the Author must have had it in mind. It would be seen on reference to these Figs., that the lower of each pair of lines had been produced, and that they all intersected the base-line at the same point. Whenever, in a straight-line diagram of an engine or anything else, the lines converged to a point, it had always an important meaning. It was here a measure of the steam used to balance the back-pressure.

He was not sure, but he believed that the distance from this point to zero, measured along the base-line, would prove to be equal to the mean back-pressure. His reason for thinking so was that, as the lines produced were all indicated water, and they were all

[1] Minutes of Proceedings Inst. C.E., vol. cvi. p. 64.

Mr. Wingfield. straight lines, which represented the result of indicated work, where they were produced they would not suddenly change their character, but must still represent steam which was doing work; and the only work in an unloaded frictionless engine was that of overcoming the back-pressure. As mentioned above, the back-pressure in the low-pressure cylinder was not given; but it would be interesting to know if it corresponded with the distance from this point to zero. This could only be ascertained by reference to cards which were not given in the Paper. The upper lines in Figs. 27 to 30 also converged towards a point which, however, was a little above the base-line. There could be no doubt that this, too, had a definite meaning; which, however, he had been unable to decipher. It would, he felt sure, repay careful examination. The steam at high-pressure cut-off should be the same per revolution, or nearly so, at all speeds, if the mean effective pressure reduced to low-pressure was also the same. Applying this as a check to Figs. 27 and 29, and dividing the height at which the lower line for 400 revolutions per minute intersected the vertical over 50 lbs. pressure per square inch into four equal parts, it would be found that the lines for indicated water at 200 revolutions and at 300 revolutions per minute passed almost exactly through the points so found. If moved so as to pass exactly through them, the lines would still pass fairly through the other points, with the exception of the highest point in the 300 revolutions per minute line of Fig. 27. Perhaps this would be a guide in selecting the right direction for these lines in future diagrams of a similar nature. It was encouraging to see (Fig. 29), that the initial condensation was only increased by increased pressure under conditions where it was least important. In the description of Fig. 38, the curved line was described as obtained by joining the points indicating 170 lbs. on the three straight lines in Fig. 36. This, he thought, only referred to the upper part of the curved line. To obtain the lower part in this way, many other lines similar to those in Fig. 36, but at 40, 50, or more expansions, would be required. The curve cut each straight line at two places, at only one of which the straight and the curved line had the same pressure, and therefore the same rate of expansion. The pressures at the other intersection were different (in Fig. 38 it was 65·85 lbs. per square inch for the straight line, and 170 lbs. for the curve), the same mean effective pressure being obtained for each by varying the rate of expansion.

Mr. Cowper. Mr. CHARLES E. COWPER confined his remarks to the connection between the formula for the work in heat-units due from 1 lb. of steam, and the value of the same in *Fig. 2*; also applying the numerical values to the $\theta\ \phi$ diagram, *Fig. 3*. For convenience of comparison, he would take 110° F. (as the Author had done on p. 7) as the lower or condenser temperature, and 310° as the higher or steam-chest temperature; or, on the absolute scale, 571° and 771°—a range of 200°. Applying these figures to the formula on p. 8, he obtained the following numerical values:— Mr. Cowper.

$$(1{,}438 - 0{\cdot}7\ T_1)\left(\frac{T_1 - T_0}{T_1}\right) = 898 \times \frac{200}{771} = 233 \text{ units.}$$

$$\begin{array}{lrr} T_1 - T_0 = 771 - 571 \quad = 200 & & \\ T_0 \log_\epsilon \frac{T_1}{T_0} = 571 \times 0{\cdot}3 = 171 & 29 & ,, \\ \hline & \text{Net Total} \quad 262 & ,, \end{array}$$

This would be seen to agree with the value of the ordinate of the curve in *Fig. 2* for steam at 310° or 78 lbs. total pressure. To apply these numerical results to the somewhat abstruse $\theta\ \phi$ diagram, *Fig. 3*, let the latter be set out to convenient scales on sectional paper with the horizontal lines at heights above the zero base-line representing the respective temperatures of 571° and 771°. The vertical strip K + M contained an area equal to 200 units; being all the heat required to raise the water from the lower to the higher temperature. Let the rectangle L + N (*Fig. 3*) contain 898 units, representing all the latent heat without deduction. Next, taking into account the intersecting horizontal line at 571° temperature, the following values would be obtained for K + L respectively, viz.:—

$$K = 200 - 171 \quad \ldots\ldots \quad = \ 29 \text{ units}$$
$$L = 898 \times \frac{200}{771} \quad \ldots\ldots \quad = 233 \ ,,$$

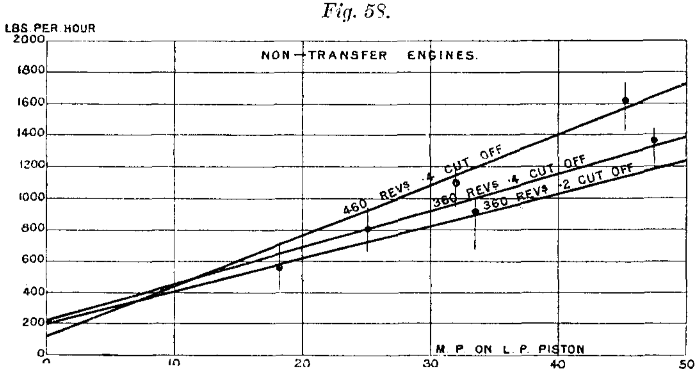
Therefore the work in heat-units due = K + L = 262 units, as before.

