

## FURTHER EXPERIMENTS ON CONDENSATION AND RE-EVAPORATION OF STEAM IN A JACKETED CYLINDER.

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The author has recently been able to utilize a series of trials, made in the Royal Carriage Department at Woolwich Arsenal, in an attempt to ascertain the amount of Initial Condensation and subsequent Re-evaporation of Steam in a jacketed Cylinder; and he has now the pleasure of laying the results before the Institution in continuation of his paper on the same subject read in September 1887 (Proceedings page 503).

The engine with which the trials were made is a double-cylinder one of 16 nominal horse-power, made by Messrs. Marshall Sons and Co. of Gainsborough, and is used in the Royal Carriage Department for factory purposes, and occasionally for electric lighting. The cylinders are horizontal and attached to a wrought-iron framing underneath the boiler, each being 10 inches diameter and 14 inches stroke; the piston-rods of 1·6 inch diameter pass through one end only, and are connected to a double-throw crank-shaft with a fly-wheel  $5\frac{1}{2}$  feet diameter on one end. The power is taken by means of a belt from a pulley 4 ft. 2 ins. diameter on the other end of the crank-shaft. The main slide-valves are of ordinary pattern, flat-faced, double-ported, with 0·7 inch outside lap, 0·125 inch inside lap, and 2·6 inches travel; the angular advance of the main eccentrics is  $30^{\circ}$ . Flat-faced expansion-valves with no lap work on the back of the main valves, over ports measuring 8·625 inches by 0·625 inch; and the cut-off is automatically regulated by the action of a governor lifting at about 206 revolutions per minute, and shifting the expansion-valve connecting-rod in a slotted

lever, which works on a fixed pin at one end, and is actuated at the other by an eccentric set at  $131^{\circ}$  angular advance with 2.75 inches throw.

The mean clearance volume in each cylinder is 0.051 cub. ft., or 0.081 of the volume swept through per stroke, which is 0.628 cub. ft. The clearance surface is 2.30 sq. ft., and the surface exposed during the stroke is 3.05 sq. ft.

The load on the engine during the experiments consisted of one Brush dynamo, running light at about 680 revolutions per minute, and one Crompton dynamo running at 825 revolutions per minute, and driving from three to fifteen arc-lamps, with a potential of 165 volts and a current of 110 amperes under the full load, the engine running at about 120 revolutions per minute. Indicator diagrams were taken from each end of each cylinder, with two Richards indicators having springs of 48 lbs. per inch, and two Crosby indicators having springs of 50 lbs. per inch.

The cylinders themselves are liners, 0.625 inch thick, inserted in a single casting, which forms the jacket, and is supplied with steam coming direct from the boiler, separately from that used in the engine. The jacket is of about 0.35 cubic foot capacity, and is provided with a drain cock at the lowest point, from which the condensed water was collected by means of a steam trap. About 7.3 square feet of the exterior surfaces of the two cylinders are exposed to the jacket steam.

The boiler is of locomotive type, with a grate area of 10.5 square feet; the firebox is of iron, measuring 3 ft. 0 in. by 3 ft. 4 ins. by 3 ft. 2 ins. deep to the bars. The heating surface is 285 sq. ft., including the firebox above the bars, and fifty iron tubes, 2.5 inches outside diameter and 7 ft. 10 ins. long. The surface covered with non-conducting material is 118 sq. ft., and the uncovered surface of the firebox is 44 sq. ft. The boiler is ordinarily lagged with wood covered with sheet iron; but the wood was removed during the progress of the trials, and various other non-conducting materials were substituted for it, the primary object of the experiments being to determine the relative values of these. The average evaporation per lb. of Barnsley hard steam coal was 8.43 lbs. of water from and

at 212° Fahr., the rate of combustion with full load being about 14.2 lbs. per square foot of grate per hour. The feed pump, consisting of a single-acting plunger 3 inches diameter and 3.375 inches stroke, was driven continuously by the engine, the excess of water not required for the feed being returned to the feed tank. Steam for the blast, when required, was obtained from an adjacent boiler.

The steam passing through the engine was led through an exhaust pipe 4 inches diameter and 17 feet long, to the same surface-condenser which was used in the author's previous experiments. The details of this condenser, which was worked by a separate boiler, are given in his former paper (*Proceedings* 1887 page 479), and it is therefore unnecessary to repeat them here.

In order to measure as accurately as practicable the quantity of feed-water used, it was determined to weigh both the feed-water into the boiler, and also the condensed water after passing through the engine. For this purpose, the feed tank, containing about 200 gallons, was mounted on a weighing machine, and filled by a hose; the collecting tank from the condenser, also holding about 200 gallons, was similarly mounted on a weighing machine; and small supplementary tanks were provided, into which the feed suction pipe and condensed-water collecting pipe could be diverted, whilst the main tanks were being refilled or emptied respectively during a trial.

As the object of the trials was twofold—firstly to ascertain the weight of water evaporated per pound of coal, and secondly to ascertain the weight of water used per stroke of the engine—the following method was adopted. Steam having been raised to the required pressure, the engine was run with the load on, and the fire was allowed to burn down until as little as possible remained in the grate, and the steam pressure began to drop; firing was then commenced with weighed coal, and the weights of water in the feed tank and in the collecting tank were noted. When the fire had been got into a proper condition for maintaining a steady pressure of steam, a counter was connected, and the weights of tanks were again noted.

The counter was disconnected after a previously arranged number of minutes had elapsed, and the weights of the tanks were noted; the difference between these and the weights at the commencement was taken as the weight of water used during the number of revolutions indicated by the counter. The running of the engine was continued until the steam pressure again began to drop, and the fire had got as nearly as practicable into the same condition as at the commencement; the weight of coal used was then noted. The weights of the tanks were also noted at this time, and the difference from the weight at the commencement of firing with weighed coal was taken as the weight of water evaporated during the trial. Any calculated amount due to difference of height in the gauge glass was added to or subtracted from the weight of the feed tank, as required. The result of this double system of weighing has certainly been to confirm the opinion expressed by the author in his previous paper, that the weight of water used can be obtained more accurately from a collecting tank than from a feed tank; and the weights employed in the calculations are those obtained from the collecting tank, with one exception, No. 26, when a leakage through the condenser was detected. (See appended Tables 9 and 10, pages 658-669.)

Indicator diagrams were taken as frequently as practicable, not less than sixteen during any one trial; and the indicator springs have been subsequently tested and found correct. Fifty-five trials in all were made, out of which the first eight, and five of the remainder were rejected for doubtful measurements, leaving forty-two of which the results are here recorded (Plates 119 to 127); the duration of each trial was between one and six hours. The tightness of the condenser was tested in every trial, and the engine was maintained in good running order throughout.

In certain of the trials, Nos. 30 to 35 and 37 to 39, an auxiliary slide-valve was fitted, communicating with each end of each cylinder by pipes furnished with a stop cock, by means of which a graduated amount of atmospheric air was admitted to the cylinder during the exhaust, and was compressed together with the steam, the object being to ascertain whether the initial condensation could be reduced by this means. This proved to be the case, but the resulting gain

in economy of steam consumed was almost exactly counterbalanced by the increased back-pressure.

Twenty-one of the trials were made with circulation of steam through the jacket, and twenty-one with the drain cock shut. Nos. 45 and 55 of the former and Nos. 39 and 40 of the latter, made with a very light load and consequent small consumption of steam per stroke, gave results which showed that the steam was being sensibly superheated, presumably by the heat of the smoke-box which envelopes the steam supply.

Three trials (Nos. 18, 21, and 22) with circulation through the jacket, and three (Nos. 23, 24, and 25) with the drain cock shut, were made with the air-pump of the condenser disconnected, and therefore condensing at atmospheric pressure.

The indicator diagrams from each trial were dealt with as follows. The initial pressure, the terminal pressure, and the pressures during the expansion at two intermediate points marked A and B (Plates 119 to 127), were measured on each diagram, and the average results were taken for the forward pressures at these points. All the diagrams were measured with a planimeter, to obtain the mean forward pressure; and a diagram corresponding as nearly as possible with the average result thus obtained, and not remarkable in any other way, has been selected as the mean diagram representing each trial. This has been done in preference to reconstructing the mean diagram from average measurements, as the author believes that most engineers who wish to analyse the trials would prefer an actual average diagram drawn by the engine itself, to a reconstructed one. The calculations made to obtain the observed condensation have been carried out in precisely the same way as that detailed in the author's previous paper (Proceedings 1887 page 492), and need not therefore be further described.

All the results obtained are shown in Table 9, and the mean diagram representing each trial is shown in the upper part of Plates 119 to 127. The average results of each series in which the conditions were intended to be the same are shown in Table 10, and have been obtained by taking the arithmetical means of the results in Table 9, every trial of more than one hour's duration being

regarded for this purpose as so many separate trials of one hour each. Each series of trials has been grouped under a separate roman numeral, I to XVIII; and these numerals are arranged in order of comparative efficiency. For comparison with calculation this efficiency has been taken as the proportion of work done to available heat in the steam used in the cylinder only. In Table 10 are also shown the actual efficiencies as measured by the water used per horse-power per hour, including the jacket steam collected during a trial, but disregarding that collected at the conclusion of trials made with the jacket drain-cock shut. This latter quantity is small and uncertain in its amount and effects, and on the whole it seemed best to neglect it.

The average results of observed net condensation in each series are shown in the lower diagrams in Plates 119 to 127; the total heights of these lower diagrams represent the number of thermal units of available heat supplied per stroke, which number is also given in figures, both including and excluding the jacket steam. The black dots in these lower diagrams are placed in such positions that the vertical distances measured downwards to them from the top of the lower diagram give the observed average number of thermal units of condensation, less re-evaporation, at the point of the stroke indicated: the lower line UU gives the calculated net condensation when the cylinder is unjacketed, and the upper line JJ when jacketed; these three quantities are also given in figures in Table 10. The numerical results have been checked over by two independent calculations, and generally by the use of different methods.

The general result of the observed amounts of net condensation appears to the author to be strongly confirmatory of the view advanced in his previous paper—that the initial condensation is extremely sudden, and that there is an excess of re-evaporation over condensation during the whole of the forward stroke.

*Clearance Surface.*—Whatever view may be taken of the nature of the process which causes condensation in a steam cylinder, it appears

to the author that the number of thermal units of heat transferred must vary directly as the area of that portion  $S_c$  of the clearance surface which is colder at the moment than the entering steam, whether the surface be that of a film of water or of the actual metal. In assigning the value of this colder portion  $S_c$  however, it is necessary to deduct from the whole clearance surface any portion which is permanently heated from the outside, as by steam-jacketing the end of the cylinder or by other means, to a temperature exceeding that of the entering steam. Such portions must remain dry throughout the whole cycle, and can produce no effect by contact either on the initial condensation or on the subsequent re-evaporation during the stroke. The effect of the cold portion of the clearance surface in producing condensation must be most marked at the first instant, when the difference of temperature is greatest; and must diminish as the surface is brought up to the same temperature as the steam in contact with it. The number of units of heat transferred at each stroke cannot therefore be assumed to vary directly as the time of exposure, or inversely as the number of revolutions in a given time; and every experiment made by the author tends to show that it varies, at any rate approximately, as the square root of the time of exposure, or as  $\frac{1}{\sqrt{N}}$ , where  $N$  is the number of revolutions per second. This result, as pointed out by Professor Cotterill (Proceedings 1887 page 536), is also to be expected on theoretical grounds. The effect of clearance surface will therefore be represented by the factor  $\frac{S_c}{\sqrt{N}}$ .

*Temperature.*—Next, as to the effect of temperature, it is frequently assumed that the condensation must vary directly as the range of temperature in the cylinder; but this view appears to the author to be based upon a fallacy. It is true that there is experimental evidence, obtained by Forbes and others, to show that the rate of transmission of heat through a metallic plate depends on the difference of temperature of the media on either side, and that therefore the condensation of steam, in long continued contact with metal, should vary as the difference of temperature of the two sides; but in that case there is a steady flow of heat,

and the temperature of the side of the plate in contact with the steam must be uniform, and sensibly the same as that of the steam. But the condition of things when steam is entering a cylinder appears to the author to be entirely different; the steam is brought into sudden contact with a surface sensibly colder than itself; and to say that the condensation will depend upon the range of temperature is equivalent to saying that there would be no condensation at all after the temperature of the inner surface of the cylinder is raised to that of the incoming steam, a result directly at variance with both theory and practice. It appears to the author that in a steam cylinder there will be a nearly constant rate of condensation due to conduction through the metal, and depending in amount on the mean temperature; and that to this should be added a variable rate due to the proportion borne by the range of temperature above the mean in the cylinder to the absolute mean temperature of the metal: so that, if the absolute temperature of the incoming steam be denoted by  $T_1$ , and the absolute mean temperature of the inner surface of the cylinder by  $T_m$ , the maximum rate of condensation will vary as  $1 + \frac{T_1 - T_m}{T_m}$ , or as  $\frac{T_1}{T_m}$ . Also that in cylinders which are jacketed, or in which the flow of heat to the outside is prevented by any other equivalent means,  $T_m$  will approach  $T_1$ , and the effect of range of temperature will become negligible.

*Density of Steam.*—Next, all the author's experiments, and all others which he has had an opportunity of analyzing, tend most conclusively to show that the initial condensation varies directly as the density of the incoming steam; and it appears to him that this result is also one which must be expected on theoretical grounds. For whatever may be the nature of the action between the steam and any given portion of the condensing surface, it cannot be sensibly affected by the precisely similar actions going on simultaneously on other portions of the surface; and whatever be the rate of condensation, whether it be the same or different on each portion, it must depend directly on the number of particles of steam brought into contact with a given area, or in other words it must vary directly as the density.



*Formulæ.*—The foregoing considerations have led the author to propose as the expression for initial condensation per stroke in an unjacketed cylinder

$$C_u W = A_u \frac{S_c}{\sqrt{N}} \frac{T_1}{T_m} \rho_1$$

where  $C_u$  is the initial condensation in thermal units per pound of steam in an unjacketed cylinder;  $W$  is the weight of water in pounds per stroke;  $S_c$  is the clearance surface in square feet after deducting any jacketed portion;  $N$  is the number of revolutions per second;  $T_1$  is the initial absolute temperature of the steam;  $T_m$  is the absolute mean temperature of the cylinder, approximately equal to the temperature due to the mean forward pressure;  $\rho_1$  is the initial density of the steam in pounds per cubic foot; and  $A_u$  is a constant, which from his own experiments and from those made in the U.S. Navy in 1874-5 the author deduces to be equal to 80 for Fahrenheit temperatures.

For jacketed cylinders of ordinary proportions,  $T_m = T_1$ ; hence the initial condensation per stroke

$$C_j W = A_j \frac{S_c}{\sqrt{N}} \rho_1$$

where  $C_j$  is the initial condensation in thermal units per pound of steam in a jacketed cylinder. The value of the constant  $A_j$ , obtained directly from the author's experiments on initial condensation in a jacketed cylinder, where the piston was blocked at the end of the stroke, was 56; and this agrees with that deduced from the present series of experiments on the ordinary working of a jacketed engine, when it cannot be directly measured.

Applying converse reasoning to the re-evaporation which takes place during the stroke, it appears to the author that, when a metallic surface is in contact with wet steam, re-evaporation will commence immediately that the steam pressure is reduced below that due to the temperature of the metal; and that the number of thermal units transferred from the metal must vary directly as the surface exposed, and approximately as the square root of the time of exposure. Also that, under the conditions of a steam cylinder, if  $T_m$  be the absolute mean temperature of the metal, between the commencement

of the stroke and the instant considered, and  $T_2$  the absolute temperature of the steam at the same instant, the total number of thermal units transferred will vary with  $\frac{T_m}{T_2}$ , and finally with  $\rho_m$ , the mean density of the steam, as this latter quantity determines the number of particles of wet steam which are brought into contact with any given area of the hot metal. As soon as the exhaust is opened, the rush of steam through the passages will probably sweep away any water remaining at the end of the stroke, and thus prevent further re-evaporation or transfer of heat from the metal during the return stroke.

It does not appear to be possible to ascertain directly the value of  $T_m$ , the mean temperature of the surface of the metal; but it evidently cannot differ much from the mean temperature of the steam; and if it is assumed equal to the latter, the expression for the total re-evaporation in unjacketed cylinders will become

$$B_v \frac{S_2}{\sqrt{N}} \frac{T_m}{T_2} \rho_m$$

where  $S_2$  is the total surface exposed up to the point of the stroke considered;  $N$  the number of revolutions per second;  $T_m$  and  $\rho_m$  respectively the mean absolute temperature and mean density of the steam, between the commencement of the stroke and the point in question; and  $T_2$  the actual absolute temperature of the steam at this point.

For jacketed cylinders  $T_m$  will be replaced by  $T_1$ , as the temperature of the surface of the metal will be maintained nearly at this constant amount, namely that of the incoming steam, by the supply of heat from without; and the expression will become

$$B_J \frac{S_2}{\sqrt{N}} \frac{T_1}{T_2} \rho_m.$$

Initial condensation and corresponding transfer of heat to the metal will of course go on upon each fresh surface exposed during the stroke; but the supply of heat to effect this is drawn by re-evaporation from that stored up in the surface already exposed; and the effect of the exposure of fresh surface will be, not to increase

the total amount of heat transferred, but merely to distribute it over a larger area. If then  $S_2$  is taken to represent, not the total surface exposed, including the clearance, but only the fresh area uncovered during the stroke, the re-evaporation expressed by  $B_U \frac{S_2}{\sqrt{N}} \frac{T_m}{T_2} \rho_m$  or  $B_J \frac{S_2}{\sqrt{N}} \frac{T_1}{T_2} \rho_m$  will represent the excess of re-evaporation over condensation, which can be directly observed.

In the author's experiments the values of  $B$  agree with those of  $A$  already determined for initial condensation: that is  $A_U = B_U = 80$  for unjacketed cylinders, and  $A_J = B_J = 56$  for jacketed cylinders. This is clearly shown by the circumstance that the lines UU and JJ in the lower diagrams in Plates 119 to 127, representing the amounts of net condensation at various points in the stroke, calculated according to these values, are more or less nearly parallel with the line which would pass through the black dots representing the observed results. These calculated amounts were necessarily based on the assumption that dry saturated steam was supplied, which no doubt was not always the case; and this directly affects to the same amount both the total number of thermal units supplied during the stroke, which are represented by the total height of the diagram, and the calculated amount of condensation, which is obtained by subtraction from the total supply. It will be seen however that the difference between the observed and calculated results is approximately constant throughout the stroke; and that the calculated rate of diminution of net condensation agrees very closely with observation in every case.

Denoting the re-evaporation per pound of steam by  $R_U$  and  $R_J$  respectively for unjacketed and jacketed cylinders, the complete formulæ which the author submits to represent the net condensation in a steam cylinder at any point of the stroke will become therefore

$$(C_U - R_U) W = \frac{80}{\sqrt{N}} \left( S_c \frac{T_1}{T_m} \rho_1 - S_2 \frac{T_m}{T_2} \rho_m \right) \text{ for unjacketed cylinders}$$

$$(C_J - R_J) W = \frac{56}{\sqrt{N}} \left( S_c \rho_1 - S_2 \frac{T_1}{T_2} \rho_m \right) \text{ for jacketed cylinders}$$

any portion of  $S_c$  which is jacketed being deducted in either case.

These are extensions of the formulæ suggested by the author in his previous paper (Proceedings 1887, page 505), the difference being that a factor for the effect of temperature is now introduced, and that the mean density of the steam  $\rho_m$  is now substituted for the sum of a constant 0.06 added to the density  $\rho_b$  which corresponds with the back pressure. The reasons why these factors were not introduced into the original formulæ were because the experiments on which they were based did not include sufficient variations of temperature and pressure to make it apparent that any correction for varying temperatures was necessary, and because the mean density happened to agree throughout nearly with  $\rho_b + 0.06$ .

*Calculation of Steam used per Stroke.*—The practical object of determining the amount of condensation and re-evaporation at any point of the stroke is to obtain some basis of calculation for the weight of steam used per stroke; and this may be readily effected as follows. Let  $X$  be the volume swept through, up to the point of cut-off, in cubic feet;  $c$  the ratio which the clearance volume bears to  $X$ ;  $n$  the ratio of volume of cushion steam to steam discharged per stroke, at the initial pressure. Then  $(1+c)(1-n)X$  is the volume in cubic feet, at initial pressure, of the mass of steam discharged per stroke; and  $\rho_1(1+c)(1-n)X$  would be the weight of steam required to fill the cylinder per stroke, if there were no condensation, or the weight per stroke accounted for by the indicator at cut-off. At the point of cut-off  $\rho_m = \rho_1$ , and  $T_m = T_2 = T_1$ , and if the fresh surface exposed during admission be denoted by  $S_1$  the weight of steam condensed and not evaporated per stroke at this point will be  $\frac{80}{\sqrt{N}} \left( \frac{S_c - S_1}{L} \right) \rho_1$  in an unjacketed cylinder, or  $\frac{56}{\sqrt{N}} \left( \frac{S_c - S_1}{L} \right) \rho_1$  in a jacketed cylinder, where  $L$  is the latent heat of evaporation. The total weight  $W$  per stroke is the sum of the weights thus found; or

$$W = \left( \frac{80}{\sqrt{N}} \frac{S_c - S_1}{L} + (1+c)(1-n)X \right) \rho_1 \text{ for unjacketed cylinders.}$$

$$W = \left( \frac{56}{\sqrt{N}} \frac{S_c - S_1}{L} + (1 + c) (1 - n) X \right) \rho_1 \quad \text{for jacketed cylinders.}$$

If  $x_2$  be the percentage of steam in the working mixture at any point of the stroke, and  $v_2$  the volume of one pound of saturated steam of pressure  $p_2$  at the same point, it is further possible after having determined  $W$ , to obtain approximately the value  $v_2 x_2$  of the volume occupied by a pound of steam in the cylinder, at any consecutive values of the pressure  $p_2$  which may be chosen during the expansion, and thus to draw an approximate expansion curve, and complete the calculated diagram. To do this we have the equations

$$Q_2 W = \left( \frac{p_2 v_2}{5.36 (1 + c) (1 - n)} + I_2 - h_2 \right) W x_2 + h_2 W$$

$$Q_2 W = Q_1 W - \frac{80}{\sqrt{N}} \left( S_c \frac{T_1}{T_m} \rho_1 - S_2 \frac{T_m}{T_2} \rho_m \right) \quad \text{for unjacketed cylinders}$$

$$Q_2 W = Q_1 W - \frac{56}{\sqrt{N}} \left( S_c \rho_1 - S_2 \frac{T_1}{T_2} \rho_m \right) \quad \text{for jacketed cylinders}$$

where  $Q_1$  is the total heat supplied per pound of steam;  $Q_2$  the heat remaining in a pound of mixed steam and water at any point of the stroke;  $I_2$  the internal heat of a pound of steam at pressure  $p_2$ ; and  $h_2$  the heat contained in a pound of water at the temperature corresponding to  $p_2$ .

The value of  $\rho_m$  is required to solve these equations, and this may be obtained by calculating the mean pressure  $P_m$  approximately step by step on the curve—on the assumption that between any two nearly adjacent points the expansion curve is a straight line—by the equation

$$P_{m2} = \left( P_{m1} - \frac{p_1 + p_2}{2} \right) \frac{v_1 x_1}{v_2 x_2} + \frac{p_1 + p_2}{2}$$

starting from the point of cut-off, where  $P_{m1} = p_1$ . A further assumption of the approximate values of  $c$  and  $n$  at each point on the expansion curve is necessary to solve the equations; these values however vary but slowly. But the calculations are tedious, and in

the author's opinion for practical purposes it is necessary to determine only the weight of steam used per stroke, and then to draw an expansion curve, either hyperbolic or according to whatever law may be considered most appropriate to the circumstances of the case. In any further calculations of efficiency the error involved by this method does not extend beyond the ratio borne by the difference of area between the curve thus drawn and the real one, to the total area of the diagram.

It will be observed that the author has adhered throughout the calculations in the present paper to Professor Cotterill's method of separating the steam discharged per stroke from the cushion steam, in preference to the method advocated by Mr. Longridge in the discussion on the previous paper (*Proceedings 1887*, pages 511-516), of determining the total heat present in the cylinder at the various points of the stroke. Both methods give practically identical results; the only difference, even theoretically, is that in Professor Cotterill's a hyperbola is taken for the compression curve, instead of that drawn by the engine. But the author considers that the method which he has followed is by far the most convenient for the calculations involved.

The weights of water per stroke, resulting from calculations made from the same data as those of the author's experiments, are given in Table 10 and Plate 128, for comparison with the observed weights. In the experiments made with the jacket drain-cock shut, the effect of the jacket is evidently reduced by an uncertain amount, and the calculated weights are given both for jacketed and unjacketed cylinders. The number of thermal units of initial condensation calculated by the author's formulæ, and of net condensation at the end of the stroke, and at the two intermediate points A and B, are also given in Table 10; and a fair line drawn through these four points in each case is shown on each of the lower diagrams in Plates 119 to 127, from which the calculated net condensation at intermediate points may be determined. These lines, JJ and UU, are shown as calculated by the formulæ for both jacketed and unjacketed cylinders, in the experiments made with the jacket drain-cock shut, Plate 128.

The author has analyzed, so far as the published data permit, the series of experiments made by Mr. Willans on a non-condensing engine and described in his paper read before the Institution of Civil Engineers in March 1888.\* Table 12 and Plates 129 to 131 have been prepared to show the comparative weights of water per stroke observed by Mr. Willans, and those calculated from the same data by the author's formula for jacketed cylinders. The calculations have been made on the basis that the portion of clearance surface which is practically jacketed in Mr. Willans's engine is the entire cylinder cover. The author is not sufficiently familiar with the construction of the engine to be sure whether this exactly represents the case, and unfortunately for the comparison, the number of thermal units abstracted per stroke is given by Mr. Willans for the point of cut-off only. The calculated amounts for this point are given in Table 12, but it is not practicable to make a full comparison of the observed condensation at different points of the stroke, with the calculated amounts.

*Conclusions.*—A consideration of the author's formulæ will show that according to them the loss caused by excess of condensation over re-evaporation, at the end of the stroke, may be reduced in three separate and independent ways: the first is to proportion the cylinder in such a manner that the re-evaporation during the stroke may as far as possible balance the condensation at the commencement; the second is to increase the rate of revolution; and the third is to reduce the area of unjacketed clearance surface to a minimum.

The first of these was alluded to by the author in his previous paper, with an example designed to show that, for working a single unjacketed cylinder at all economically, it is absolutely necessary that the stroke should be increased, in relation to the diameter, to far beyond the usual proportions. If the latter are adhered to, and a small weight of steam, designed to expand several times, is introduced per stroke, it must be contained in such a shape at cut-off

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\* Proceedings of the Institution of Civil Engineers 1888, vol. xciii, page 128.

as to render it unavoidable that a large proportion should be initially condensed; and further there will not be sufficient re-evaporative surface exposed during the stroke to recover the heat thus communicated to the metal. If on the other hand a larger weight of steam is introduced, by using a late cut-off, the loss due to not being able to work expansively will more than counterbalance the saving of condensation. The proved economy of compound and triple cylinders is in great measure due, in the author's opinion, to the weight of steam enclosed at cut-off in each cylinder being generally large in proportion to the amount condensed on the clearance surface; whilst expansive working, though not carried out as economically in itself as it can be in a single cylinder, is yet conducted without any very serious loss.

The second method of avoiding initial condensation, by a higher speed of revolution, appears to be productive of unmixed gain, as far as the actual working of the steam is concerned; but it is of course generally limited by practical considerations.

The third method, by reducing the area of unjacketed clearance surface as far as possible, appears to the author to be unattended with any counterbalancing disadvantages; and he is of opinion that it is of greater importance effectually to jacket the cylinder covers and piston than the sides of the cylinder themselves; and that the economical results obtained by Corliss and other similar valve-gear are more directly attributable to short steam-passages and consequent reduction of clearance surface, than to any other cause.

In conclusion, the author is fully aware that no general formulæ for such complicated conditions as prevail in a steam cylinder can be expected to give more than approximate results. He ventures to express a hope that those which he has put forward may be regarded, not as representing any particular theory, but as the outcome of an attempt to supply the want, which he has often experienced in practice, of some basis of calculation, even though an imperfect one, for the steam likely to be used in any given engine.

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**TABLES 9 to 12.**

TABLE 9. (continued to page 665)

*Results of Trials made to ascertain  
Water used per stroke  
and Steam Pressures.*

Series of trials		I		II		a	
Register number of trial	No.	43	44	46	47	b	
Duration of trial	mins.	360	300	191	180	c	
Revolutions, total during trial	revs.	42234	35579	21920	20919	d	
Thermometer	Fahr.	65°	76°	70°	70°	e	
Barometer, inches of mercury	ins.	30.2	30.0	30.0	29.9	f	
Vacuum, inches of mercury	ins.	21.0	22.0	24.0	24.0	g	
Boiler pressure per sq. inch above atm.	lbs.	42	44	60	60	h	
Feed Water, total		lbs.	3195	2539	3192	3140	i
Collected Water.	Total	lbs.	3122	2491	3114	3079	j
	From Cylinders during trial	lbs.	3075	2438	3035	2971	k
	„ Jacket „ „	lbs.	0	0	0	0	l
	„ Jacket drain-cock after trial	lbs.	17	17	27	27	m
Steam Pressures, lbs. per square inch.	Admission, absolute	48.2	49.6	67.9		n	
	Forward, absolute at point A on diagram*	25.8	27.7	45.7		o	
	„ „ „ „ B „ „	10.8	11.7	19.7		p	
	Terminal, absolute	7.8	8.6	14.5		q	
	Back pressure, absolute, } beginning of compression }	5.1	5.7	5.0		r	
	Cushion pressure, absolute, end of stroke	9.3	10.5	10.1		s	
	Mean { up to point A on diagram*	37.6	41.4	61.3			
	Forward { „ „ „ B „ „	22.2	23.3	38.0		u	
	Pressure { throughout stroke	16.0	17.0	29.6		v	
	Mean Back pressure throughout stroke	3.0	3.7	3.2		w	
	„ Cushion „ „ „	1.9	2.0	2.5		x	
	„ Effective „ „ „	11.1	11.3	23.9		y	
Number of Indicator Diagrams taken in trial		95		48		z	
* See diagrams in Plate		119		119			

(continued on next page) TABLE 9.

*Results of Trials made to ascertain  
Water used per stroke  
and Steam Pressures.*

a	III		IV	V				
b	16	17	39	14	15	26	28	42
c	60	60	60	60	60	360	60	360
d	7259	7161	7252	7107	7203	43891	7359	44257
e	68°	68°	62°	66°	65°	66°	69°	76°
f	29·6	29·6	29·9	29·7	29·6	30·0	29·7	30·0
g	26·0	25·0	15·0	26·5	26·0	26·0	25·5	24·0
h	55	55	50	70	70	70	70	70
i	1295	1195	600	1550	1220	6162	1494	6256
j	1351	1261	520	1434	1185	?	1394	6157
k	989	1027	428	963	1014	?	978	5877
l	0	0	0	0	0	0	0	0
m	22	21	21	23	19	20	3	27
n	60·5	60·2	58·1	73·9	75·0	72·7	72·0	74·8
o	45·8	44·1	33·3	54·9	54·0	52·9	54·8	54·2
p	19·2	19·2	13·9	20·9	20·7	20·0	20·5	19·8
q	14·3	14·2	9·2	13·7	14·0	13·8	14·1	13·6
r	4·3	4·0	7·9	4·5	4·4	5·8	5·1	5·2
s	7·7	7·6	17·2	7·3	7·6	16·5	16·1	9·8
t	57·6	58·5	42·4	69·4	68·8	68·6	69·9	66·3
u	36·8	38·5	23·8	40·4	40·0	40·1	40·5	38·7
v	28·9	30·1	18·0	29·5	29·3	30·0	29·9	28·8
w	3·1	2·9	4·9	3·2	2·9	2·8	3·4	3·5
x	1·5	1·5	3·7	1·4	1·5	2·0	1·8	1·9
y	24·3	25·7	9·4	24·9	24·9	25·2	24·7	23·4
z	40		16			152		
	120		120			121		

TABLE 9 (continued from preceding page)

*Results of Trials made to ascertain  
Water used per stroke  
and Steam Pressures.*

Series of trials		VI	VII				a
Register number of trial	No.	38	52	54	53		b
Duration of trial	mins.	60	60	60	360		c
Revolutions, total during trial	revs.	7212	7172	7256	42918		d
Thermometer	Fahr.	62°	66°	67°	67°		e
Barometer, inches of mercury	ins.	30·0	29·8	29·9	29·9		f
Vacuum, inches of mercury	ins.	18·5	21·5	21·0	21·0		g
Boiler pressure per sq. inch above atm.	lbs.	55	55	55	55		h
Feed Water, total	lbs.	1199	784	794	4490		i
Collected Water.	Total	lbs.	1164	745	757	4349	j
	From Cylinders during trial	lbs.	958	654	705	4258	k
	„ Jacket „ „	lbs.	72	0	0	0	l
	„ Jacket drain-cock after trial	lbs.	0	24	12	25	m
Steam Pressure, lbs. per square inch.	Admission, absolute	63·1	59·5	59·8			n
	Forward, absolute at point A on diagram*	54·0	39·0	40·4			o
	„ „ „ „ B „ „	22·8	15·7	16·3			p
	Terminal, absolute	16·0	11·0	11·3			q
	Back pressure, absolute, } beginning of compression }	7·0	5·5	5·7			r
	Cushion pressure, absolute, end of stroke	16·7	11·5	15·6			s
	Mean { up to point A on diagram*	61·5	51·0	52·0			t
	Forward { „ „ „ B „ „	42·5	29·5	30·6			u
	Pressure { throughout stroke	33·2	22·5	23·3			v
	Mean Back pressure throughout stroke	4·0	3·3	3·3			w
	„ Cushion „ „ „	3·4	2·2	2·1			x
	„ Effective „ „ „	25·8	17·0	17·9			y
Number of Indicator Diagrams taken in trial		16	76				z
* See diagrams in Plate		121	122				

(continued on next page) TABLE 9.

*Results of Trials made to ascertain  
Water used per stroke  
and Steam Pressures.*

<i>a</i>	VIII		IX	X	XI		
<i>b</i>	45	55	35	37	23	24	25
<i>c</i>	360	60	60	60	60	360	60
<i>d</i>	42642	7395	7134	7159	7219	43676	7240
<i>e</i>	76°	67°	62°	62°	62°	62°	70°
<i>f</i>	30·0	29·9	30·2	30·2	30·1	29·8	30·0
<i>g</i>	22·0	21·0	18·5	18·5	0	0	0
	44	44	70	55	80	80	80
<i>i</i>	2619	447	1250	1218	1611	6814	1655
<i>j</i>	2483	450	1076	1119	1573	6734	1568
<i>k</i>	2185	357	974	956	1093	6461	1068
<i>l</i>	230	40	0	0	0	0	0
<i>m</i>	0	0	21	20	19	3	13
<i>n</i>	49·8	51·3	77·0	61·7	85·7	85·2	85·3
<i>o</i>	27·4	26·3	63·0	51·8	70·0	67·5	65·3
<i>p</i>	11·3	11·3	22·6	21·2	29·4	28·3	28·0
<i>q</i>	8·1	7·8	15·1	15·2	20·0	20·1	19·6
<i>r</i>	5·8	4·9	7·0	6·8	14·8	14·8	14·8
<i>s</i>	10·6	9·0	16·0	14·8	32·2	32·2	31·0
<i>t</i>	39·6	39·2	74·0	60·0	83·0	83·4	82·7
<i>u</i>	21·6	18·7	44·2	41·1	55·2	53·6	54·0
<i>v</i>	16·1	15·7	32·7	31·6	43·3	42·4	39·5
<i>w</i>	3·4	3·1	4·0	4·1	9·2	8·4	9·2
<i>x</i>	2·1	1·8	2·9	2·9	7·3	7·1	6·4
<i>y</i>	10·6	10·8	25·8	24·6	26·8	26·9	23·9
<i>z</i>	64		20	16	74		
	122		123	123	124		

TABLE 9. (continued from preceding page)

*Results of Trials made to ascertain  
Water used per stroke  
and Steam Pressures.]*

Series of trials		XII			a	
Register number of trial	No.	49	50	51	b	
Duration of trial	mins.	360	60	60	c	
Revolutions, total during trial	revs.	42569	7197	7130	d	
Thermometer	Fahr.	63°	65°	66°	e	
Barometer, inches of mercury	ins.	29·8	29·8	29·8	f	
Vacuum, inches of mercury	ins.	21·5	21·5	21·5	g	
Boiler pressure per sq. inch above atm.	lbs.	55	55	55	h	
Feed Water, total		lbs.	4374	707	756	i
Collected Water.	Total	lbs.	4202	686	679	j
	From Cylinders during trial	lbs.	3938	634	550	k
	„ Jacket „ „	lbs.	230	38	55	l
	„ Jacket drain-cock after trial	lbs.	0	0	0	m
Steam Pressure, lbs. per square inch.	Admission, absolute		59·5	60·3		n
	Forward, absolute at point A on diagram *		35·5	40·3		o
	„ „ „ „ B „ „		15·7	15·9		p
	Terminal, absolute		11·4	10·7		q
	Back pressure, absolute, } beginning of compression }		5·4	5·4		r
	Cushion pressure, absolute, end of stroke		8·2	10·8		s
	Mean { up to point A on diagram *		49·0	52·7		t
	Forward { „ „ „ B „ „		31·0	31·0		u
	Pressure { throughout stroke		23·8	23·1		v
	Mean Back pressure throughout stroke		3·3	3·3		w
	„ Cushion „ „ „		1·6	2·1		x
	„ Effective „ „ „		18·9	17·7		y
Number of Indicator Diagrams taken in trial			80		z	
* See diagrams in Plate			124			

(continued on next page) TABLE 9.

*Results of Trials made to ascertain  
Water used per stroke  
and Steam Pressures.*

a	XIII	XIV			XV		
b	48	18	21	22	9	10	11
c	360	60	60	360	60	60	60
d	41500	7146	7205	43559	7251	7217	7228
e	65°	74°	68°	65°	65°	64°	66°
	29·8	29·8	30·3	30·2	30·3	30·3	30·3
g	22·0	0	0	0	27·5	27·5	27·0
h	56	80	80	80	55	55	55
i	4980	1422	1334	6367	1169	1096	1191
j	4828	1401	1240	6198	1189	1054	1149
k	4422	936	958	5788	822	826	789
l	340	61	42	249	62	39	48
m	0	0	0	0	0	0	0
n	63·5	86·0	86·5	86·4	62·0	61·4	60·7
o	45·2	68·3	68·8	68·0	47·0	46·8	42·8
p	19·5	29·6	28·4	27·8	20·2	19·9	18·8
q	13·9	20·6	19·3	18·8	13·8	13·9	12·2
r	5·3	14·8	14·8	14·8	3·8	4·1	3·8
s	10·0	30·9	32·2	31·0	6·8	7·3	7·3
t	57·5	81·6	80·6	81·6	58·2	59·4	55·5
u	36·6	54·6	53·6	53·8	37·2	39·5	35·1
v	28·8	42·8	41·8	41·6	28·7	30·9	27·7
w	3·5	8·9	8·7	8·7	2·5	3·5	2·9
x	1·9	6·0	6·3	7·6	1·3	1·4	1·4
y	23·4	27·9	26·8	25·3	24·9	26·0	23·4
z	48	56			54		
	125	125			126		

TABLE 9. (continued from preceding page)

*Results of Trials made to ascertain  
Water used per stroke  
and Steam Pressures.*

Series of trials		XVI			a	
Register number of trial	No.	12	13	41	b	
Duration of trial	mins.	60	60	360	c	
Revolutions, total during trial	revs.	7234	7353	43682	d	
Thermometer	Fahr.	65°	65°	66°	e	
Barometer, inches of mercury	ins.	30·4	30·4	30·1	f	
Vacuum, inches of mercury	ins.	27·0	27·0	24·0	g	
Boiler pressure per sq. inch above atm.	lbs.	70	70	70	h	
Feed Water, total		lbs.	1031	1145	5194	i
Collected Water.	Total	lbs.	1021	1136	5172	j
	From Cylinders during trial	lbs.	790	768	4698	k
	„ Jacket „ „	lbs.	76	62	328	l
	„ Jacket drain-cock after trial	lbs.	0	0	0	m
Steam Pressure, lbs. per square inch.	Admission, absolute		75·5	75·5	76·1	n
	Forward, absolute at point A on diagram*		51·7	51·1	52·9	o
	„ „ „ „ B „ „		20·2	20·0	21·5	p
	Terminal, absolute		12·5	12·5	13·3	q
	Back pressure, absolute, } beginning of compression }		3·9	3·7	5·2	r
	Cushion pressure, absolute, end of stroke		6·3	6·1	9·8	s
	Mean { up to point A on diagram*		67·7	70·4	69·0	t
	Forward { „ „ „ B „ „		39·1	41·4	39·3	u
	Pressure { throughout stroke		29·5	31·3	30·9	v
	Mean Back pressure throughout stroke		2·4	4·1	3·0	w
	„ Cushion „ „ „		1·7	1·9	2·7	x
	„ Effective „ „ „		25·4	25·3	25·2	y
Number of Indicator Diagrams taken in trial		88				
* See diagrams in Plate		126				



(concluded from page 658) TABLE 9.