He ventured to think that this illustration, by means of definite numerical values, would assist in showing the practical bearing of Mr. Macfarlane Gray's diagram.

Captain H. R. SANKEY, R.E. (retired), said he rose with some diffidence to reply, but his task had been made comparatively easy by the kind manner in which the Paper had been received and discussed. The key-note of the discussion had been praise of the Author and his Paper, and he was certain this would be a source of Capt. Sankey.

Capt. Sankey. gratification to the family of the Author, as it had been to himself and to his colleagues. One of the most gratifying features of the discussion had been the complete confidence which had been accorded to the results of these experiments, and he knew that the Author, had he been with them, would have felt more pleased with this than with anything else that had been said. It might, however, be interesting to have a verification of the accuracy of the testing-apparatus at Thames-Ditton, by a comparison with the tests made by Messrs. Sulzer Brothers, of Winterthur, with an ordinary "G G" Willans engine (80 I.HP.), purchased by them last year. The results were shown in *Fig. 58*. The straight lines showed the average of many trials at Thames-Ditton, made with engines of the ordinary non-condensing type when working condensing, so that the absolute results were not so good as those given in the

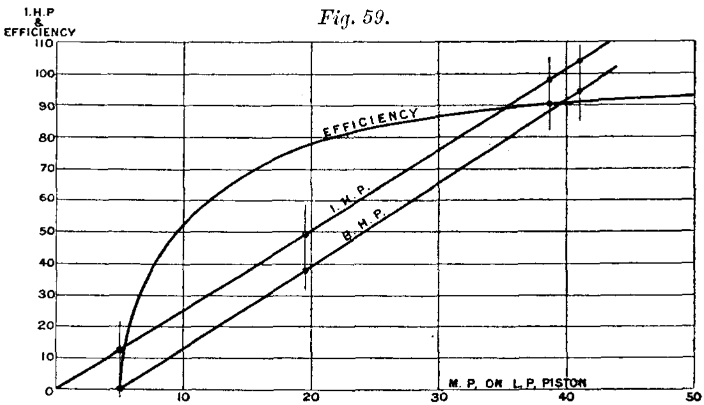
Fig. 58.



Paper, which were obtained with an engine of the condensing type, as explained at page 2. The dots represented the tests made by Messrs. Sulzer, and it would be observed that they were very close to the corresponding Thames-Ditton results. The trials were made with all the care and precautions that might be expected from a firm of Messrs. Sulzer's reputation, and the water used was determined by weighing the condensed steam. Several questions had been asked referring to the effective power developed by the engine: Mr. Cowper wanted to know what quantity of water had to be evaporated for an effective horse-power free from all frictional and other losses; Mr. Davey asked whether any note had been taken of the effective power developed; and Mr. Beaumont wished to know the power required to drive the air-pump. The answer to all such questions was, that these trials had reference only to the behaviour of the steam under various conditions, and that it was therefore quite immaterial whether the load on the engine was internal or external, and for this reason no note was taken of the effective power developed. To ensure due accuracy in the trials it was essential that the load should be steady; hence the air-pump, involving, as was well known, an unsteady load, was not driven by the engine itself, but by another engine. But as the question of effective HP. had been raised, he would say that they had ample evidence from tests made with "steam-dynamos" that the efficiency of the Willans compound-engine was about 90 per cent. With some few unimportant exceptions, however, these results had been obtained from friction-cards, and by deduction from the combined efficiency of a number of steam-dynamos. A combined efficiency of 84 per cent. was frequently obtained, and taking the dynamo-efficiency at 93 per cent., this left a little over 90 per cent. for the engine. He had, however, been so pressed by Mr. Cowper after the reading of the Paper to make a brake-trial, that he had determined to do so, and he now had pleasure in bringing the results of this trial before the Institution. The trial had been made with an HH.S engine, capable of developing 150 I.HP., which was now on its way to drive one of the shafts at the Chicago Exhibition. A similar trial had been attempted with an engine of the III.S size, indicating 350 HP., also going to drive another line of shafting at the Chicago Exhibition, but unfortunately the brake-wheel was broken. The result of the trials with the HH.S engine was shown graphically in *Fig. 59*. The I.HP. obtained by measuring the diagrams was plotted on a mean-pressure base, and of necessity gave a straight line. The corresponding brake HP. points lay, it would be seen, sensibly in a straight line very nearly parallel to the former. The efficiency curve was given by these two straight lines, and the efficiency at four-fifths of full load (40 lbs. mean pressure) was shown to be 90·1 per cent. That afternoon another brake-power trial had been made with a smaller engine, a simple transfer engine, and he had just been handed the result. The results were again similar to those shown in *Fig. 59*, and the efficiency came out at very nearly 90 per cent. at full load. The brake used was of the ordinary rope type; the lower half only of the circumference was in contact with the ropes. One end of the strap was attached to a spring balance, and the other to a Denison weigher. It was unnecessary to enter into the precautions taken to ensure accuracy. When, however, the question at issue was only the commercial economy of a steam-dynamo, the simplest and best criterion was the water Capt. Sankey.