*Results of Trials made to ascertain  
Water used per stroke  
and Steam Pressures.*

a	XVII	XVIII				
		30	31	32	33	34
b	40	60	60	60	300	60
c	60	60	60	60	300	60
d	7180	7135	6957	7259	36261	7273
e	63°	66°	70°	66°	62°	63°
f	29·9	29·9	29·9	30·0	30·0	29·9
g	23·0	11·0	18·0	19·5	18·0	18·5
h	40	70	70	70	72	70
i	513	1263	1157	1313	4869	1232
j	434	1191	1035	1159	4905	1146
k	354	878	832	857	4321	873
l	0	74	79	59	333	56
m	19	0	0	0	0	0
n	44·8	78·4	78·0	76·9	78·8	77·8
o	24·8	56·4	51·8	48·3	53·1	60·8
p	11·1	24·0	22·4	21·1	21·8	22·9
q	7·5	16·6	15·5	14·8	14·9	14·9
r	5·2	11·1	7·6	6·6	7·0	6·0
s	7·5	22·4	15·5	13·2	17·0	13·0
t	34·6	72·0	69·8	67·4	74·3	74·7
u	20·5	46·6	44·0	41·6	45·0	45·5
v	14·9	36·2	35·1	31·5	34·9	33·9
w	3·1	6·6	4·3	3·5	4·1	4·3
x	1·5	4·4	3·0	2·6	3·3	2·5
y	10·3	25·2	27·8	25·4	27·5	27·1
z	16	110				
	127	127				

TABLE 10. (continued to page 669)

*Comparison of Average Results of Table 9 with Calculation.*

Series of trials			I	II
Register number of trials	Nos.		43, 44	46, 47
Indicated Horse-Power	I.H.P.		14.8	30.7
Number of Expansions	times		8.5	5.5
Steam Pressure, lbs. per square inch.	Admission, absolute		48.9	67.9
	Terminal, absolute		8.2	14.5
	Back pressure, absolute, beginning of compression		5.4	5.0
	Cushion pressure, absolute, end of stroke		9.9	10.1
	Mean Forward pressure throughout stroke		16.5	29.6
	" Back " " "		3.4	3.2
	" Cushion " " "		1.9	2.5
	" Effective " " "		11.2	23.9
Water per stroke.	From Jacket, collected during trial	lb.	0	0
	" Cylinder, " " "	lb.	0.0176	0.0350
	" " calculated as unjacketed	lb.	0.0241	0.0393
	" " " " , jacketed	lb.	0.0194	0.0332
	Accounted for by indicator at cut-off	lb.	0.0083	0.0190
Jacket Steam during trial, percentage of total			0	0
Cylinder " " " " " "			100	100
Work, thermal units.	Total, per lb. of cylinder steam		111	101
	Back-pressure, " "		22	11
	Cushion, " "		13	9
	Effective, " "		76	81
	" per lb. of steam supplied		76	81
	" " stroke		1.34	2.83
Heat, th. units.	Per lb. of steam supplied		1167	1174
	" " " water at back-pressure temperature		134	133
	Available per lb. of steam supplied		1033	1041
	" " " stroke, including jacket steam		18.1	36.0
Efficiency, or Effective Work in percentage of Available Heat			7.4	7.7
Water per horse-power per hour, including jacket			33.8	31.7
Condensation per stroke, thermal units.	Initial, calculated as unjacketed		16.8	23.2
	" " " " , jacketed		10.8	15.1
	Net at point A on diagrams, calculated as unjacketed		14.5	18.3
	" " " " " " " " , jacketed		9.1	11.6
	" " " " " " " " observed		9.3	16.0
	" at point B on diagrams, calculated as unjacketed		11.0	12.7
	" " " " " " " " , jacketed		6.3	7.5
	" " " " " " " " observed		6.3	12.7
	" at end of stroke, calculated as unjacketed		9.1	9.5
	" " " " " " " " , jacketed		4.9	5.0
	" " " " " " " " observed		3.4	9.2

(continued on next page) TABLE 10.

*Comparison of Average Results of Table 9 with Calculation.*

III	IV	V	VI	VII	VIII	IX
16, 17	39	{ 14, 15, } 26, 28, 42 }	38	52, 53, 54	45, 55	35
33.0	13.8	32.8	34.3	23.9	13.7	33.8
5.7	10.0	6.6	4.8	8.0	9.6	6.2
60.3	58.1	73.7	63.1	59.7	50.5	77.0
14.2	9.2	13.7	16.0	11.3	8.1	15.1
4.1	7.9	5.3	7.0	5.7	5.6	7.0
7.6	17.2	12.6	16.7	14.6	10.3	16.0
29.5	18.0	29.4	33.2	23.1	16.0	32.7
3.0	4.9	3.2	4.0	3.3	3.3	4.0
1.5	3.7	1.8	3.4	2.1	2.1	2.9
25.0	9.4	24.4	25.8	17.7	10.6	25.8
0	0	0	0.0025	0	0.0013	0
0.0350	0.0147	0.0339	0.0332	0.0245	0.0127	0.0341
0.0337	—	0.0392	—	0.0289	—	0.0408
0.0284	0.0206	0.0326	0.0312	0.0233	0.0186	0.0339
0.0162	0.0073	0.0172	0.0191	0.0102	0.0072	0.0178
0	0	0	7.0	0	9.2	0
100	100	100	93.0	100	90.8	100
99	151	102	118	114	146	113
10	38	11	14	16	30	14
5	30	6	12	11	19	10
84	83	85	92	87	97	89
84	83	85	86	87	88	89
2.92	1.22	2.88	2.85	2.13	1.12	3.03
1171	1170	1175	1172	1171	1167	1176
122	150	133	145	136	136	143
1049	1020	1042	1027	1035	1031	1033
36.7	15.0	35.3	36.7	25.4	14.4	35.2
8.0	8.1	8.2	8.3	8.4	8.5	8.6
30.5	30.9	30.3	30.0	29.4	29.4	28.8
19.7	—	24.1	—	19.9	—	25.1
13.1	12.6	15.6	13.7	12.8	10.9	16.4
15.0	—	20.3	—	17.0	—	21.0
9.8	10.9	12.8	10.4	10.7	9.4	13.5
16.5	5.0	16.5	12.2	11.9	4.9	14.8
9.2	—	14.3	—	12.3	—	14.1
5.5	8.0	8.4	5.3	7.2	6.9	8.3
13.3	1.1	13.4	8.6	8.3	1.7	11.8
6.2	—	10.6	—	9.3	—	10.5
3.0	6.2	5.6	2.7	4.8	5.3	5.4
9.7	-0.9	10.0	5.8	4.8	-0.9	7.9

TABLE 10. (continued from preceding page)

*Comparison of Average Results of Table 9 with Calculation.*

Series of trials		X	XI
Register number of trials	Nos.	37	{ 23, 24, 25 }
Indicated Horse-Power	I.H.P.	32.8	36.2
Number of Expansions	times	5.0	4.9
Steam Pressure, lbs. per square inch.	Admission, absolute	61.7	85.3
	Terminal "	15.2	20.0
	Back pressure, absolute, beginning of compression	6.8	14.8
	Cushion pressure, absolute, end of stroke	14.8	32.1
	Mean Forward pressure throughout stroke	31.6	42.2
	" Back " " "	4.1	8.6
	" Cushion " " "	2.9	7.0
	" Effective " " "	24.6	26.6
Water per stroke.	From Jacket, collected during trial	lb. 0	0
	" Cylinder, " " "	lb. 0.0334	0.0371
	" " calculated as unjacketed	lb. 0.0354	0.0473
	" " " " " jacketed	lb. 0.0302	0.0402
	Accounted for by indicator at cut-off	lb. 0.0181	0.0238
Jacket Steam during trial, percentage of total		0	0
Cylinder " " " " " "		per cent. 100	per cent. 100
Work, thermal units.	Total, per lb. of cylinder steam	113	133
	Back-pressure, " "	15	25
	Cushion, " "	10	21
	Effective, " "	88	87
	" per lb. of steam supplied	88	87
	" " stroke	2.94	3.23
Heat, th. units.	Per lb. of steam supplied	1172	1178
	" " " water at back-pressure temperature	144	181
	Available per lb. of steam supplied	1028	997
	" " " stroke, including jacket steam	34.3	37.0
Efficiency, or Effective Work in percentage of Available Heat		8.6	8.7
Water per horse-power per hour, including jacket		lbs. 29.1	29.8
Condensation per stroke, thermal units.	Initial, calculated as unjacketed	20.2	27.2
	" " " " " jacketed	13.3	17.9
	Net at point A on diagrams, calculated as unjacketed	15.5	20.8
	" " " " " " " " " " " jacketed	10.0	13.4
	" " " " " " " " " " " observed	13.0	12.4
	" " at point B on diagrams, calculated as unjacketed	8.8	12.3
	" " " " " " " " " " " jacketed	5.1	7.1
	" " " " " " " " " " " observed	9.9	8.1
	" " at end of stroke, calculated as unjacketed	6.1	8.6
	" " " " " " " " " " " jacketed	2.7	4.1
	" " " " " " " " " " " observed	7.0	4.6

(concluded from page 666) TABLE 10.

*Comparison of Average Results of Table 9 with Calculation.*

XII	XIII	XIV	XV	XVI	XVII	XVIII
49, 50, 51	48	18, 21, 22	9, 10, 11	12, 13, 41	40	{ 30, 31, 32, 33, 34 }
24.1	29.1	35.3	32.9	33.1	13.9	36.3
7.3	6.5	5.2	5.6	6.8	9.5	6.1
59.9	63.5	86.4	61.4	75.9	44.8	78.3
11.0	13.9	19.1	13.3	13.1	7.5	15.1
5.4	5.3	14.8	3.9	4.8	5.2	7.4
8.9	10.0	31.1	7.1	8.9	7.5	16.6
23.6	28.8	41.8	29.1	30.8	14.9	34.5
3.3	3.5	8.7	3.0	3.1	3.1	4.4
1.7	1.9	7.2	1.4	2.5	1.5	3.0
18.6	23.4	25.9	24.7	25.2	10.3	27.1
0.0014	0.0020	0.0015	0.0017	0.0020	0	0.0024
0.0225	0.0266	0.0332	0.0281	0.0268	0.0123	0.0299
—	—	—	—	—	—	—
0.0251	0.0283	0.0394	0.0290	0.0325	0.0169	0.0342
0.0121	0.0144	0.0224	0.0167	0.0166	0.0068	0.0182
5.8	7.0	4.4	6.2	7.0	0	7.6
94.2	93.0	95.6	93.8	93.0	100	92.4
122	125	149	123	135	146	139
17	15	30	13	14	30	17
9	9	25	6	11	15	12
96	101	94	104	110	101	109
90	94	90	98	102	101	101
2.02	2.50	2.99	2.75	2.73	1.24	3.02
1171	1172	1179	1172	1176	1165	1177
134	133	181	120	129	132	147
1037	1039	998	1052	1047	1033	1030
24.8	29.7	34.5	31.3	30.2	12.7	33.3
8.7	9.0	9.0	9.3	9.7	9.8	9.8
28.2	27.3	28.4	26.2	25.4	25.5	25.6
—	—	—	—	—	—	—
13.0	14.0	18.1	13.2	16.0	9.9	16.7
—	—	—	—	—	—	—
10.4	10.7	13.7	10.1	13.3	8.4	12.5
8.6	9.2	8.6	9.3	10.2	4.5	9.9
—	—	—	—	—	—	—
6.8	6.5	7.6	5.5	8.8	5.9	7.3
5.5	5.4	4.1	5.7	5.2	0.9	6.5
—	—	—	—	—	—	—
4.9	4.1	4.4	3.3	5.4	4.6	5.0
3.1	2.6	1.8	3.9	3.6	1.1	4.1

TABLE 11. (continued on opposite page)

*Summary of observed results from Table 10,  
arranged in each group in order of comparative efficiency.*

Condensing or Non-Condensing.		CONDENSING.						
Series of Trials in Table 10		I	II	III	V	VII	IX	X
Cylinders:— U = Unjacketed J = Jacketed		U	U	U	U	U	U	U
Initial Pressure, absolute, lbs. per square inch		48.9	67.9	60.3	73.7	59.7	77.0	61.7
Number of Expansions		8.5	5.5	5.7	6.6	8.0	6.2	5.0
Back Pressure, absolute, lbs. per square inch		5.4	5.0	4.1	5.3	5.7	7.0	6.8
Thermal Units per stroke.	Effective Work	1.34	2.83	2.92	2.88	2.13	3.03	2.94
	Useless Work	0.62	0.70	0.52	0.58	0.66	0.81	0.83
	Steam and Water at end of stroke	12.7	23.3	23.6	21.8	17.8	23.5	23.5
	Condensation at end of stroke	3.4	9.2	9.7	10.0	4.8	7.9	7.0
	Total Heat excluding Jacket	18.1	36.0	36.7	35.3	25.4	35.2	34.3
	Heat supplied by Jacket	?	?	?	?	?	?	?

The initial pressure, number of expansions, back pressure, effective work, and condensation at end of stroke, are all copied from Table 10.

The useless work is the sum of the back-pressure work (line 21 in Table 10) and of the cushion work (line 22), each per lb. of cylinder steam, multiplied by the weight of water per stroke from the cylinder (line 14).

The thermal units in the condensation at end of stroke are the remainders left after deducting from the total heat (excluding jacket) the effective and useless work and the heat left in the steam and water at end of stroke.

(continued from opposite page) TABLE 11.  
*Summary of observed results from Table 10,  
 arranged in each group in order of comparative efficiency.*

NON- CONDENSING.		CONDENSING.						CONDENSING AND SUPERHEATED.		
XI	XIV	VI	XII	XIII	XV	XVI	XVIII	IV	VIII	XVII
U	J	J	J	J	J	J	J	U	J	U
85.3	86.4	63.1	59.9	63.5	61.4	75.9	78.3	58.1	50.5	44.8
4.9	5.2	4.8	7.3	6.5	5.6	6.8	6.1	10.0	9.6	9.5
14.8	14.8	7.0	5.4	5.3	3.9	4.8	7.4	7.9	5.6	5.2
3.23	2.99	2.85	2.02	2.50	2.75	2.73	3.02	1.22	1.12	1.24
1.70	1.83	0.84	0.58	0.64	0.53	0.67	0.87	1.00	0.62	0.55
27.5	26.4	24.6	17.7	21.9	22.2	21.1	22.8	13.7	12.3	12.0
4.6	1.8	5.8	3.1	2.6	3.9	3.6	4.1	-0.9	-0.9	-1.1
37.0	33.0	34.1	23.4	27.6	29.4	28.1	30.8	15.0	13.1	12.7
?	1.5	2.6	1.4	2.1	1.9	2.1	2.5	?	1.3	?

The thermal units left in the steam and water at end of stroke are calculated in the manner detailed in Proceedings 1887, page 492.

The total heat excluding jacket is the sum of the four lines immediately above it, and is the number of thermal units available per stroke (excluding jacket), copied from the diagrams, Plates 119 to 127.

The heat supplied by jacket is the difference between the heat available per stroke including jacket steam, and the heat excluding jacket, taken from the diagrams, Plates 119 to 127.

TABLE 12. (continued to page 675)

*Comparison of Mr. Willans' Observed results with Calculation.**See Proceedings Inst. C. E. 1888, vol. xciii, pages 164-169.*

- P** Admission pressure, absolute, lbs. per square inch.
- A** { Trial letter, S simple, C compound, T triple; intended absolute mean  
admission pressure, lbs. per square inch; and intended ratio of expansion.
- R** Revolutions per minute.
- W** Lb. weight of Steam per stroke, accounted for by indicator at cut-off.
- FO** Lb. weight of Feed-Water per stroke, Observed.
- FC** Lb. do. do. Calculated =  $p_1 \left\{ \frac{56}{\sqrt{N}} \frac{S_c - S_1}{L} + (1+c)(1-n)X \right\}$
- HO** Heat units per stroke, missing at cut-off, Observed.
- HC** Do. do. do. Calculated =  $\frac{56}{\sqrt{N}} (S_c - S_1) p_1$

Mr. Willans' Table I. See Fig. 41, Plate 129.							
<b>A</b>	S $\frac{40}{1.57}$	S $\frac{50}{2.17}$	S $\frac{70}{2.8}$	S $\frac{80}{3.2}$	S $\frac{90}{3.6}$	S $\frac{100}{4}$	S $\frac{110}{4.4}$
<b>R</b>	393.5	408.4	409.1	403.2	400.9	397.7	406.2
<b>W</b>	0.02639	0.02342	0.02486	0.02507	0.02656	0.02531	0.02527
<b>FO</b>	0.0299	0.0290	0.0338	0.0329	0.0353	0.0368	0.0359
<b>FC</b>	0.0273	0.0247	0.0297	0.0299	0.0327	0.0321	0.0329
<b>HO</b>	3.269	5.166	8.168	7.048	7.863	10.261	9.436
<b>HC</b>	0.8	1.2	3.4	4.2	5.4	6.0	6.7

Mr. Willans' Table II. Ratio of Expansion = $\frac{P}{25}$ . See Fig. 43, Plate 130.							
<b>A</b>	C $\frac{80}{3.2}$	C $\frac{90}{3.6}$	C $\frac{100}{4}$	C $\frac{110}{4.4}$	C $\frac{120}{4.8}$	C $\frac{130}{5.2}$	C $\frac{140}{5.6}$
<b>R</b>	400.0	397.6	405.3	402.7	404.1	401.9	405.1
<b>W</b>	0.02576	0.02478	0.02410	0.02435	0.02485	0.02397	0.02506
<b>FO</b>	0.0272	0.0268	0.0269	0.0275	0.0284	0.0279	0.0294
<b>FC</b>	0.0268	0.0267	0.0267	0.0279	0.0289	0.0288	0.0306
<b>HO</b>	1.271	1.819	2.459	2.748	3.122	3.468	3.781
<b>HC</b>	1.0	1.7	2.3	2.9	3.5	4.2	4.8



(continued on next page) TABLE 12.  
*Comparison of Mr. Willans' Observed results with Calculation.*  
*See Proceedings Inst. C. E. 1888, vol. xciii, pages 166-173.*

Mr. Willans' Table II. Ratio of Expansion = $\frac{P-10}{25}$ . See Fig. 44, Plate 130.								
A	C $\frac{90}{3.2}$	C $\frac{100}{3.6}$	C $\frac{110}{4}$	C $\frac{120}{4.4}$	C $\frac{130}{4.8}$	C $\frac{140}{5.2}$	C $\frac{150}{5.6}$	C $\frac{160}{6}$
R	401.1	401.5	402.9	402.7	405.5	398.7	404.0	401.2
W	0.02768	0.02686	0.02641	0.02673	0.02672	0.02642	0.02627	0.02616
FO	0.0292	0.0286	0.0292	0.0299	0.0303	0.0307	0.0310	0.0315
FC	0.0289	0.0290	0.0293	0.0304	0.0311	0.0316	0.0321	0.0327
HO	1.404	1.586	2.464	2.742	3.110	3.742	4.091	4.657
HC	1.1	1.9	2.5	3.2	3.8	4.5	5.1	5.6

Mr. Willans' Table III. See Fig. 51, Plate 131.					
A	Ratio of Expansion = $\frac{P}{25}$		Ratio of Expansion = $\frac{P-10}{25}$		
	T $\frac{150}{6}$	T $\frac{160}{6.4}$	T $\frac{150}{5.6}$	T $\frac{160}{6}$	T $\frac{170}{6.4}$
R	409.0	408.4	405.6	401.2	400.4
W	0.02578	0.02596	0.02734	0.02764	0.02805
FO	0.0268	0.0279	0.0289	0.0289	0.0295
FC	0.0261	0.0273	0.0273	0.0280	0.0290
HO	1.285	1.632	1.316	1.101	1.263
HC	0.3	0.7	0.0	0.3	0.8

Mr. Willans' Table IV. See Fig. 48, Plate 131.							
A	C $\frac{130}{4}$	C $\frac{130}{4.4}$	C $\frac{130}{4.8}$	C $\frac{130}{5.2}$	C $\frac{130}{5.6}$	C $\frac{130}{6}$	C $\frac{130}{8}$
R	406.8	405.0	405.5	401.9	402.6	400.0	404.4
W	0.03098	0.02876	0.02672	0.02397	0.02323	0.02155	0.01649
FO	0.0340	0.0320	0.0303	0.0279	0.0271	0.0264	0.0220
FC	0.0344	0.0327	0.0311	0.0288	0.0284	0.0270	0.0227
HO	2.679	2.86	3.110	3.468	3.395	4.291	4.848
HC	3.0	3.4	3.8	4.2	4.5	4.7	5.4

TABLE 12. (*continued from preceding page*)*Comparison of Mr. Willans' Observed results with Calculation.**See Proceedings Inst. C. E. 1888, vol. xciii, pages 174-177.*

- A** { Trial letter, S simple, C compound, T triple; intended absolute mean admission pressure, lbs. per square inch; and intended ratio of expansion.
- R** Revolutions per minute.
- W** Lb. weight of Steam per stroke, accounted for by indicator at cut-off.
- FO** Lb. weight of Feed-Water per stroke, Observed.
- FC** Lb. do. do. Calculated  $= \rho_1 \left\{ \frac{56}{\sqrt{N}} \frac{S_c - S_1}{L} + (1+c)(1-n) X \right\}$
- HO** Heat units per stroke, missing at cut-off, Observed.
- HC** Do. do. do. Calculated  $= \frac{56}{\sqrt{N}} (S_c - S_1) \rho_1$

Mr. Willans' Table V ( <i>continued below</i> ). See Figs. 39-40, Plate 129.						
<b>A</b>	S $\frac{50}{2.174}$			S $\frac{70}{2.8}$		
<b>R</b>	408.4	200.6	110.5	409.1	205.2	112.7
<b>W</b>	0.02342	0.02462	0.02488	0.02486	0.02574	0.02590
<b>FO</b>	0.0290	0.0323	0.0380	0.0338	0.0393	0.0478
<b>FC</b>	0.0247	0.0264	0.0273	0.0297	0.0313	0.0332
<b>HO</b>	5.166	7.139	11.97	8.168	12.262	19.864
<b>HC</b>	1.2	1.7	2.2	3.4	5.0	6.6

Mr. Willans' Table V ( <i>continued from above</i> ). See Figs. 39-40, Plate 129.						
<b>A</b>	S $\frac{90}{3.6}$			S $\frac{110}{4.4}$		
<b>R</b>	400.9	223.0	122.8	406.2	223.7	138.0
<b>W</b>	0.02656	0.02616	0.02657	0.02527	0.02659	0.0274
<b>FO</b>	0.0353	0.0348	0.0461	0.0359	0.0461	0.0494
<b>FC</b>	0.0327	0.0340	0.0372	0.0329	0.0371	0.0413
<b>HO</b>	7.863	7.564	17.523	9.436	14.338	19.475
<b>HC</b>	5.4	7.0	9.5	6.7	9.3	11.8

(concluded from page 672) TABLE 12.

*Comparison of Mr. Willans' Observed results with Calculation.**See Proceedings Inst. C. E. 1888, vol. xciii, pages 178-185.*

Mr. Willans' Table VI. See Figs. 45 to 47, Plate 130.									
A	C $\frac{90}{3.2}$			C $\frac{110}{4}$			C $\frac{130}{4.8}$		
R	401.1	210.8	122.0	402.9	212.0	123.8	405.5	216.4	130.9
W	0.02768	0.02920	0.02951	0.02641	0.02645	0.02753	0.02672	0.02692	0.02686
FO	0.0292	0.0334	0.0370	0.0292	0.0332	0.0368	0.0303	0.0333	0.0382
FC	0.0289	0.0309	0.0318	0.0293	0.0304	0.0328	0.0311	0.0329	0.0346
HO	1.404	3.786	6.682	2.464	6.000	8.230	3.110	5.611	9.94
HC	1.1	1.5	2.0	2.5	3.5	4.6	3.8	5.0	6.7

Mr. Willans' Table VII. See Fig. 42, Plate 130. * Throttled									
A	C $\frac{60}{4}$	C $\frac{70}{4}$	C $\frac{80}{4}$	C $\frac{90}{4}$	C $\frac{100}{4}$	C $\frac{110}{4}$	C $\frac{120}{4}$	C $\frac{130}{4}$	*C $\frac{60}{4}$ *
R	399.9	413.1	399.8	405.7	405.3	402.9	409.6	406.8	400.3
W	0.01508	0.01745	0.02103	0.02169	0.02410	0.02641	0.02852	0.03099	0.01447
FO	0.0183	0.0206	0.0224	0.0250	0.0269	0.0292	0.0325	0.0340	0.0171
FC	0.0167	0.0194	0.0232	0.0241	0.0267	0.0293	0.0317	0.0344	0.0161
HO	2.931	2.845	2.055	2.959	2.459	2.464	3.505	2.679	2.405
HC	1.5	1.7	1.9	2.1	2.3	2.5	2.8	3.0	1.5

Mr. Willans' Tables VIII and IX. See Figs. 49 and 50, Plate 131.							
Table VIII. Fig. 49.				Table IX. Fig. 50.			
A	C $\frac{160}{5.2}$	C $\frac{160}{5.6}$	C $\frac{160}{6}$	C $\frac{130}{5.6}$	C $\frac{140}{5.6}$	C $\frac{150}{5.6}$	C $\frac{160}{5.6}$
	421.7	411.3	401.2	402.6	405.1	404.1	411.3
W	0.02985	0.02773	0.02616	0.02323	0.02506	0.02627	0.02773
FO	0.0344	0.0325	0.0315	0.0271	0.0294	0.0310	0.0325
FC	0.0355	0.0339	0.0327	0.0284	0.0306	0.0321	0.0339
HO	3.894	4.095	4.656	3.396	3.781	4.091	4.095
HC	4.8	5.3	5.6	4.5	4.8	5.1	5.3

*Discussion.*

Mr. P. W. WILLANS thought any experiments of the sort described in the paper just read must throw great light on matters which all engineers wished to investigate. In making his own trials, which had been alluded to in the paper, he had started with very different opinions from the author's; and after reading the paper he did not feel inclined to alter his opinions.

In page 643 it was stated that, in order to measure as accurately as practicable the quantity of feed-water used, it was determined to weigh both the feed-water into the boiler, and also the condensed water after passing through the engine. After doing this the author came to the conclusion (page 644) that it was best to weigh the water as it came out; and he asked why that was considered the best plan.

Major ENGLISH replied the only reason was because there were a great many slight discrepancies in the weight of the feed-water.

Mr. WILLANS said it appeared to him that the figures calculated from the water collected as it came out from the engine showed more economical results than those calculated from the water supplied, because in most trials the water coming out seemed less than the water which went in; but he wished to understand the author's ground for considering that the former were more accurate. In some of his own intended trials he was going to measure the water when it came out. There were many cases in the paper where there was as much as 10 per cent. difference between the water going in and the water coming out; and of course such a difference must much affect the economical result.

The PRESIDENT asked what Mr. Willans thought would be the real difference between the water going in and that coming out.

Mr. WILLANS was unable to say, and he did not see why there should be any difference; he had made the enquiry only in order to know whether there was any real reason for taking the figures for

the weight of the water as it came out from the engine in preference to as it went into the boiler. In Table 9 the total collected water in line *j* did not agree with the water collected from the cylinders and from the jacket together in lines *k*, *l*, and *m*: which seemed rather puzzling.

Major ENGLISH explained that the total collected water included all the water passing through the engine from the commencement of firing with weighed coal, and was given separately in line *j* in Table 9. There was therefore no reason why it should agree with the water shown in lines *k*, *l*, and *m*, which was that coming out from the engine during the number of revolutions indicated by the counter.

Mr. WILLANS considered the feed-water, being really the water going in, was comparable with the water collected from the cylinders and jackets.

Major ENGLISH said it was comparable only with the total water collected, not with the water collected from the cylinders. The total collected water was the water collected during the whole time that evaporation was going on from the burning of weighed coal; but the water collected from the cylinders and jacket was the water collected only during the connection of the engine with the counter.

Mr. WILLANS thought it was important that the distinction should be made clear; but there appeared even then to be grave differences between the feed-water and the collected water. For in series IV of Table 9 (page 659) the feed-water was given as 600 lbs., while the total water collected was only 520 lbs., showing a difference of 13 per cent., which had the appearance of being rather a serious difference in trials of this kind.

In the conclusions at the end of the paper (page 655) three ways were mentioned for reducing the loss caused by excess of condensation over re-evaporation at the end of the stroke. But he himself did not admit that there was any loss from the excess of

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condensation over re-evaporation. As he understood the diagrams in Plates 119 to 127, the heat units had been deduced from the water missing at certain points of the stroke: that is, at the point A in Fig. 1, for instance, the steam pressure had been measured and the steam present calculated, and the heat units corresponding with the condensation of the steam not so accounted for had been plotted downwards in Fig. 2 from the zero or datum line, and similarly at the point B; and thence certain conclusions had been deduced. But it appeared to him that the author had omitted to take account of the water which had been formed, due to the work done during the period between the cut-off and the point of measurement; and in some of the diagrams this omission was all the more serious a matter because the figures actually showed an excess of re-evaporation (see Figs. 8, 16, and 34). This excess appeared to be in spite of work done; and therefore the omission appeared to him seriously to affect the results. The paper seemed to proceed on the assumption that it was desirable that re-evaporation should as far as possible balance condensation: not merely, he imagined, that the re-evaporation after the cut-off should balance the condensation before; but that the whole condensation and re-evaporation in the entire stroke should balance each other. The latter was a physical impossibility: they could not do so. The other might happen; or again the re-evaporation after the point of cut-off might balance or more than balance during the forward stroke the condensation after the point of cut-off, but this could only be in an engine working under excessively bad conditions; this at least was his own experience, in cases where a jacket was not in use. In his own trials with simple engines, as a matter of fact the re-evaporation after the point of cut-off exceeded the condensation; and it would do so wherever the initial condensation was very large; but in all those cases the efficiency was extremely low. The balance of condensation before cut-off and of re-evaporation after was therefore not a thing to aim at in any way; and accordingly engineers should not be satisfied with large initial condensation accompanied by large subsequent re-evaporation, but should aim at reducing both to the smallest possible amounts.

In order to arrive at this balance it was then argued by the author (page 655) that it was desirable to have a very long cylinder of a comparatively small diameter. His own trials however had been made on an engine which was proportioned the other way, with a large diameter of cylinder and a short stroke; and even when it was tried at the slowest speed, most unfavourable to that particular kind of engine which presented so large an extent of surface to the steam, the results were broadly speaking more favourable than the author's under similar conditions. In page 646 it was stated that the several series of trials had been grouped in Tables 9 and 10 in the order of their comparative efficiency. For the purpose however of comparing them more readily with his own figures, he had re-arranged the trials in the order of increasing steam-pressure, as shown in Table 13, on page 680. Starting from the left-hand end of the Table, the first three series of trials were made with 45 to 50 lbs. steam, the first two being unjacketed, and the third jacketed; then came four unjacketed series at about 60 lbs., and then four jacketed, also at about 60 lbs.; next followed three unjacketed at 68 to 77 lbs., and then two jacketed at about the same pressure; and last of all came two non-condensing series, one not jacketed and one jacketed, at about 85 and 86 lbs. pressure. It appeared to him that, by grouping these series in the order of efficiency in Tables 9 and 10, the fact was lost sight of that there were serious discrepancies between the groups of trials. For instance, the group which was ranked in Tables 9 and 10 as No. XVII, because it showed so high an efficiency, he himself had put first in Table 13 because it had the lowest steam-pressure, namely 44·8 lbs. only; and when this was compared with the next higher in pressure, which was No. I in Tables 9 and 10 with a steam-pressure of 48·9 lbs., the expansions were not very different, being 9·5 and 8·5 times respectively, but the water per horse-power per hour including the jacket was in the one case 25·5 lbs. and in the other 33·8 lbs. It seemed to him that, when these two groups of trials were thus brought into juxtaposition, this was a large discrepancy to get in the water, bearing in mind that the comparison was not between single indicator diagrams, but between groups of

TABLE 13.—*Re-arrangement of results from Table 10.*

- 1 Series of trials in Tables 9 and 10.
- 2 Cylinders : U = Unjacketed ; J = Jacketed.
- 3 Steam Pressure, absolute on admission, lbs. per square inch, from Table 10.
- 4 Number of Expansions, from Table 10.
- 5 Initial Condensation, being excess of water collected from cylinder per stroke above water accounted for by indicator at cut-off, in percentage of water collected from cylinder per stroke ; from Table 10.
- 6 Back Pressure, absolute, lbs. per square inch, from Table 10.
- 7 Water, lbs. per horse-power per hour, including jacket, from Table 10.
- 8 Range of Temperature in steam, degrees Fahr., from admission pressure in line 3 to back pressure in line 6.

																Non-condensing.		
1	XVII	I	VIII	IV	VII	III	X	XV	XII	XIII	VI	II	V	IX	XVII	XVI	XI	XIV
2	U	U	J	U	U	U	U	J	J	J	J	U	U	U	J	J	U	J
3	44.8	48.9	50.5	58.1	59.7	60.3	61.7	61.4	59.9	63.5	63.1	67.9	73.7	77.0	78.3	75.9	85.3	86.4
4	9.5	8.5	9.6	10.0	8.0	5.7	5.0	5.6	7.3	6.5	4.8	5.5	6.6	6.2	6.1	6.8	4.9	5.2
5	45%	53%	43%	50%	58%	54%	46%	41%	46%	46%	43%	44%	49%	48%	39%	38%	36%	33%
6	5.2	5.4	5.6	7.9	5.7	4.1	6.8	3.9	5.4	5.3	7.0	5.0	5.3	7.0	7.4	4.8	14.8	14.8
7	25.5	33.8	29.4	30.9	29.4	30.5	29.1	26.2	28.2	27.3	30.0	31.7	30.3	28.8	25.6	25.4	29.8	28.4
8	110	114	115	108	125	139	119	142	127	132	119	139	142	132	131	148	104	105



trials and groups of indicator diagrams of not less than sixteen in any one trial. Both series of trials, No. I and No. XVII, were unjacketed; and when alongside them was placed the next in order of increasing steam-pressure, namely the jacketed series No. VIII with 50·5 lbs. pressure, it appeared to him that the figures were so widely discrepant as to allow of arguing from them in almost any direction. One person who did not believe in jackets might support his view by arguing that, while in No. XVII with 44·8 lbs. pressure and no jacket the efficiency was 9·8 in Table 10, it was only 8·5 in No. VIII with 50·5 lbs. pressure and with the jacket in use; but another person who did believe in jackets might say that No. VIII was so much more economical than No. I, because in No. VIII with the jacket in use the efficiency was higher and the water consumption lower than in No. I without the jacket. Before therefore any definite conclusions could really be arrived at, he thought that trials or groups of trials were wanted which should be rather more concordant in the figures they gave.

In pages 647 and 648 the opinion was strongly expressed that the range of temperature in the cylinder had comparatively little to do with the condensation. In the discussion upon the author's former paper (*Proceedings*, 1887, page 529) he had pointed out an example in which the initial condensation in a condensing engine appeared to be less than in a non-condensing engine, in spite of the smaller range of temperature in the cylinder of the latter. In the trials recorded in the present paper there did not appear to be a sufficient difference in range of temperature for enabling any decided opinion to be formed upon the relation between range of temperature and initial condensation. Thus in Table 13, where there was only 5° difference in range of temperature between group XVII and groups I and VIII, the initial condensation varied no less than from 45 per cent. to 53 and then back to 43 per cent. Altogether in Table 13, excluding the last two non-condensing groups, the utmost difference in the range of temperature was seen to be only 40°, namely from 108° to 148°. There were also discrepancies in the water consumption in similar trials, the water per horse-power per hour in group I being about 33 per

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cent. greater than in group XVII. So that it appeared to him to be idle to argue either one way or the other, as to either the existence or the absence of any relation between range of temperature and initial condensation: the recorded figures were hardly close enough to bring out in clear relief such a relation if it did exist. Moreover it seemed to him that these ranges of temperature were all much too high for a single cylinder, and consequently that from such an engine it was idle to hope for economical results in any case; the expansion in the single cylinder was seen in Table 13 to range from 4.8 times to as high as 10.0 times, and it was not surprising therefore that the initial condensation rose as high as 58 per cent. These percentages he had calculated from the figures given in Table 10 of the water collected from the cylinder per stroke and of the water accounted for by the indicator at the point of cut-off; and assuming them to be correct, it was seen that in the highest instance as much as 58 per cent. of the steam which went into the cylinder was condensed before cut-off. In the two groups of non-condensing trials, Nos. XI and XIV, where the range of temperature was least, namely  $104^{\circ}$  and  $105^{\circ}$ , it would be seen that the initial condensation had gone down to 36 per cent. and 33 per cent. only: which was in accordance with the effect of reduced range of temperature in other engines. All through the trials with such an engine he should have been inclined to say that jackets ought to do a great deal of good; but in some way or other the jacketing seemed not to have been well arranged. In the non-jacketed trials it appeared from page 646 that the water which was in the jackets had not been debited, and the curious method had been adopted of putting the jackets out of action by shutting the jacket drain-cock; probably that was owing to some peculiarity in the construction of the engine.

Major ENGLISH said it was impossible to do otherwise.

Mr. WILLANS inferred that, during the first half-hour or so of the engine running, the cylinder must have been acting to a certain extent as though it were jacketed, until the jacket got full of water;

and therefore the jacket water ought properly to be debited to the account, though of course it was but a small matter, and as soon as the jacket was full of water it became not a steam jacket but a water jacket.

As to the effect of density of the steam, it was stated in page 648 that all the author's trials, and all others which he had had an opportunity of analyzing, tended most conclusively to show that the initial condensation varied directly as the density of the incoming steam. This was one of the points to which he had himself referred in his own paper in 1888 (Proceedings Inst. C.E., vol. xciii, page 155), and he had made the trials in Table VII (page 183) on purpose to see, if he could, whether that was so or not. The results were plotted from the line HO (Table VII, page 675) by the black dots in Fig. 52, Plate 132, in which it was seen that the density of the steam varied from 0.14 to 0.29. This was probably the most unsatisfactory of all the series of his own trials, because the plotted black dots were here wider apart than in almost any others of them. But when the straight line CC was drawn to represent the condensation at cut-off varying directly as the density, the results of his own trials were seen to be so far removed from this line that he thought the condensation could not be said to vary as the density. The line CC was here drawn starting from the dots on the left, because at the lowest density there were two trials, one checking the other. On the other hand he had then taken the converse cases where the density of the steam did not vary, and had plotted in Fig. 53, Plate 132, both the observed condensation at cut-off as given in his own Table IV (page 673) and shown by the black dots and the average line WW, and also the author's calculated condensation at cut-off as given in Table 10 and shown by the open circles and the average line EE. It was seen that the two appeared to go pretty well together, so far as their general direction went. These diagrams might be wrong, but at any rate one was a curious corroboration of the other; and they could hardly be held to justify the author's inference from them, namely that the initial condensation varied directly as the density of the incoming steam.