Capt. Sankey. required per electrical HP. delivered by the dynamo. To ascertain this only three things had to be measured, namely, the total water-consumption per hour, the amperes, and the volts, and it was quite easy, with ordinary precautions, to make each of these measurements with errors not exceeding 1 per cent., so that the error of the combined measurements would be under 2 per cent. With the apparatus available at Thames-Ditton, the errors of such combined measurements were certainly within $\frac{1}{4}$ per cent. The remarks of Mr. Davey and of Mr. Crompton as to the effect of leaks, radiation, &c., on the economical results were of great importance; and, although from the point of view of the Paper not strictly an engine question, leaks and radiation were factors in determining the boiler-pressure at which it was economical to work. To illustrate this he

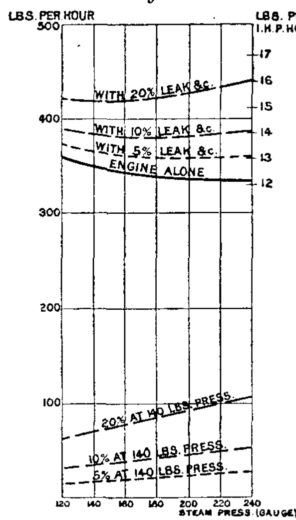
Fig. 59.



BRAKE-TRIAL HH.S WILLANS ENGINE.

had prepared a diagram (*Fig. 60*); the curve "engine alone" showed the best results obtainable with the triple-engine when working with different boiler-pressures deduced from the trials under discussion. The I.HP. for the engine was the same for all points of the curve, namely, 27·4. This curve might be conveniently called the best economy curve for the engine. As regards the losses in the boiler and steam-pipes due to radiation and leakage, he was not aware that any reliable data were available to determine the law connecting these losses with the steam-pressure for any given boiler or boilers, or system of steam-pipes; and he would therefore assume that those losses increased proportionally to the pressure, so that they would be represented by straight lines, as shown in *Fig. 60*, for the three cases taken for illustration, namely, a loss of 5 per cent., 10 per cent., and 20 per cent. at 140 lbs. gauge-pressure. By adding the losses shown by these straight lines to the engine-curve, the dotted curves, showing the actual consumption at various pressures, were obtained; and it would be noticed that for 5 per cent. loss (at 140 lbs. gauge-pressure) the total consumption was increased when working beyond about 190 lbs. gauge-pressure; for 10 per cent. loss beyond 160 lbs.; and for 20 per cent. beyond 145 lbs. A loss of 20 per cent. at 140 lbs. gauge-pressure was undoubtedly a very extreme case, but was nevertheless not impossible, judging from the remarks of Mr. Crompton, who said that in one case he had found these losses (combined, however, with the steam required for the feed-pumps and a mechanical-stoker) to be no less than 45 per cent. of the steam required by the engine. If reliable loss-curves for boilers and steam-pipes could be obtained, it would be possible, by combination with the engine-curve, to determine the most economical pressure to work at under any given set of conditions. It was, however, certain that for economy, a higher pressure could be used in the case of one engine with one short steam-pipe, than with a group of engines (at electric-lighting stations, for instance) connected to the boiler by long, many-jointed steam-pipes. This question also required further study with regard to the increased cost of producing high-pressure steam, the possible reduction of boiler-efficiency at high pressures, and in particular the use of economisers. Capt. Sankey.

Fig. 60.

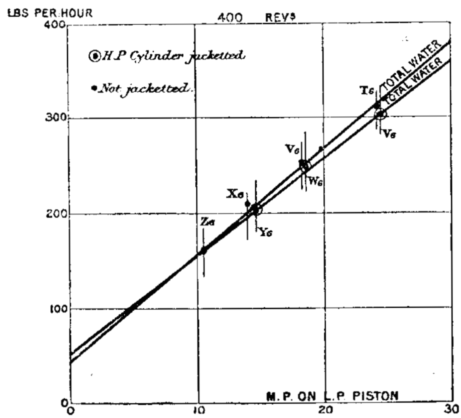


EFFECT OF LEAKS &c. ON CONSUMPTION.

The question of jackets had been referred to by many speakers; on the whole, he thought it might fairly be said that a jacket was of great advantage to a low-speed engine, otherwise given to much initial condensation; but was of comparatively little use for a high-speed engine designed so that the temperatures were well divided and the cylinder-drainage good. A comparison of *Fig. 33* with *Fig. 34* threw some light on this point, for it seemed evident from the proportion of steam to water in the cylinders as shown by these figures that jackets would have improved the consumption of the engine when running at 100 revolutions (*Fig. 33*); but when the steam condensed in the jackets was taken into account, it did not seem that they could do much good when the engine was running at

Capt. Sankey. 380 revolutions (*Fig. 34*). Reference had been made by the Author (page 44) to some jacket-trials he had made: in one set the jacket was placed round the high-pressure (intermediate) cylinder (*Fig. 1*), and these trials had been plotted on *Fig. 61*, together with comparable non-jacketed trials.[1] It would be seen from this figure that with the addition of the steam condensed in the jacket reduced the advantage gained was inconsiderable. Some trials had also been made by the Author with what might be called a hood-jacket, as shown in dotted lines in *Fig. 1*. This jacket was not actually used with the present experimental engine; but with the engine with which the Author had made his non-condensing trials.[2] Those

Fig. 61.