He quite agreed with the author's concluding remark that it would be a most useful thing if a formula could be arrived at from

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which it could be ascertained beforehand exactly how much steam was likely to be used in any engine. The probability was, he thought, that there would be very different constants for different kinds of engines; and although it seemed consequently almost impossible to construct any general formula, still any attempt to do so ought to be welcomed. If therefore he criticised any formula in the paper, he hoped he might be regarded as doing so only in the hope, however remote, that some practically useful expression might ultimately be arrived at.

Starting from the author's position that range of temperature had nothing to do with the initial condensation, it could but be expected that very little about range of temperature would be found in the formula. At the bottom of page 652 there was a formula for the weight of steam used per stroke in unjacketed cylinders, of which only the two factors,  $\frac{80}{\sqrt{N}}$  and  $\frac{S_c - S_1}{L}$ , represented the portion that applied to initial condensation. Here the constant 80 was of course only deduced from a series of trials, and  $N$  was the number of revolutions per second. This he believed was Professor Cotterill's expression, and he supposed it was quite right: although he thought his own experiments justified the opinion that besides mere surface there were other causes for condensation, which did not follow the same law. Then as to the other factor,  $S_c$  was the unjacketed clearance surface, agreeably with the assumption in page 647 that any surface which was jacketed had no effect in causing initial condensation; but although he thought the jacketing of the clearance surface diminished its condensing effect, he did not agree with the author that it eliminated it. From the unjacketed clearance surface  $S_c$  was then subtracted the fresh surface  $S_1$  exposed during admission. In regard to this difference  $S_c - S_1$  it would be noticed that if  $S_c$  equalled  $S_1$  there ought to be no initial condensation whatever; and there must be a large number of engines in which it was the case that the clearance surface  $S_c$  did equal the fresh surface  $S_1$  exposed during admission. It therefore seemed to him that the minus sign ought to be plus, changing the difference  $S_c - S_1$  into the sum  $S_c + S_1$ ; for he considered the fresh surface  $S_1$  exposed during

admission was as important a factor in the condensation as was the unjacketed clearance surface  $S_c$ : the one was just as true a cause of initial condensation as the other: understanding by initial condensation the condensation up to the point at which it could first be accurately measured, namely up to cut-off. To prevent initial condensation it was necessary that both the clearance surface and the fresh surface exposed during admission should be presented to the entering steam at a temperature as little below that of the entering steam as possible. It seemed to him a great pity that the steam condensed in the ports and in the body of the cylinder should be all included in the same formula. There was no difficulty in calculating the steam required to fill the body of the cylinder during the stroke; what was wanted to be ascertained was merely the portion of steam that got condensed at the start, that is, up to the point of cut-off. If the two were mixed, it seemed likely that only an approximate result would be arrived at.

As to the general results of the author's formula, the agreement of his calculations with the speaker's observed results was certainly very close in many of the figures shown in Plates 129 to 131; and it was all the more curious, because in his own engine there was a considerable clearance space, which the author did not appear to know anything about, and which therefore his formula did not cover. There was a considerable amount of steam supplied to fill a passage in the trunk, which had to be filled from the back pressure up to the pressure at cut-off. Hence the agreement between the author's formula and the speaker's results appeared to be much closer than it actually was. The filling up of the clearance space was of course a much more important matter when the pressure was high than when it was low, that is, when the density was higher and more steam was required to fill it; and the omission of this steam, which was not covered by the author's formula, appeared to lend colour to the view that the condensation increased with the density.

Another point he should like to raise was in connection with the remark in page 647 that the jacketed surface had nothing at all to do either with the initial condensation or with the subsequent re-evaporation during the stroke. What then was the good of having

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two formulæ, or rather one formula with two coefficients, one for unjacketed cylinders and the other for jacketed? In the first case a formula was arrived at by eliminating the jacketed surface and treating only of the remaining surface which was unjacketed; and then after doing so this same formula with a change of coefficient was adopted for the jacketed cylinder. In Fig. 2, Plate 119, he observed that the dots denoting the observed results agreed very well with the line JJ calculated for the jacketed cylinder, and yet this particular trial happened to be with the cylinder unjacketed; and the same remark applied also to Fig. 14, Plate 122, and Fig. 22, Plate 124: so that it seemed to him that the formula was only approximate, and that the one coefficient fitted quite as well as the other, irrespective of whether the cylinder was jacketed or not.

In the trials made with air admitted into the cylinder during the exhaust (page 644), for the purpose of seeing whether the initial condensation could thereby be reduced, it was mentioned that this result was obtained, but that the back-pressure was increased. It seemed as though the author had not realised that this experiment amounted in effect to opening an air-cock into the condenser, and to that extent spoiling the vacuum and diminishing the range of temperature. The reference in page 647 to experimental evidence showing that the rate of transmission of heat through a metallic plate depended on the difference of temperature of the media on either side seemed to him not to bear at all on the subject of the paper. Surface condensation and re-evaporation in a cylinder depended on the film of metal exposed to the steam; and this film probably alternated between the higher and lower temperature of the entering and the exhaust steam. It seemed to him impossible to imagine cylinder condensation apart from range of temperature.

Professor JAMES H. COTTERILL said the author's formulæ were mainly based on three suppositions: first, that initial condensation would be proportional to the density of the incoming steam (page 648); second, that it did not depend on the range of temperature (page 648); and third, that it was proportional to the area of the surface, and inversely as the square root of the speed (page 647).

With regard to density, it appeared to him that there were conceivable circumstances in which the rate of condensation might vary as the density. If the whole mass of the cylinder were imagined to be at a uniform low temperature, and the steam to be suddenly admitted to it, then the metal would absorb heat with extreme rapidity, and the condensation would probably depend on two things: on the obstruction which was offered to the passage of heat by the film of water condensed upon the surface; and again on the number of particles of steam which could come into contact with the surface in a given time. His own idea was that it would depend mainly on the obstruction which the film of water offered. But if access of the steam to the surface was obstructed sufficiently by contracted passages and a slowly opening slide-valve, condensation might be conceived to vary as the number of particles of steam which were capable of coming into contact with the cylinder surface in a given time: which meant that it would be in proportion to the quantity of steam within a given distance of the surface, and hence to the density of the steam, as the author supposed. But it seemed to him that this was not at all the condition of things in the actual cylinder, which was being alternately heated and cooled. Every particle of the metal was going through a cycle of changes of temperature; and under these circumstances it seemed to him that the condensation must vary as the range of temperature of the metal. Moreover the changes of temperature penetrated the metal to a very short distance, and the absorption of heat was limited by the necessity of giving out the same amount when the temperature fell. Obstructed access to the surface, though not without influence, did not seem to him so important as to cause the condensation to vary as the density of the incoming steam. It might depend on the density of the exhaust steam; but that was a different question. It seemed then that the initial condensation must depend on the range of temperature of the metal; but it did not follow that the range of temperature of the metal was the same as the range of temperature of the steam. Although the temperature of the metal might be approximately the same as that of the steam during admission and during expansion, yet in many cases, and whenever

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there was a wide range of temperature due to a wide difference between the terminal pressure and the exhaust pressure, the temperature of the surface of the metal would not descend to the exhaust temperature. During exhaust the surface of the metal would be dry; and under these circumstances the escape of heat from the dry surface would probably depend on the density of the exhaust steam. No doubt the escape of heat from the dry surface would be comparatively feeble, so that its direct influence would be very small. But indirectly it might have a great influence in another way, by widening the range of temperature of the metal, and so increasing the initial condensation. It was possible to show that the escape of heat from the dry surface during exhaust would have this effect upon the range of temperature of the metal; and where the steam was admitted throughout the entire stroke, it was possible to find a formula for the initial condensation, which in that case would depend partly on the range of temperature and partly on the density of the exhaust steam. Let  $W$  = weight in lbs. of steam condensed per revolution per square foot of surface;  $t_1 - t_o$  = range of temperature of the steam;  $L_1$  = latent heat of evaporation at the admission temperature;  $N$  = revolutions per minute. Then

$$W = \frac{t_1 - t_o}{L_1 \sqrt{\frac{N}{B} + \frac{t_1 - t_o}{K} N}}, \text{ which determined } W \text{ in terms of two}$$

constants  $B$  and  $K$ ; of these  $B$  depended on the conductivity of the metal and the nature of the temperature-cycle, and  $K$  depended on the escape of heat from a dry surface per minute per degree of difference of temperature. With regard to speed, the initial condensation would vary in part inversely as the square root of the revolutions, and in part inversely as the revolutions themselves. There was one conceivable case in which the condensation might be supposed to be independent of the range of temperature of the steam, and that was at a high speed when the expansion was not great, that is, when the steam was admitted through nearly the full stroke. Then the formula showed that the initial condensation might be independent of the range of temperature of the steam; but this was the only instance, as it seemed to him, in which such



could be the case. In other cases the initial condensation would depend upon the range of temperature of the steam; but it would not necessarily be directly proportionate to the range of temperature. The formula was of limited application, and the values of the constants uncertain, especially  $K$ ; but he thought it worth giving, as showing that the theory of the conduction of heat did not necessarily require the supposition that condensation should be proportional to the range of temperature of the steam and inversely to the square root of the speed.

Professor ALEXANDER B. W. KENNEDY, Member of Council, said the paper contained the result of an immense amount of work very much elaborated. A question had already been asked (pages 676-7) about the water measurement, and the want of agreement between the two totals in lines  $i$  and  $j$  in Table 9, where in several cases there seemed to be a wider disagreement than he could understand. His own experience would lead him distinctly to prefer the measurement of the feed-water as it went in; but of course it would be expected that the two measurements would agree fairly well. There were five cases in Table 9 in which they practically did agree within 1 per cent., but there were a number of cases in which they did not; and out of the whole forty-one there were five in which the water measured out exceeded the feed measured in, while in the remaining thirty-six cases the feed measured in was more than the water measured out. It would be interesting to those who were working at engine trials if the author would explain why he preferred the one measurement to the other, and what the actual cause of these serious differences was, because they were so large that it was impossible to pass them over.

As to range of temperature, he presumed that by this expression as used in page 647 of the paper was meant the difference of temperature on the two sides of the cylinder wall; whereas of course the expression was generally understood to mean the range between the highest and lowest temperature of the steam. He could not agree in any way with the author's treatment of the question of temperature; and it certainly did not appear how the difference of temperature

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between the two sides of the cylinder wall could have so much more to do with the matter of initial condensation than the working range of temperature had. The assumption also of the absolute mean temperature  $T_m$  of the cylinder really seemed almost in the nature of a guess in page 649, where it was taken as approximately equal to the temperature due to the mean forward pressure. Why it should be so, he thought there hardly seemed much reason; because for at least half the time the temperature of the cylinder walls must surely depend more or less—Professor Cotterill had shown (page 688) why it should only depend partially—upon the temperature of the back pressure. No doubt the author would explain his reason for so assuming the absolute mean temperature of the cylinder, as it was not clear on the face of it why he had done so.

In examining Table 10 he was much struck with the fact that under the heading of condensation per stroke the calculated results and the observed results either did not agree or agreed in a very odd fashion; they agreed so little that some explanation seemed to be needed from the author as to why exactly he thought his formulæ thoroughly represented these experiments. For instance, taking No. I, which was a non-jacketed trial, the three observed results (9.3 and 6.3 and 3.4) agreed pretty fairly with those calculated for a jacketed trial (9.1 and 6.3 and 4.9); whereas in No. II, which was also a non-jacketed trial under different conditions, the three observed results (16.0 and 12.7 and 9.2) agreed rather with the calculated results for a non-jacketed trial (18.3 and 12.7 and 9.5). Both being non-jacketed trials, the agreement of the observed results ought in both cases, as far as he understood matters, to be with those calculated for the cylinder as non-jacketed. There were several other instances of that kind; and there were some instances, such as No. VI and No. VIII and others, in which the calculated results did not really agree at all well with any of the observed results. That might possibly be really due to the treatment of temperatures, which as already mentioned he had not been able to make out.

The separation of the cylinder surface into two such very distinct portions appeared to him to want something more of proof;

at any rate it seemed to be empirical in itself, rather than based on any scientific reason. For it did not appear as if the whole cylinder surface, either up to the cut-off or up to the end of the stroke, could quite fairly be divided into two distinct parts, one of which was the clearance surface and the other all the rest. Unless the cylinder surface happened to become so divided in an empirical formula, there did not seem in the absence of proof to be any scientific reason why it should be divided in that particular manner.

It would add he was sure to the ease of reading the paper and Tables if the author would append to them a concise tabular summary, giving just the leading characteristics of each trial. These could of course be found out by going carefully through the present Tables, in which all the information was given in the fullest manner; but he had himself had to go over them in order to mark the various points he had alluded to, and in doing so it had occurred to him that a small synopsis would help a good deal, because no doubt these experiments would be frequently looked at afterwards. (See Table 11 subsequently added, pages 670-1.) It was rather unfortunate that the engine which the author had experimented with had been one that condensed half its steam before it commenced to do any work. It was no doubt interesting to know what it actually did perform; but he hoped there were other engines, that would not behave so badly in this particular, out of which some information could be got on a future occasion.

Mr. J. MACFARLANE GRAY, instead of accepting the view expressed in pages 647 and 648 of the paper, that range of temperature did not materially affect the amount of initial condensation, had been led to think that this influence might be even greater than in the simple ratio of that range. If the depth of penetration of change of temperature into the cylinder metal varied as the range of temperature, the heat missing per unit of surface up to the point of cut-off would vary as the square of the range of temperature. Although he did not think this was really the case, he had nevertheless thought it worth while, in the present position of the question, to apply this assumption to Mr. Willans' Table I as given in page 672 of the

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present paper. Taking the full range of temperature in each case, the heat units per stroke, missing at cut-off, as calculated by himself on this assumption, were given in the third line HG below, in comparison with the two lines HO and HC, copied from page 672, which represented respectively the heat units missing as actually observed and as calculated by the author:—

HO	3·269	5·166	8·168	7·048	7·863	10·261	9·436
HC	0·8	1·2	3·4	4·2	5·4	6·0	6·7
HG	3·147	4·326	11·948	7·637	9·279	9·980	11·090

He had not been able to get any corroboration of this assumption from the other tabulated results; but he thought that Table I gave the only set of Mr. Willans' experiments here quoted in which range of temperature was not inextricably mixed up with other varying influences. The effect of compression-heating and of piston-leakage might however have contributed to produce the more approximate run of numbers in the line HG here given. The author had started a most important investigation in an eminently practical manner; and if his conclusions were not yet quite satisfactory, this was only because of the problem being extremely complicated and beset with almost insuperable difficulties. The present paper he considered a valuable one for the Institution, and the author deserved the best thanks of the Members.

Mr. G. R. BODMER drew attention to the opinion expressed in page 647 of the paper, that the effect of the cold portion of the clearance surface in producing condensation must be most marked at the first instant, when the difference of temperature was greatest; and must diminish as the surface was brought up to the same temperature as the steam in contact with it. This seemed to be a clear admission that initial condensation depended upon the difference in temperature between the steam and the metal; but then later on in page 647 the author seemed to contradict it again, by saying that the assumption that the condensation must vary directly as the range of temperature in the cylinder appeared to be based upon a fallacy; and still further on (in page 648) it was added that to say the condensation would depend upon the range of temperature was equivalent to saying that

there would be no condensation at all after the temperature of the inner surface of the cylinder was raised to that of the incoming steam. It was thus apparently admitted that the range of temperature had some influence; and the author proceeded to introduce the ratio of the initial temperature of the steam to the mean temperature of the cylinder metal, though apparently only to eliminate it again by assuming the two to be equal. It would be interesting to know on what ground it could be assumed that, during the period of the steam coming in contact with the clearance surface, the temperature of the incoming steam was equal to the mean temperature of the cylinder metal throughout that period. It seemed to himself almost obvious that the temperature of the metal, during the first instant in which the steam at its initial pressure came in contact with the clearance surface, must be much lower than the temperature of the steam coming in contact with it. The maximum temperature which the clearance surface could attain at the first moment when the steam was admitted could not very well be higher he thought than the temperature due to the pressure of the cushion steam. Probably if the difference between the temperature of the admission steam and the effective mean temperature of the clearance surface, during the period of condensation, was introduced into the calculation, the lower temperature should be something in excess of the temperature of the cushion steam, since after the first instant the metal surface would be rapidly heated up to nearly the temperature of the admission steam. Yet again in page 648 it was said that in a steam cylinder there would be a nearly constant rate of condensation due to conduction through the metal. Even in that case difference of temperature would come in, only it would be the difference between the temperature of the metal of the cylinder and that of the outside atmosphere or jacket; because the rate of conduction must depend, to some extent at any rate, on the difference between the temperature of the metal and that of the outside medium, such as the air.

The hypothesis that range of temperature had a good deal to do with initial condensation was borne out by the principles which were now generally applied to the construction of two-cylinder compound and triple-expansion engines. Such engines were

(Mr. G. R. Bodmer.)

proportioned chiefly on the supposition that the range of temperature in each of the cylinders ought to be reduced as much as possible, and to be about equal in each cylinder, with the view of reducing condensation as much as possible; and the results seemed to bear out the accuracy of this hypothesis.

The expressions on pages 652 and 653 for representing the weight of steam condensed during the admission period—namely  $\frac{80}{\sqrt{N}} \frac{S_c - S_1}{L}$  and  $\frac{56}{\sqrt{N}} \frac{S_c - S_1}{L}$ —involving as they did the factor  $S_1$  which denoted the fresh surface uncovered during admission, seemed to him to imply the rather strange assumption that re-evaporation might occur even during the admission period. But he did not see how it was possible to find out practically whether condensation or re-evaporation was really going on during that period; because until the cut-off had taken place it could not be known what weight of steam there was in the cylinder. Assuming that the valve was tight, the weight of steam in the cylinder at the point of cut-off in each stroke could be ascertained from the measurement of the feed-water or of the steam condensed; but at any period antecedent to the cut-off there appeared to him to be no means whatever of knowing how much steam there was in the cylinder, and therefore no conclusions could be drawn as to whether any re-evaporation was going on. It seemed to him indeed impossible that there could be any re-evaporation then, unless there was a very rapid fall in pressure, due to wire-drawing.

For reducing the loss caused by excess of condensation over re-evaporation, one of the three methods proposed in page 655 consisted in increasing the length of the stroke. But even if in that way it were possible, which he believed it was not, to re-evaporate the whole of the steam initially condensed, the advantage so obtained would be comparatively trifling, because the heat would then be re-communicated to the steam under unfavourable conditions, and not in the most effective way. There was one possible method, he thought, of improving the economy of an engine, which seemed not to have been noted by the author, and to which he had observed that not much attention was usually paid: namely by increasing

the amount of compression, that is, increasing the pressure of the cushion steam; by so doing the initial difference of temperature would be reduced, by bringing the temperature of the clearance surface more nearly up to the temperature of the fresh steam entering the cylinder.

Mr. CHARLES E. COWPER called attention to the high consumption of water per horse-power per hour, which in Table 10 ranged from 25.4 lbs. to 33.8 lbs. It might not be obvious perhaps, to those not accustomed to independent engine trials, what this meant; users of engines thought more about the coal. Dividing these quantities of water by  $8\frac{1}{2}$  lbs. of water evaporated per lb. of coal, the coal consumption would be found to vary from 3 lbs. to 4 lbs. per horse-power per hour. In comparison with the economy obtained in good steam-engines of the present day, this consumption involved considerable waste of fuel. It would have afforded useful information he thought if the author, who had closely observed many details in connection with the working of the engine, had pointed out what he considered to be the chief reasons of this waste.