COMPOUND SERIES, HP. CYLINDER JACKETED.

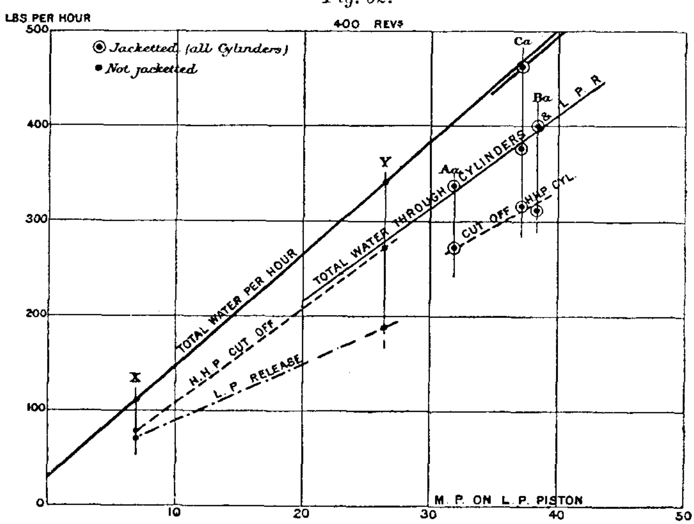
trials were shown in *Fig. 62*, together with two comparable non-jacketed trials, X and Y. It would be noticed that all the steam condensed at H.H.P. cut-off was re-evaporated at L.P. release. The steam condensed in this jacket was of course enormous (25 per cent. of steam going through the engine), so the only lesson to be learnt was as to the saving in the steam actually passing through the engine. The result of all these jacketed trials might be said to be that with high-speed engines almost all the saving in the steam going through the engine was lost in the steam condensed in the jacket itself.

[1] None of these trials were given by the Author in Appendix III.

[2] This engine was exhibited at the President's reception on the 18th of April, having been cut in two to exhibit the motion and the steam-distribution.

He quite agreed with Mr. Davey that water would lie at the bottom of the receivers of the engine. As a matter of fact, in the new condensing-engines now being designed, arrangements had been made to prevent this. In this connection a copper coil would have the effect of more or less drying the steam, and to test this point he made four experiments last winter. The water per I.HP. was slightly in favour of the jacket coil, namely, 15·89 lbs. per hour, as against 15·97 for the non-transfer engine and 14·93 against 15·02 for the transfer engine, and the drying effect of the coil was clearly shown by the steam present at cut-off in the low-pressure cylinder being increased about 8 per cent. Attention had Capt. Sankey.

Fig. 62.



Triple Non-Transfer.

been drawn by Mr. Davey to trials C_4 and D_4 to show that only one-seventh of the feed-water was saved by increasing the pressure from 55 lbs. to 130 lbs. in the triple engine. It was to be observed that the water theoretically required per I.HP. (line 34) is 9·5 lbs. and 8·22 lbs. in the two cases respectively, showing a theoretical gain of $\frac{1}{7\cdot 4}$th, so that the actual engine followed the theoretical engine. It should be noticed also that in trial C_4 the corrected ratio of expansion was 14·10 (line 11), and that the total mean pressure referred to the low-pressure piston was only 10·84 lbs. per square inch, so that very little power was got out of the cylinders, and the consumption per brake HP. would be correspondingly

Capt. Sankey. increased. In other words, the expansions were carried too far in trial C_4 for practical purposes, and from this point of view trial D_4, requiring 13·39 lbs. of feed per hour, ought to be compared with trial L_3, requiring 18·25 lbs. per hour, or even with trial E_5, requiring 24·03 lbs. per hour. This illustrated very forcibly how excellent results per indicated HP. could be obtained at the expense of increased consumption per brake HP. and increased initial cost of the engine; a point, it was believed, not infrequently lost sight of. This later argument also dealt with Mr. Davey's remark, that trials C_4 and D_4 showed that *Fig. 7* did not correctly show the limit of useful ratio of expansions. This figure had reference to the economical results per brake HP., inasmuch as T_2 (page 12) took into account the friction of the engine; but it appeared needless to say anything further on this point as Dr. Hopkinson had made the matter quite clear in his remarks. The remark of Mr. Davey that in all results there was shown to be a very large percentage of water, appeared to require some qualification, because a considerable portion of the condensation was due to work done. To illustrate this, two of the trials had been selected and compared with a perfect engine working between the same limits. The respective percentages of water present at various points in trial E_4 were as follows:—

—	H.H.P.		H.P.		L.P.	
	Cut-off.	Release.	Cut-off.	Release.	Cut-off.	Release.
Actual engine . .	12·92	10·93	17·06	14·35	34·86	26·46
Perfect engine . .	0	5·17	7·73	10·00	13·30	16·00

In trial N_3, however, conditions were so arranged as to produce a great deal of initial condensation, and in this case there resulted—

—	H.P.		L.P.	
	Cut-off.	Release.	Cut-off.	Release.
Actual engine . .	30·83	14·07	36·20	25·32
Perfect engine . .	0	10·00	13·30	17·20

In this connection it might be interesting to point out that if the results given in lines 48 to 53 of the Tables were plotted, it would be found that the condensation at the point of cut-off in each cylinder, and the subsequent re-evaporation at the end of the stroke, not only depended on the range of temperature of the cylinder, but also on the actual temperature of the steam, and was greater the higher the temperature, and to a very marked extent. The remarks that had been made on the Cornish cycle by Mr. Davey were extremely interesting, and it was gratifying to the makers of the Willans engine, to hear that Mr. Davey had practically found this cycle to be the best; he thought much credit was due to him as being the moderniser of the Cornish cycle. This cycle had been from the very first employed by the Author in his central-valve engine in connection with the H.H.P. and H.P. cylinders; but he used it for the first time in the low-pressure cylinder in the engine with which these trials were made, and when thus applied it was called the transfer arrangement. In this connection it might be interesting to mention that a short time ago, when designing the new line of condensing-engines, he thought it was worth while to ascertain definitely the advantage of the transfer by making two trials with the experimental engine, one working with and another without the transfer arrangement. In order to make the comparison as definite as possible the transfer trial E_7 was purposely arranged to compare with the Author's trial E_3, and the result was a very close agreement even in some of the more delicate indicator diagram measurements. The non-transfer trial G_7 was arranged to compare with E_7 and showed a very distinct gain in favour of the transfer arrangement, namely, 15·97 as against 15·02 lbs. of water per I.HP. per hour, and the same was true of two trials (F_7, H_7) in which the coil in the receiver was used. Comparing the transfer trials with the non-transfer trials, the salient points of difference were these: the consumption was less, the thermal efficiency was greater, and the initial condensation was less. Trials had been made by the Author with the engine working as a simple transfer and as a simple non-transfer. These trials proved, as might be expected, that the transfer arrangement had more influence in a simple than in a compound engine. In one case, for instance, the water per I.HP. was reduced by the transfer from 29·31 to 26·19 lbs. In the Paper and elsewhere, the Author had expressed the opinion that the drop of pressure at the toe of the diagram tended to dry the cylinder-walls, and to considerably reduce initial condensation. It seemed reasonable to suppose that the condition of the cylinder-walls would affect the behaviour of steam during compression, so that, if the cylinder-walls were dry, they would expect less condensation than if the cylinder-walls were Capt. Sankey.

Capt. Sankey. wet. The above trials threw some light on that point. With the transfer arrangement there was generally little or no toe to the low-pressure diagram proper, and it was found that steam was condensed during compression in the transfer trials; whereas in the non-transfer trials, where there was a toe to the diagram, evaporation took place during compression. On referring to the Tables, Appendix III, and comparing lines 101 and 102 it would also be apparent that, with very few exceptions, steam was condensed during compression.

The masterly exposition of the Willans law by Professor Kennedy had materially added to the value of the discussion. He would like, however, to point out that line G had another meaning; it was the consumption line of an engine working in an atmosphere hotter than the working fluid—for instance, a carbonic-acid-gas engine. In such a case heat would be radiated into the engine, and not out of it. It might also be interesting to attach a meaning to a consumption line sloping in the opposite

Fig. 63.

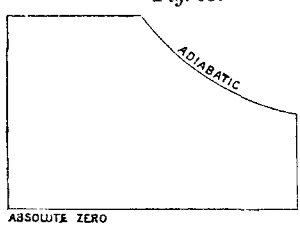
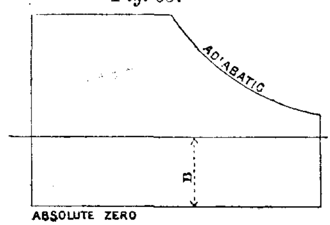


Fig. 65.