Mr. G. S. YOUNG asked whether the pressure in the jacket was constant, or increased as the pressure increased in the boiler; or whether the steam supplied to the jacket was somewhat reduced in pressure below the boiler pressure. Also were there any means provided to prevent water from passing into the cylinder with the steam, such as a separator fitted in the steam-pipe, close to the cylinder? Assuming that the pressure of steam in the jacket was equal to the pressure in the cylinder, there was such a great deal of condensation attributed to the cylinder that it seemed to him almost impossible for the major part of it to be taking place in the cylinder at all; and he thought the water was going in as water, and was not actually condensed in the cylinder, but part of it was condensed before it came to the cylinder and part had passed from the boiler in the shape of priming water. If saturated steam only was entering the cylinder, it seemed extraordinary that, out of a loss of about 50 per cent. to be accounted for, only about 5 per

(Mr. G. S. Young.)

cent. of condensation was prevented by the use of the steam-jacket ; and he thought that from 40 to 50 per cent. of what was put down to condensation in the cylinder should be looked for in some other direction. The use of the steam blast at intervals when required, as mentioned in page 643, he also thought would, by increasing the rate of evaporation in the boiler, increase the amount of priming, and thus probably account for part of the irregularity in the observed results.

Mr. ARTHUR PAGET, Vice-President, drew the attention of the Members to the fact that at all events the present paper and discussion would prove, if it were needful to do so, the wisdom of the Institution in having appointed a Research Committee to study the subject of steam-jacketing. Seeing that engineers who were known authorities on the subject differed so widely in their opinions and conclusions, he thought it was evident that there was a serious necessity for such an investigation, to give the certain knowledge upon this subject which did not seem now to be possessed.

Major ENGLISH in reply considered that the discrepancies between the total feed-water and the total collected water in lines *i* and *j* in Table 9, referred to by Mr. Willans (page 677) and Professor Kennedy (page 689), were due to the fact that a boiler of this class would vary considerably in internal capacity according to the varying action of the furnace. The results of five separate trials made with this boiler to determine the amount of variation under different conditions of firing were shown in Figs. 54 to 58, Plate 133. In these trials the engine was standing, and no water was introduced into the boiler, which was practically tight, and measurements of the water-level were taken at two gauge-glasses every five minutes. An apparent increase or decrease in the weight of water in the boiler, amounting in some cases to 50 lbs., could be readily obtained with a constant steam pressure by variations in the state of the fire and the damper ; and discrepancies due to this cause became larger when, as in his trials, the measurements of the feed-water were begun and ended with the engine in motion.



Mr. Willans had spoken (page 678) of the omission of the heat due to work; but by the method of calculation adopted in the paper this heat was duly accounted for in Table 10. For example, in series III, at the end of the stroke the distribution of heat, calculated as in page 490 of Proceedings 1887, was as follows per lb. of cylinder steam :—

	Thermal units.
Total external work . . . . .	99
Internal heat remaining in steam and condensed water . . . . .	673
Condensation, or heat abstracted by cylinder . . . . .	277
Available heat supplied . . . . .	<u>1049</u>

Multiplying the condensation 277 by 0·035 lb., the weight of steam per stroke, the result was the net observed condensation at the end of the stroke, namely 9·7 thermal units, as given in the bottom line in Table 10.

The question of advantage in increasing the length of the cylinder, referred to by Mr. Willans (page 679), applied to simple engines only, and not to a compound engine, in which, for the reasons given in page 656, the difference between long and short cylinders had much less effect. Mr. Willans's own engine, when worked as a simple engine with a very short stroke and a large range of temperature, certainly showed considerably more condensation than the average of engines of ordinary proportions.

Referring to Mr. Willans's comparison in page 679 of the group of trials No. I, using 33·8 lbs. of water per horse-power per hour, with No. XVII using 25·5 lbs. under similar conditions, it had been pointed out in the paper (page 645) that the results showed that the steam used in group XVII was being sensibly superheated, as it was also in groups IV and VIII, since in each of these cases there was more heat remaining in the steam at the end of the stroke than would, when added to the external work done, correspond with the total heat of the weight of saturated steam at the initial pressure. If this view were accepted, it was clear that the effect of such superheating, though not admitting of definite measurement, must be to increase the efficiency of the steam used.

(Major English.)

As regarded the question of the density of the steam having an effect on the condensation (page 683), he quite agreed that between the observed results plotted in Fig. 52, Plate 132, and the line CC there drawn for the heat units missing at cut-off, there was a wide discrepancy. There might be any number of straight lines representing calculated results, starting from the zero point of the vertical and horizontal scales, and varying as the density; but out of these the dotted line BB was the only one in accordance with his own calculations, which were here plotted by the open circles from the bottom line HC in Table VII, page 675.

Another point which had been raised (page 684) was that, in the case where the additional surface exposed during the stroke was equal to the clearance surface, there ought to be no initial condensation at all. Probably what was meant was no condensation at the point of cut-off; and this had all but occurred in Mr. Willans's triple engine when the additional surface exposed during the stroke approached the clearance surface.

The clearance space in the trunk of Mr. Willans's engine (page 685) he thought would not affect the calculated figures in Table 12 and Plates 129 to 131, since the weight of steam accounted for by indicator at cut-off was deduced directly from Mr. Willans's own tables, in which the steam required to fill this clearance space would necessarily be included.

The fact had apparently been overlooked by Mr. Willans (page 686) that the difference between the complete formulæ in page 651, for net condensation in jacketed and unjacketed cylinders, was more than a change in the constant; and that, so far as these formulæ represented the facts, the varying temperatures of the inner surface of the cylinder would have more effect in increasing the initial condensation and diminishing the re-evaporation in an unjacketed than in a jacketed cylinder.

The air-cock placed on the cylinder (page 686), in order to see whether the admission of air would affect the initial condensation, had been fixed so that any air passing through it must necessarily pass over the internal surface of the cylinder before going on to the condenser.

In reply to Professor Cotterill (page 687), he would venture to recall attention to the conclusion set forth in page 646 of the paper, that the initial condensation was extremely sudden—so sudden in his opinion as to be practically instantaneous in comparison with any present means of measuring its rate. Unless this conclusion was agreed to, he was quite prepared to admit that there would be no solid foundation for the formulæ which he had suggested; but if all or any large proportion of the action of condensation took place in an interval of time too short to allow the quantity of heat necessarily liberated from the steam to be transferred to the interior substance of the metal according to the known laws of conduction, it seemed to him that, whatever the action of condensation might be, it would be independent of any cyclical changes in the temperature of the body of the metal. Initial condensation apparently took place at the highest speeds of revolution yet experimented on: not certainly to the same extent as at slow speeds, but still at a sufficiently appreciable rate; and until some process could be devised for obtaining quantitative results of the time occupied in condensing a given weight of steam brought suddenly into contact with a comparatively cold metallic surface, it seemed to him hardly practicable to do more than connect the amount of condensation with the mean temperature of the metal and the known temperature of the steam; and this was what he had attempted to do in the formulæ.

Replying to Professor Kennedy (page 690), the reason why the mean temperature of the cylinder had been taken at page 649 as approximating to that due to the mean forward pressure only of the steam was stated in page 650, to the effect that the surface of the cylinder during the exhaust was probably dry; and he was glad to find that Professor Cotterill concurred in this view. It seemed to him to follow therefrom that practically no cooling effect on the metal of the cylinder would be produced by re-evaporation during the exhaust stroke; and that the re-evaporation induced by the opening of the exhaust port took place as suddenly as the initial condensation.

Referring to Professor Kennedy's criticism (page 689) regarding the use of the expression "range of temperature," what he had

(Major English.)

attempted to show in page 647 of the paper was that the only experimental evidence in favour of condensation being directly proportional to range of temperature was derived from Forbes' results, which led to the commonly used formula—Flow of heat = constant  $\times \frac{t_A - t_B}{y}$ , where  $t_A$  and  $t_B$  were the temperatures of the media on either side of a metallic plate of thickness  $y$ . Although no doubt by the expression "range of temperature" was generally understood the range between the highest and lowest temperatures of the steam during a stroke, he thought it was usually taken for granted that in some way or other the formula just quoted would apply to a steam cylinder; and it was to this view that he himself took exception. It was certain at any rate that if the various trials made by the U.S. Navy in 1874-5, and by Mr. Willans, and by himself, were taken as a whole, the observed condensation, either near the point of cut-off or at the end of the stroke, showed no indication of being in any way proportional to the range between the highest and lowest temperatures of the steam. Much less would they agree with Mr. Macfarlane Gray's view (page 691) that the condensation should vary as the square of the range of temperature.

To Professor Kennedy's question (page 690) as to why in some cases the observed results in a non-jacketed trial agreed with the formula for a jacketed cylinder, he would reply that he did not consider any of the trials to be absolutely non-jacketed. The jacket steam was taken direct from the boiler to the cylinder casting, which formed the bottom of the smoke-box, and there was no possibility of shutting off the communication; the only way of stopping the passage of steam through the jacket was by shutting the drain-cock, but steam from the boiler could still enter the jacket freely; and the high temperature of the smoke-box had in some cases an unmistakable effect. For these reasons he had drawn two curves, representing condensation according to the formulæ for both jacketed and unjacketed cylinders, in all the diagrams relating to groups in which the jacket drain-cock was shut, except in groups IV, VIII, and XVII, where the steam was manifestly superheated; and he was obliged to leave the comparison of the observed results to be made

with one curve or the other according to opinion. It was certainly unfortunate that more definite results could not be obtained on this point; but it was impossible for that to be done without undesirable structural alterations to the engine and boiler.

As to the division of the surfaces into clearance surface and stroke surface (page 691) being empirical, the empiricism appeared to him to depend on whether it was considered that the condensation was extremely sudden and took place during the time when the clearance surface only was exposed, or whether it was considered that it lasted during the stroke. If it took place only, or in far greater part, at the commencement of the stroke, a natural division of the two portions of the surface would thereby be defined.

In Table 11 he had much pleasure in submitting the short synopsis asked for (page 691), so as to do the best he could for making the paper fully intelligible.

Replying to Mr. Bodmer (page 693), it was intended to be implied in page 648 that the temperature of the incoming steam was equal to the mean temperature of the cylinder metal throughout the stroke, only in the case when the cylinder was kept continuously at the temperature of the steam, by preventing the flow of heat through it outwards, and by creating a flow inwards either by thoroughly efficient jacketing or by superheating. It was only in this case that he thought the effect of range of temperature on the initial condensation would become negligible. The hypothesis, and of course it could be no more than a supposition, that re-evaporation occurred during the admission portion of the stroke (page 694), was absolutely necessary to the train of reasoning in the paper. It certainly could not be directly verified; but according to all observations made by himself, excess of re-evaporation over condensation was going on at a rate at least as rapid immediately after the cut-off as later in the stroke; and it seemed to him that the conclusion thence to be drawn was that this excess was also going on before the cut-off.

Replying to Mr. Young (page 695), the only check possible upon priming water in this engine lay in the rate of evaporation per pound of coal, which had been very satisfactorily consistent in all cases.

(Major English.)

As to the pressure in the jacket (page 695), he had already explained that the jacket was in direct communication with the boiler, and carried the boiler pressure in all cases: it was impossible to prevent its doing so.

The PRESIDENT said a doubt had been expressed as to what was the meaning of the range of temperature alluded to in page 647: whether the author simply meant variation in the temperature of the cylinder metal, or whether he alluded to the range of temperature in the steam itself within the cylinder.

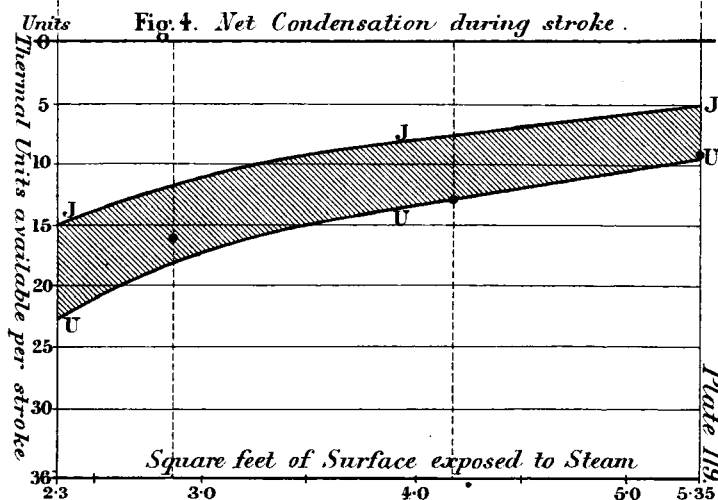
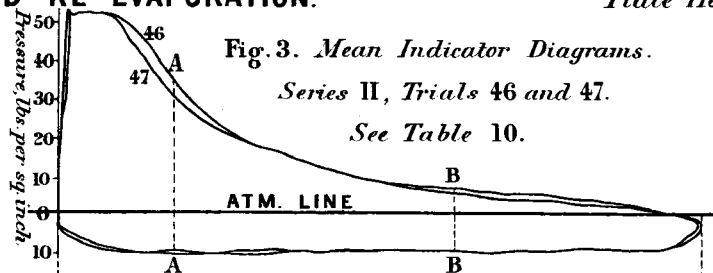
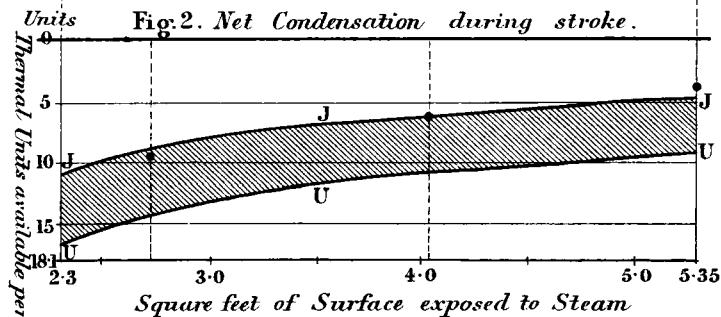
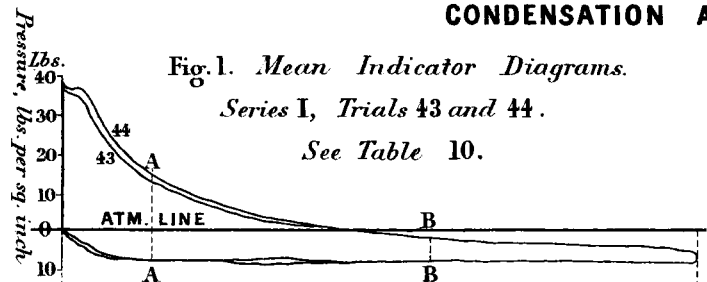
Major ENGLISH said that in speaking of range of temperature he was alluding to the temperature of the inner surface of the cylinder metal. As to the character of an engine which required 3 lbs. or 4 lbs. of coal per indicated horse-power per hour (page 695), he did not feel it at all necessary to defend the engine itself, the makers themselves being well able to do so; but he would take the opportunity of recording his opinion that it was capable of working more economically than the average of engines of its class.

The PRESIDENT said he had been anticipated by Mr. Paget's happy allusion to the appointment of the Research Committee on the value of the steam-jacket. An investigation of this subject was evidently most desirable; for there were many points on which in the present discussion such varied opinions had been expressed, that it was time an attempt should be made to see whether they could be reduced to law and order. The Members were much indebted to Major English for bringing before them his experiments, which represented a vast amount of labour. The interesting discussion which had followed the reading of the paper was evidence that it had been thoroughly appreciated; and he was sure that the meeting would pass a hearty vote of thanks to the author for having prepared the paper and brought it before the Institution.

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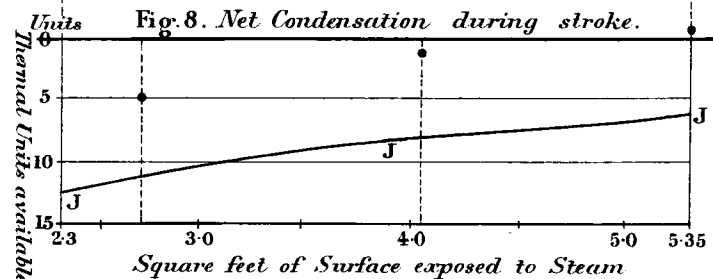
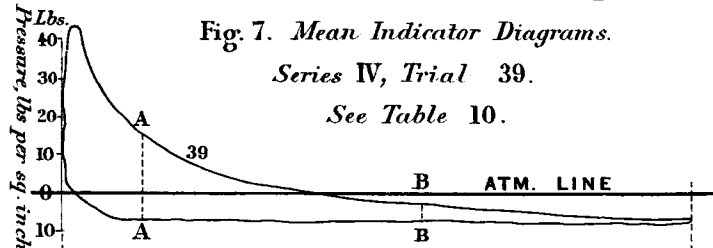
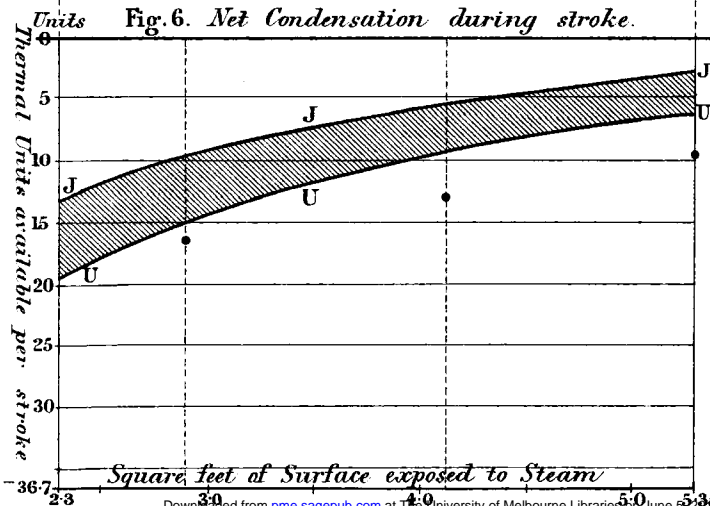
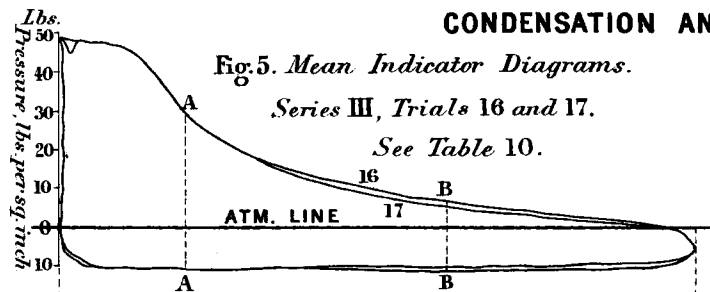
# CONDENSATION AND RE-EVAPORATION.

Plate 119.



# CONDENSATION AND RE-EVAPORATION.

Plate 120.



(Mechanical Engineers 1889)

Plate 120.



# CONDENSATION AND RE-EVAPORATION.

Plate 121.

Fig. 9. Mean Indicator Diagrams.  
Series V, Trials 14, 15, 26, 28, and 42.  
See Table 10.

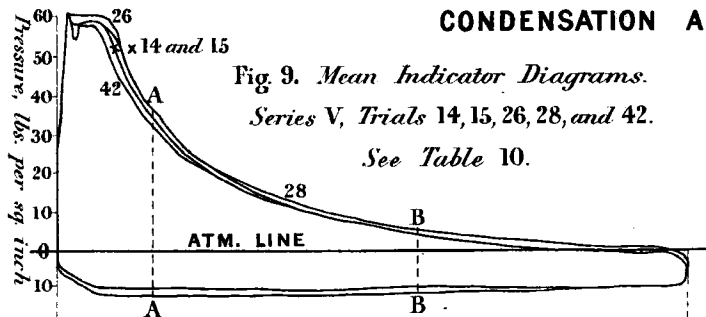
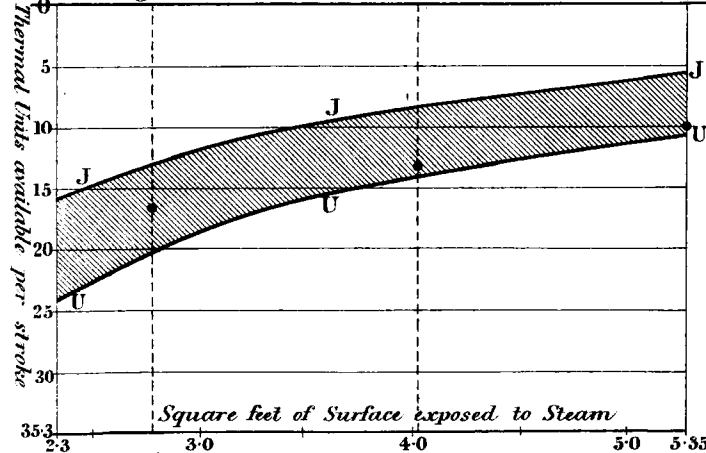


Fig. 10. Net Condensation during stroke.