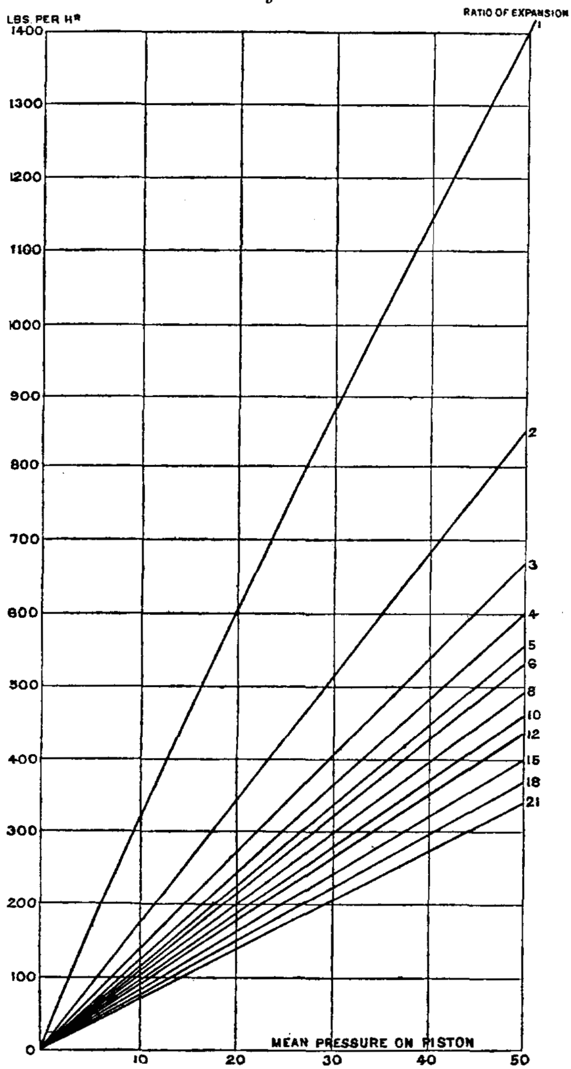


direction, in which case, the greater the mean pressure the greater the quantity of negative working fluid; this was evidently the case of a pump or of a compressor. The Willans law for oil-engines had not been shown by Prof. Kennedy. It appeared to be somewhat different from that for gas-engines, that was, there was a greater initial loss, possibly owing to the imperfect combustion of the oil when the engine was working at light loads. This had been remarked by the Author in the discussion on Prof. Unwin's Paper on "Petroleum Engines."[1] The Willans straight-line law was also found to hold for the original Willans three-cylinder engine, the steam-distribution in which was totally different to that in the central valve-engine, and was also true for the "Willans-Robinson-Scott" engine, another type of single-acting engine with an entirely different steam-distribution. In point of fact, the law held for a theoretical engine working at various loads

[1] Minutes of Proceedings Inst. C.E., vol. cix. p. 1.

with constant ratio of expansion. The diagram of such a theoretical engine could be supposed to be as shown in *Fig. 63*; the admission Capt. Sankey.

Fig. 64.

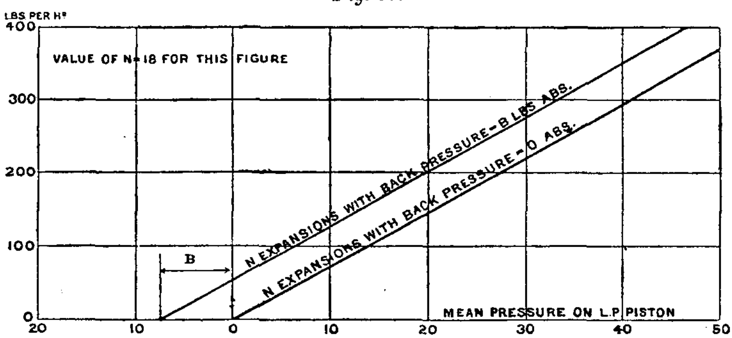


THEORETICAL WILLANS LAW.

line was at constant pressure, the expansion adiabatic, the release instantaneous, the back-pressure absolute zero; there was no

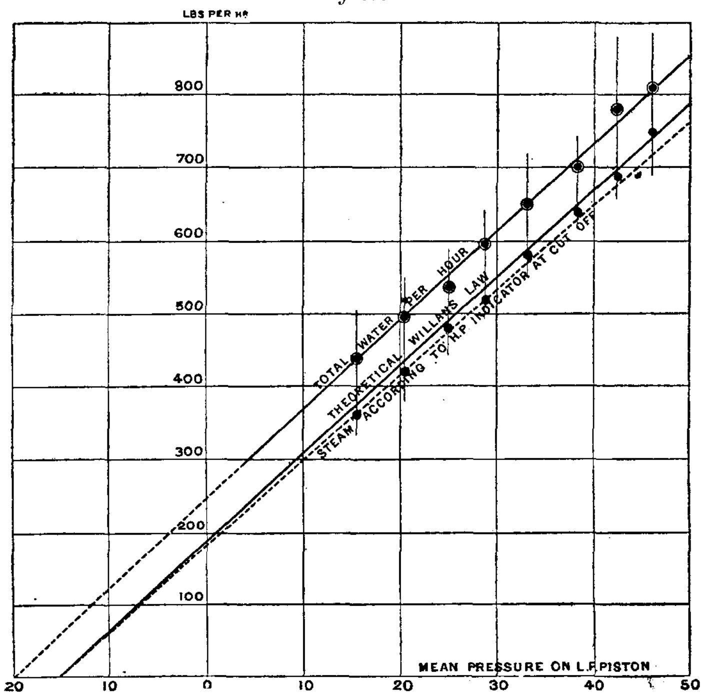
Capt. Sankey. compression and no clearance, and initial condensation, radiation, and all other losses were supposed to be nil. The steam shown by the indicator at cut-off, which would also be the feed, and the mean pressure of such a diagram, could be obtained in the usual way, and if this was done for a series of such diagrams, differing only as regards steam-pressure, that was, with constant ratio of expansion, it was found that if the total steam per hour shown by the indicator at cut-off were plotted on a mean-pressure base, the result was a straight line, or, more strictly speaking, a curve so flat that it was indistinguishable from a straight line. A series of such lines for different ratios of expansion could be drawn, as was shown in *Fig. 64.* It would be noticed that for a ratio of expansion of one (that was, with no expansion) the curvature of the line was somewhat marked. If instead of zero the back-pressure was B lbs. per square inch, as

Fig. 66.



shown in *Fig. 65*, it was evident that the steam shown by the indicator remained the same as before, but that the mean pressure was reduced to the extent of B lbs. per square inch. The consumption line for x expansions in this case would therefore be parallel to the corresponding consumption line for zero back-pressure, at a horizontal distance B lbs. per square inch from it, as given in *Fig. 66.* This proved that the distance between the zero of mean pressure and the intersection of any consumption line with the mean pressure base, was equal to the back-pressure. It had been thought originally by the Author that the total feed-line intersected the base line at a distance equal to the back-pressure from the origin, but he soon gave this idea up. Mr. Wingfield, referring to Figs. 27 to 30, suggested that this might be true of the steam shown by the indicator at cut-off. It appeared from the above, however, that this was true of neither the one nor the other, but that it was true for the steam shown by the indicator of a theoretical engine. Captain Sankey thought that possibly valuable information might be obtained by comparing the actual lines shown in Figs. 11 to 24 with the corresponding theoretical lines, and for this purpose he was having them plotted on the large scale drawings which the Author had originally prepared when writing this Paper. It was, however, *à priori*, evident that the actual feed-line must in all cases lie above the corresponding theoretical consumption line. Capt. Sankey.

Fig. 67.

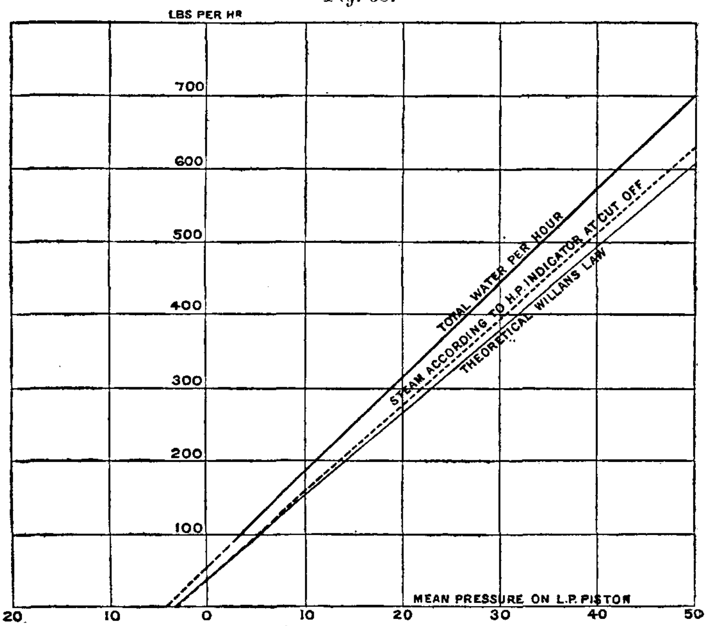


COMPOUND. CONDENSING 4 EXPANSIONS.

As regards the line for the steam shown by the indicator at cut-off in the first cylinder (H.HP., HP. or LP., as the case might be) initial condensation tended to place it below the theoretical line; inasmuch as the steam initially condensed was, at any rate, partially re-evaporated later on in the expansion, and fattened the toe of the diagram, thus increasing the mean pressure. Radiation, conduction and leakage, on the contrary, tended to place the line above the theoretical line. Conditions might, therefore, Capt. Sankey. evidently be such that the two lines coincided, or, again, that, although not coinciding, they might intersect the base at the same point.

Figs. 67 and *68* gave two examples, comparing the theoretical Willans law with corresponding feed-lines and also with the steam-lines at HP. cut-off; in either case the engine was working compound, but in one case as a non-condensing engine, and in the second as a condensing engine. *Fig. 67* had been obtained by plotting the results given in Table VII of the Author's trials on

Fig. 68.



COMPOUND. CONDENSING 4·8 EXPANSIONS.

non-condensing engines,[1] and it was interesting to note that, as might be expected, observation-points for steam at HP. cut-off lay as near the straight line in that case as they did in the various cases given in the present Paper, Figs. 11 to 24, Plate 1; but the observation-points for the feed did not agree nearly so well with the fair line as in the present condensing trials; that could only be attributed to the different and inferior method employed for measuring the consumption, viz., by weighing the feed-water

[1] Minutes of Proceedings Inst. C.E., vol. xciii. p. 54.