(Mechanical Engineers 1889)

Fig. 11. Mean Indicator Diagrams.  
Series VI, Trial 38.  
See Table 10.

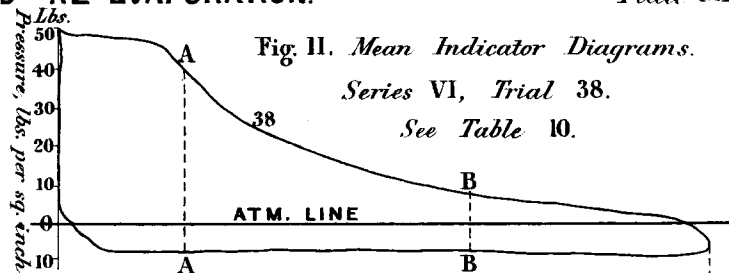


Fig. 12. Net Condensation during stroke.

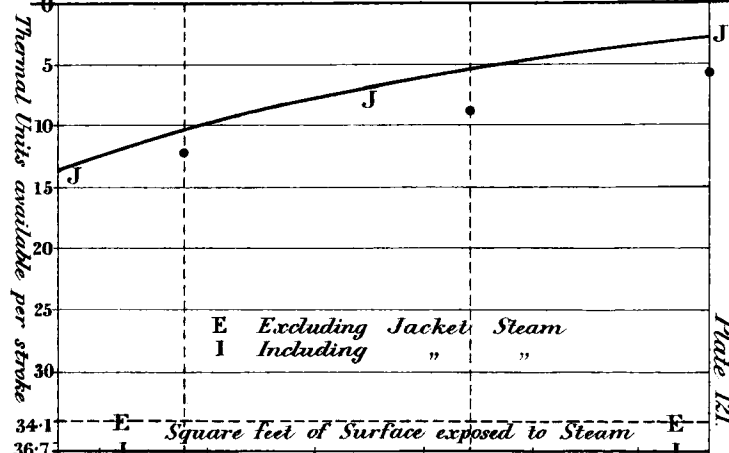


Plate 121.

# CONDENSATION AND RE-EVAPORATION.

Plate 122.

Fig. 13. *Mean Indicator Diagrams.*  
Series VII, Trials 52, 53, and 54.  
See Table 10.

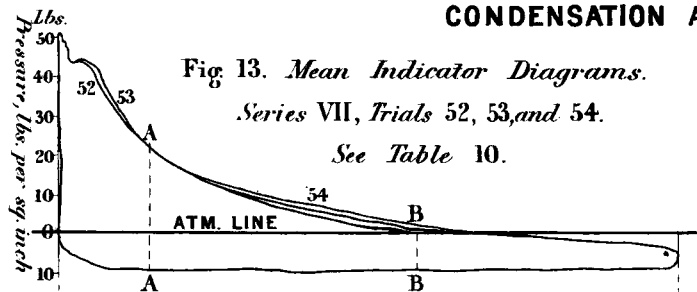


Fig. 14. *Net Condensation during stroke.*

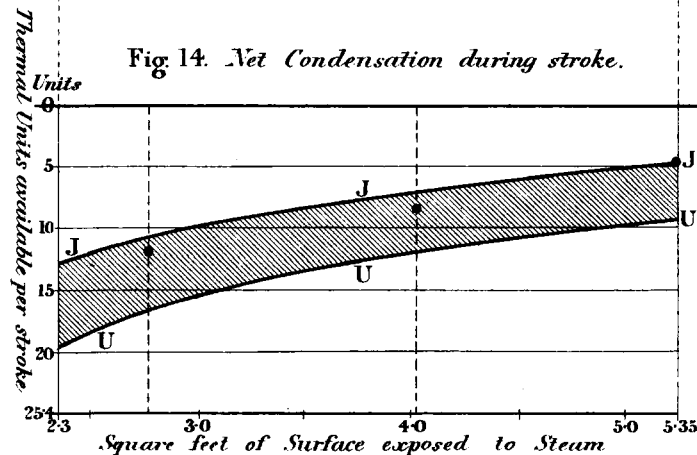


Fig. 15. *Mean Indicator Diagrams.*  
Series VIII, Trials 45 and 55.  
See Table 10.

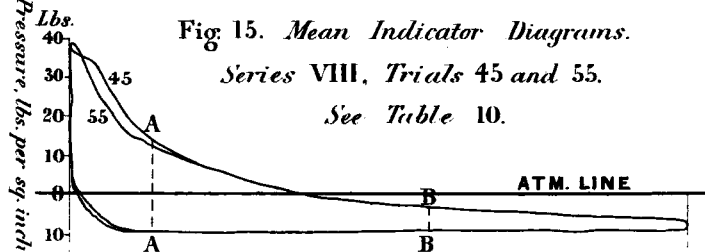
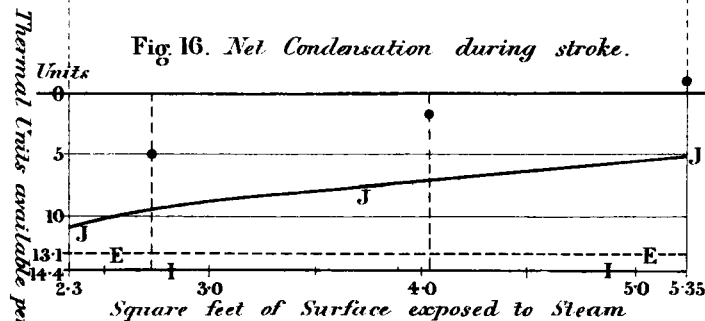


Fig. 16. *Net Condensation during stroke.*



E *Excluding Jacket Steam*  
I *Including*

(Mechanical Engineers 1889)

Plate 122.

# CONDENSATION AND RE-EVAPORATION.

Plate 123.

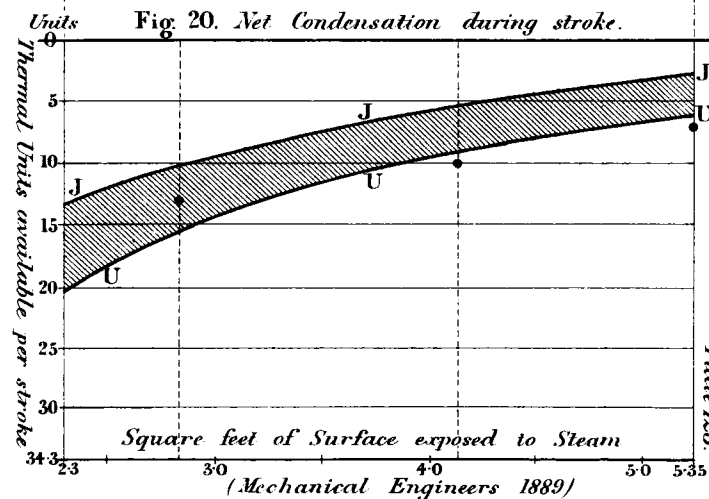
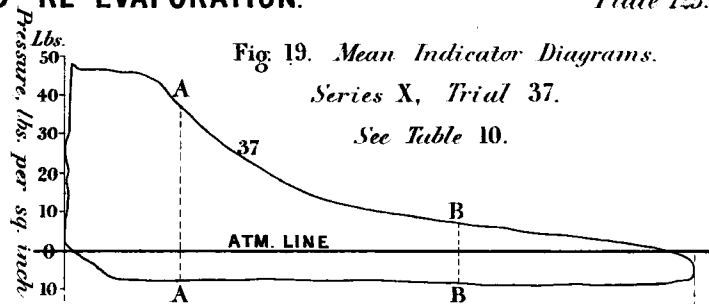
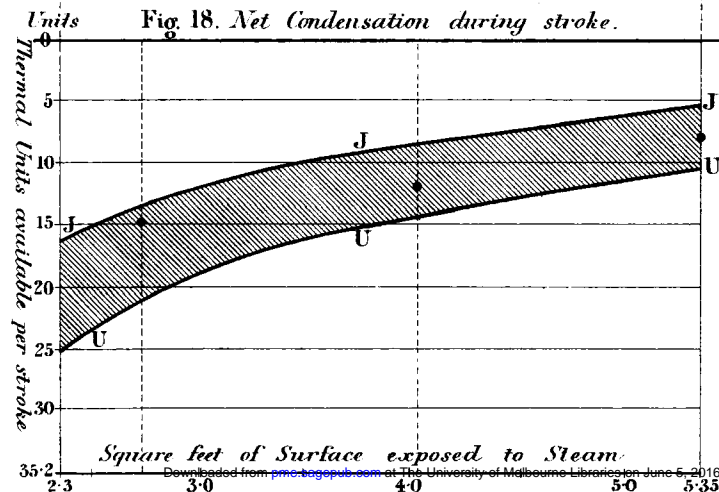
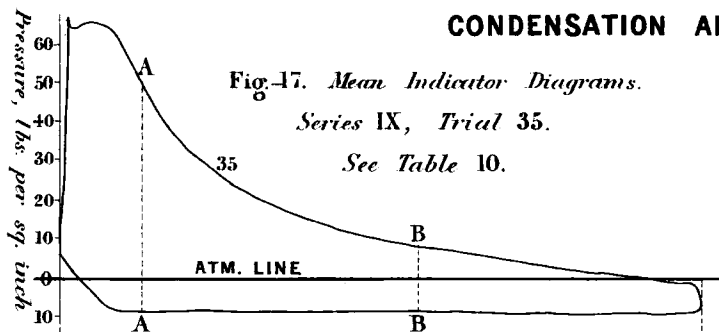
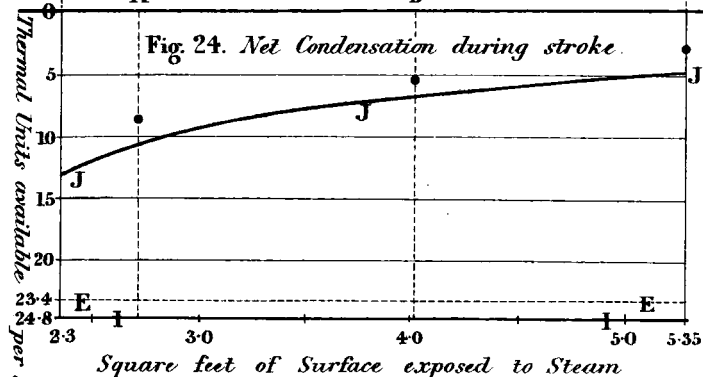
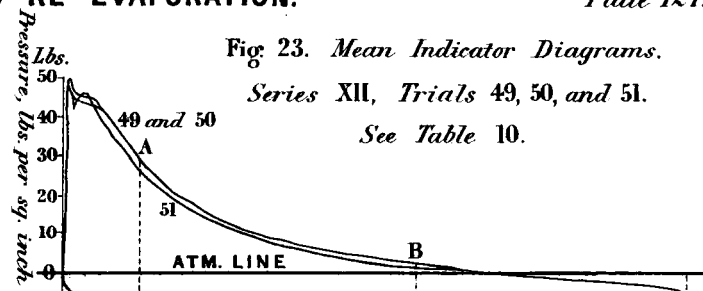
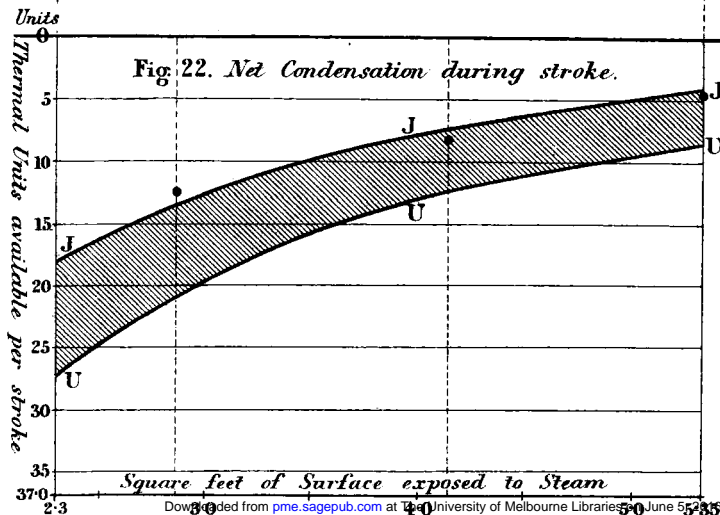
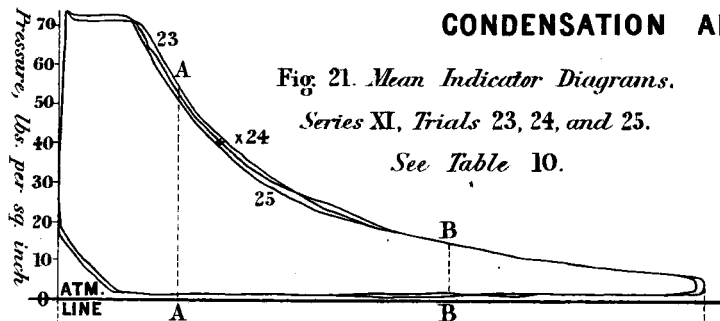


Plate 123.

# CONDENSATION AND RE-EVAPORATION.

Plate 124.



E. Excluding Jacket Steam  
I. Including " "  
(Mechanical Engineers 1889)

Plate 124.

# CONDENSATION AND

Fig. 25. Mean Indicator Diagrams.  
Series XIII, Trial 48.  
See Table 10.

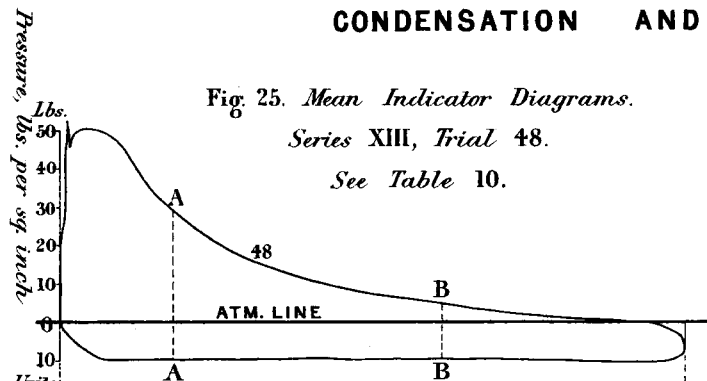
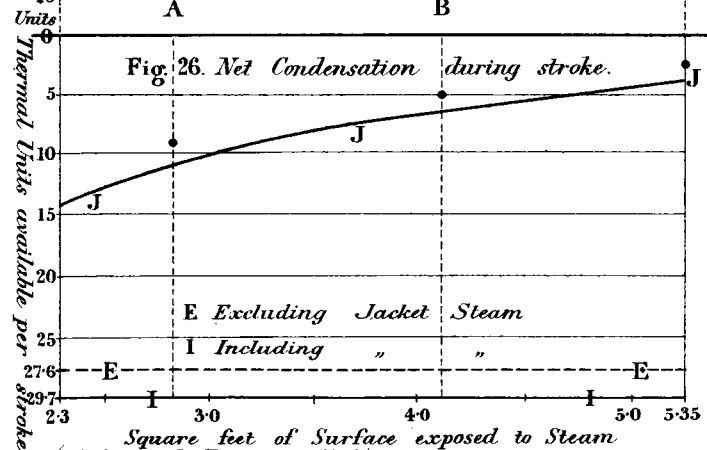


Fig. 26. Net Condensation during stroke.



# RE-EVAPORATION.

Fig. 27. Mean Indicator Diagrams.  
Series XIV, Trials 18, 21, and 22.  
See Table 10.

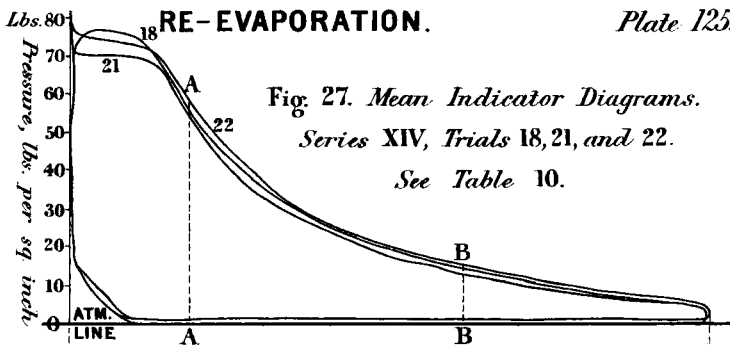
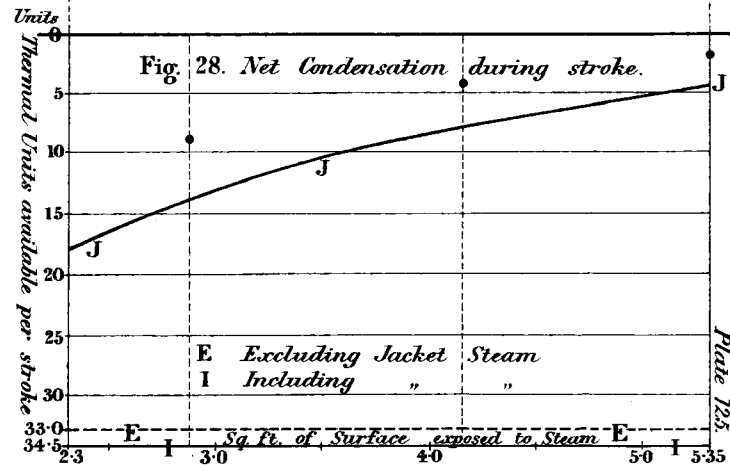
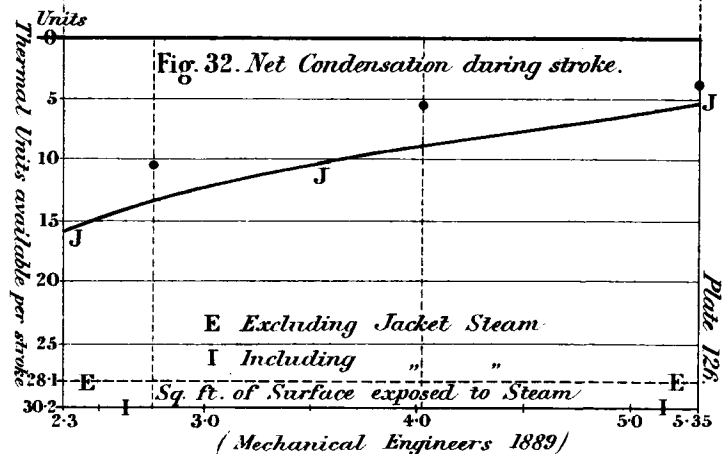
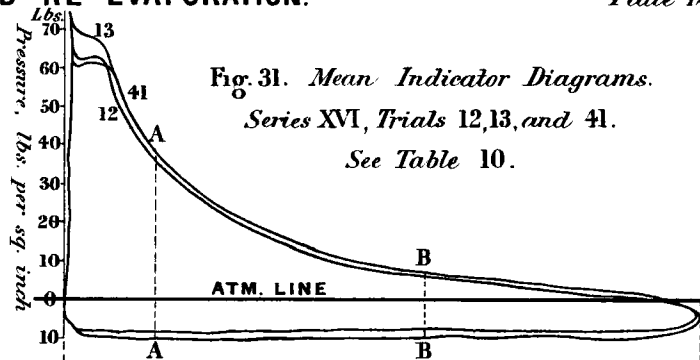
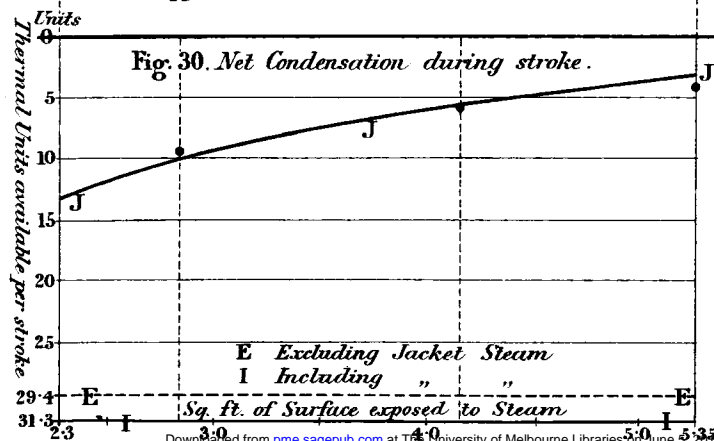
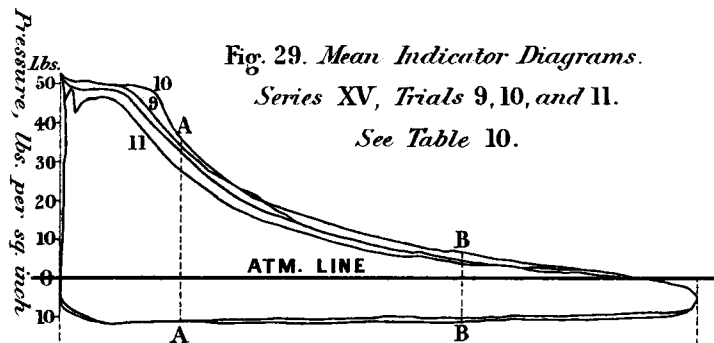


Fig. 28. Net Condensation during stroke.