into the boiler, even though all possible precautions were taken to ensure accuracy. This must be looked upon, therefore, as another proof to be added to the many already adduced that the method of weighing the condensed exhaust is more accurate than weighing the feed into the boiler, at any rate for an engine where glands are as tight as those of the Willans engine. It had been also suggested by Mr. Wingfield, that the point where the various lines, showing steam according to the indicator in Fig. 27, Plate 2, cut the base line "would prove to be at a distance equal to the mean back-pressure from the origin." It followed from the above that it might be so under certain circumstances; as a matter of fact it was not so in the case referred to—the point lay about $\frac{1}{4}$ lb. per square inch further from the origin than the mean back-pressure. The various lines were, however, correctly drawn through a point, because the element of change in these lines was the number of revolutions per minute, which would clearly have but an inappreciable effect on the position of their intersection with the base line. These latter remarks applied also to the point where the total-consumption lines intersected. On further considering this matter, he had come to the conclusion that the feed-line and the HP. *cut-off line* curved downwards at very low and negative mean pressures, and would intersect the base at a point nearer the zero of mean pressure than the intersection of the theoretical Willans law, but for want of space was unable to give his reasons. In reply to Mr. Wingfield the method employed for measuring the diagrams was to use a drawing-board, to which a small piece of paper had been pinned, and the tracing-point of the planimeter was placed on this paper at a point marked close to the edge; the first card was then slipped under the paper until some convenient point on the diagram was close to the tracing point. The area of the diagram was then planimetered, taking care to finish off with the tracing point in the same position on the piece of paper. The second card was then substituted, and so on. In this manner the planimeter was never lifted, and the combined area of all the cards was taken at one reading. The theoretical mean pressures (reckoned for adiabatic expansion and given in line 27 of Tables I to IV) against the actual mean pressure (given in line 25), it was found that the points also lay in straight lines, the position of each straight line depending on the number of expansions and upon whether the engine was simple, compound or triple; but all passed through the origin, so there was no virtual back pressure to estimate. The tangent of the angle included between these straight lines and the axis of abscissæ was a true diagram-factor in the sense that it was Capt. Sankey.

Capt. Sankey. also an efficiency. The theoretical mean pressure, reckoned on adiabatic expansion, could be more easily obtained for any given conditions of working of the engine from the $\theta\ \phi$ diagram by the help of the planimeter than by calculation from the formula given by Mr. Wingfield. He had been much interested in Mr. Wingfield's method of predicting the mean pressure of an engine, but he had found on plotting and by applying the corresponding diagram-factor the actual mean pressure could be predicted; space did not, however, permit going into the details of the process.

It had been suggested by Mr. Beaumont that a term was required for expressing the commercial efficiency of an engine in contradistinction to its thermal efficiency; but surely the water per indicated HP., or more strictly, per brake HP., gave the information needed on this point. Conceivably, however, an expression for the commercial value of an engine might be obtained on some such considerations as the following:—The horse-power developed would be in the numerator, and the denominator would comprise the cost of evaporating the feed, the cost of lubrication, the cost of maintenance and repairs, the cost of attendance, depreciation and interest on first cost, &c. Brake-trials to ascertain "at what point the triple-expansion advantages were lost in the disadvantages connected with that form" in the Willans engine would be made; but it was to be observed that such experiments would not throw much light on the general question, because the Willans engine could be changed from compound to triple expansion by the simple addition to each line of parts of one small cylinder and its valve, and the additional friction was therefore small. The term "plant efficiency" had been questioned by Mr. Davey, but Mr. Macfarlane Gray had explained the meaning of the term, so that it did not appear necessary to say anything further. The latter speaker had also introduced a new term which he called "engine efficiency," and it might at first sight appear that this efficiency was the same as that used by Prof. Osborne Reynolds, and to which the Author objected strongly (Appendix V); but there was a distinct and important difference, for Prof. Reynolds took the pressure at release at the same point as in the engine under review; and, as pointed out by the Author, this involved getting the best efficiency from a square diagram without expansion. The terminal pressure would, however, be fixed by Mr. Macfarlane Gray at some value obtainable under the best conditions in practice, and then exclude the resulting toe. In this manner any trial was compared with the theoretical result obtainable with a theoretical, but nevertheless possible, engine. The standard of efficiency proposed by Mr. Macfarlane Gray had thus the advantage of being a possible standard; and in this respect was not open to the objection the Author so strongly raised in his former Paper against taking the Carnot-cycle as the standard of efficiency. The difficulty, however, was in fixing the terminal pressure. For the purposes of the Paper the Author had fixed a pressure corresponding to 170° Fahrenheit, although he did not use this figure in calculating thermal efficiencies (p. 9), but others might disagree with this figure. If Mr. Macfarlane Gray's proposition were agreed to—and it seemed desirable that it should—some authoritative statement would be necessary on the point. In conclusion, he would like to remark that one of the most noticeable features in the whole Paper was the extreme modesty with which the Author had brought forward his results, and the entire absence of any claim to credit on behalf of the admirable engine he had designed, but which he described merely as a piece of apparatus employed in making experiments of purely thermodynamic interest. He believed that his name would remain with them not principally as the designer of the Willans engine, but as the Author of this and other Papers of deep scientific interest, and he would venture to add, as the discoverer of what he felt would henceforth be known as the "Willans Law." Capt. Sankey.

Correspondence.

Prof. J. Boulvin observed that the experimental results arrived at by the Author disagreed in no respect from the conditions established by the science of thermodynamics, if not quantitatively, at least qualitatively. The facts presented did not admit of discussion; and it was only by subsequent practice that the value of the data contained in the Tables appended to the Paper could be fully appreciated. The Author had been well advised in stating the results by the medium of the $\theta \phi$ diagram. In section E, it would have been useful to develop somewhat the method employed to find the losses due to wire-drawing (see, for instance, the hatched surfaces between the temperatures T_1 and T_2, T_3 and T_4 (*Fig. 32*)). Similarly, the energy given as lost below temperature T_5 (*Fig. 34*), was possibly shown correctly by the shaded portions of the figure, but the Author's explanations were too far summarised to allow of verification. It might be interesting to show here how the lines of transformation of the Prof. Boulvin.