# CONDENSATION AND RE-EVAPORATION.

Plate 127.

Fig. 33. Mean Indicator Diagrams.  
Series XVII, Trial 40.  
See Table 10.

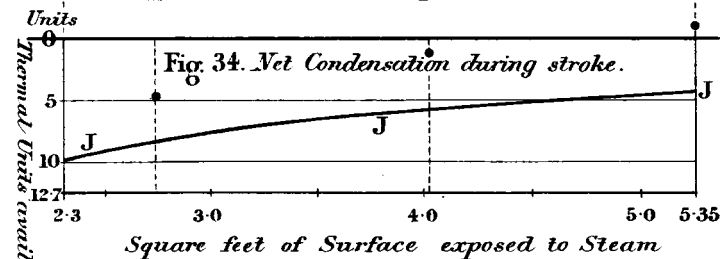
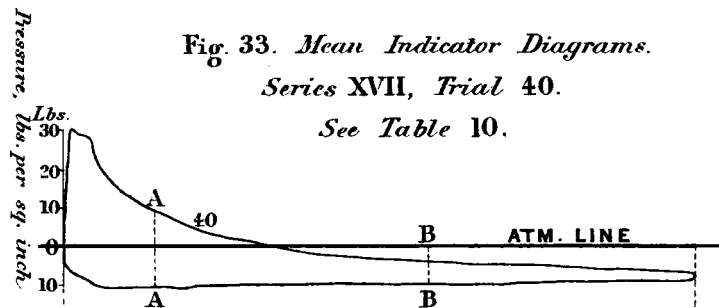
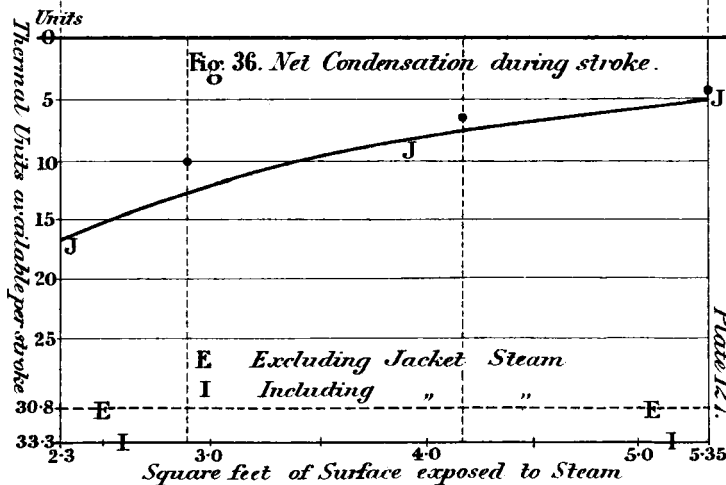
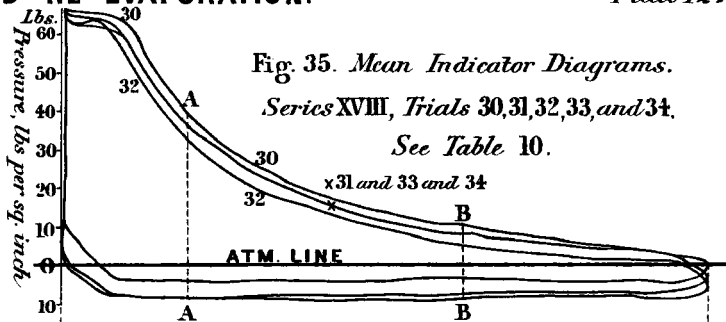


Fig. 35. Mean Indicator Diagrams.  
Series XVIII, Trials 30, 31, 32, 33, and 34.  
See Table 10.



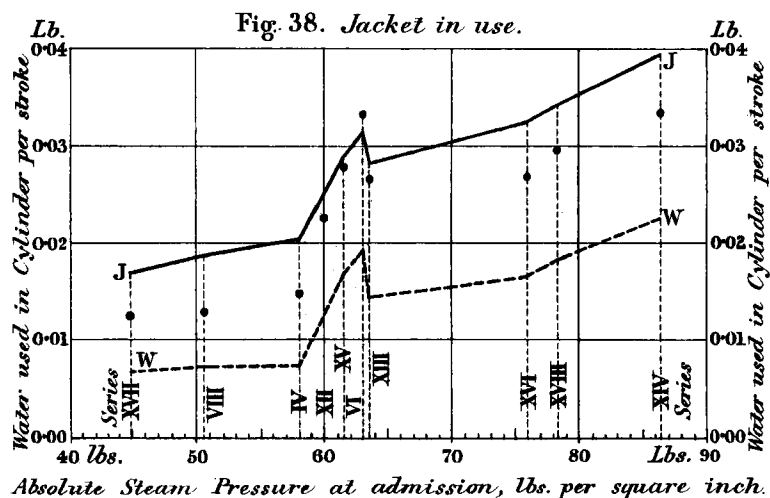
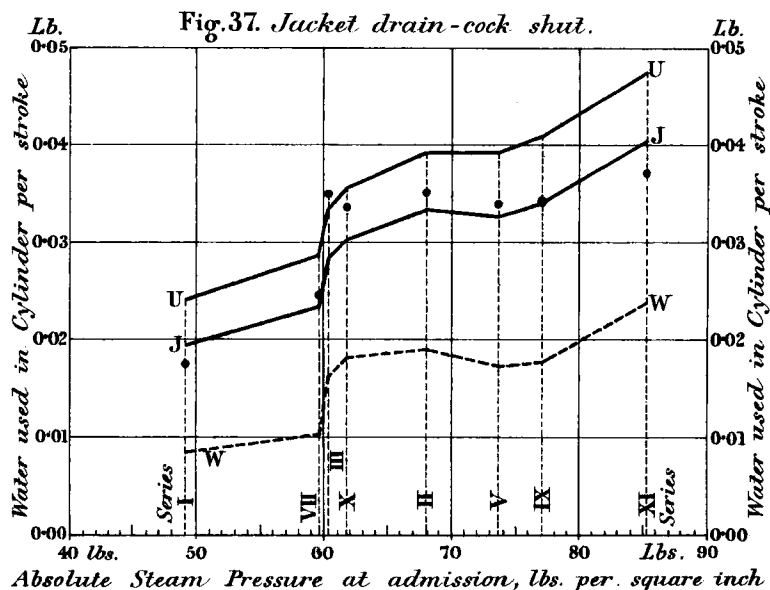
*Water used in Cylinder per stroke.*

• • • • *Observed results.*

*See Table 10.*

UJ — *Calculated results: U as Unjacketed; J as Jacketed.*

W----- *Accounted for by indicator at cut-off.*





# CONDENSATION AND RE-EVAPORATION. *Plate 129.*

*Comparison of Mr. Willans' Observed results with Calculation.  
Non-Condensing Simple Engine. See Table 12.*

• • • • *Observed results.*

FC ——— *Calculated results.*

W ----- *Accounted for by indicator at cut-off.*

Fig. 39. *Mr. Willans' Table V.*

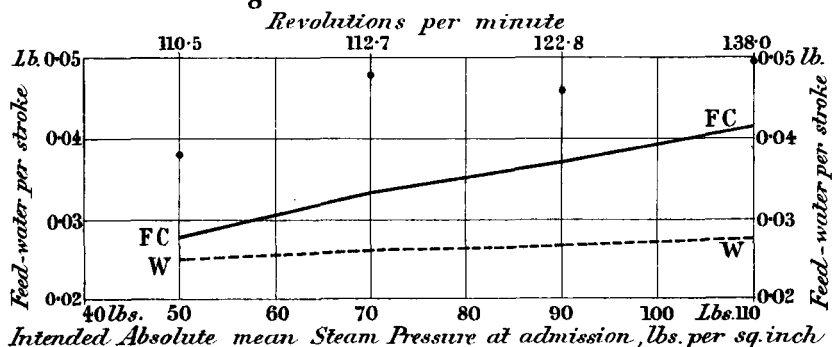


Fig. 40. *Mr. Willans' Table V.*

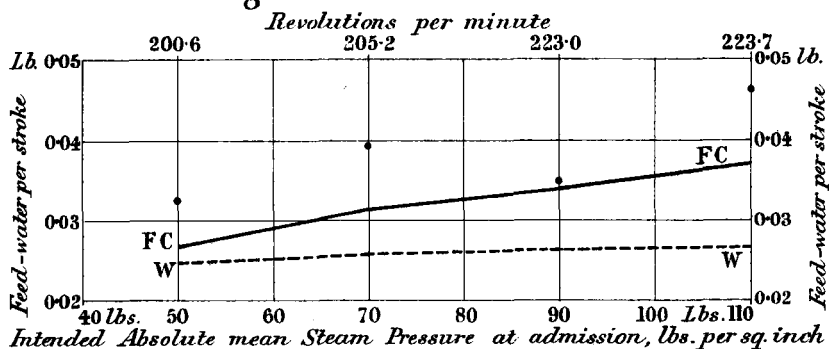
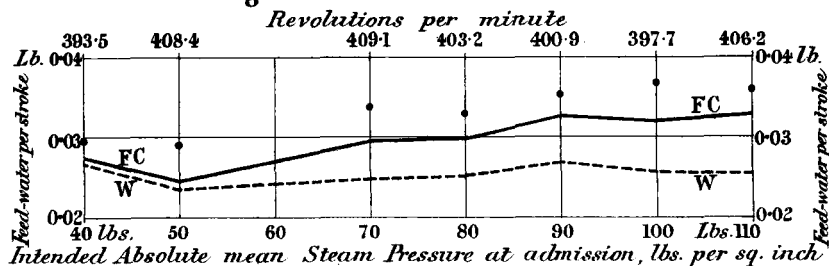


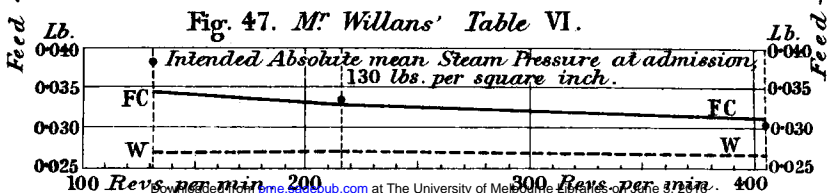
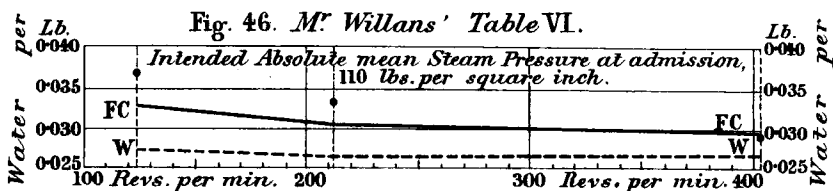
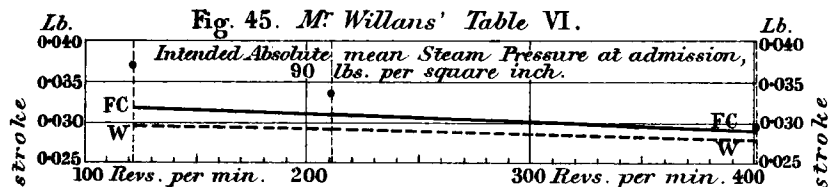
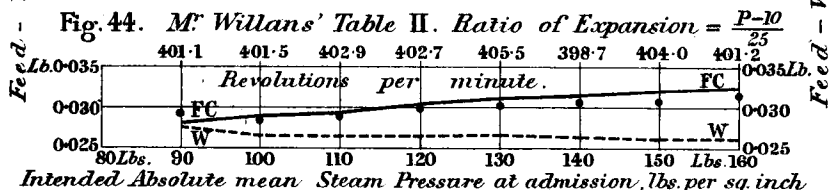
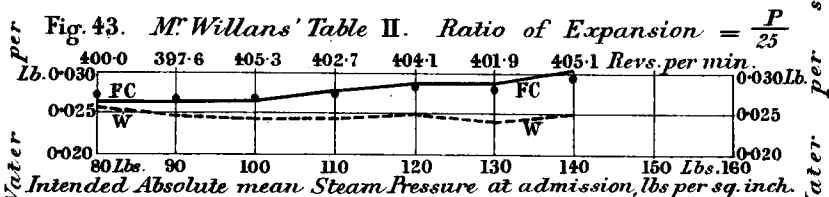
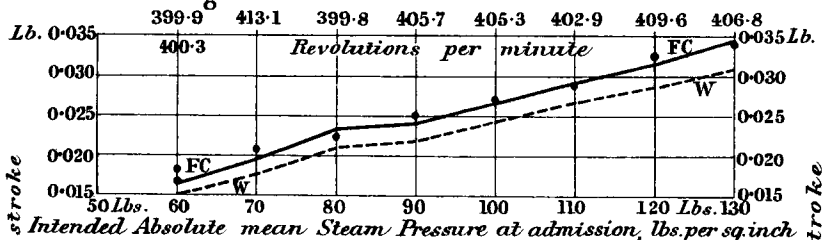
Fig. 41. *Mr. Willans' Table 1.*



*Comparison of Mr Willans' Observed results with Calculation.*  
*Non-Condensing Compound Engine. See Table 12.*

• • • • • Observed results. FC — Calculated results.  
W ---- Accounted for by indicator at cut-off.

Fig. 42. Mr Willans' Table VII.



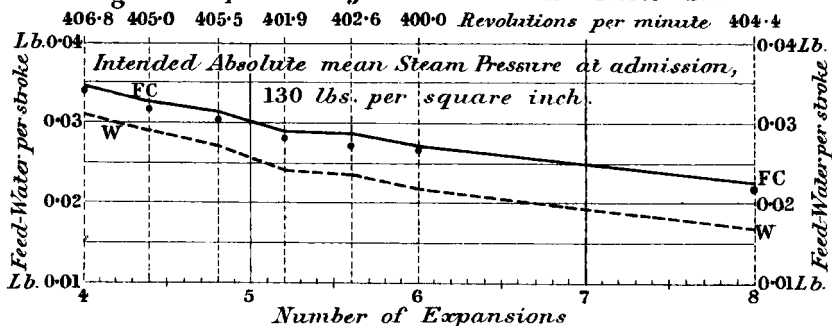
# CONDENSATION AND RE-EVAPORATION. *Plate 131.*

*Comparison of M<sup>r</sup> Willans' Observed results with Calculation.*  
*Non-Condensing Compound and Triple Engine. See Table 12.*

• • • • Observed results. FC ——— Calculated results.

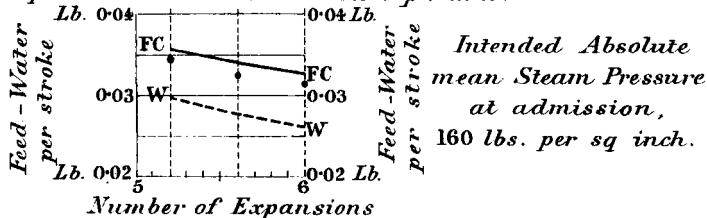
W----- Accounted for by indicator at cut-off.

**Fig. 48. Compound Engine. M<sup>r</sup> Willans' Table IV.**



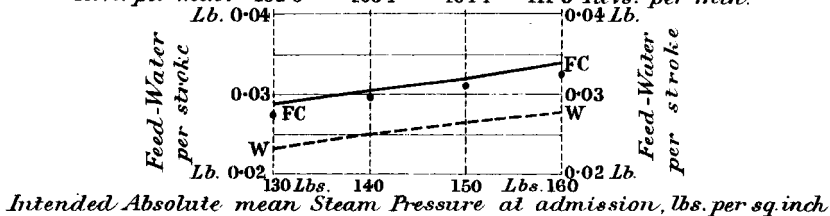
**Fig. 49. Compound Engine. M<sup>r</sup> Willans' Table VIII.**

Revs. per min. 421.7 411.3 401.2 Revs. per min.

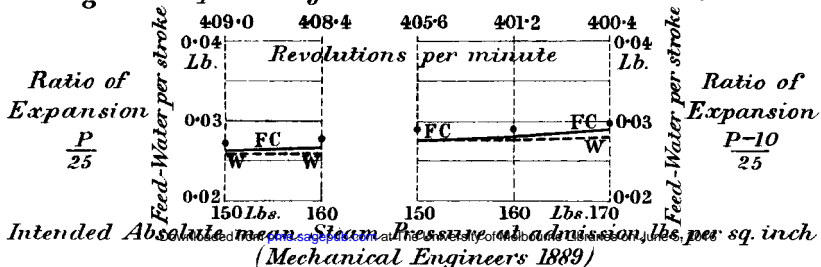


**Fig. 50. Compound Engine. M<sup>r</sup> Willans' Table IX.**

Revs. per min. 402.6 405.1 404.1 411.3 Revs. per min.



**Fig. 51. Triple Engine. M<sup>r</sup> Willans' Table III.**



*Density of Steam and Initial Condensation.*

Fig. 52. *Varying Density of Steam. Constant Cut-off.*

● ● ● ● Observed results. ○ ○ ○ ○ Calculated results.

See Mr Willans' Table VII under Table 12.

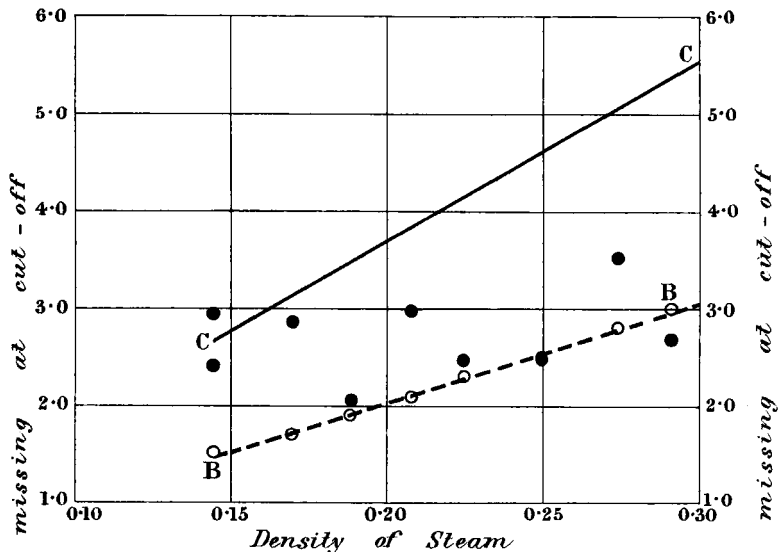
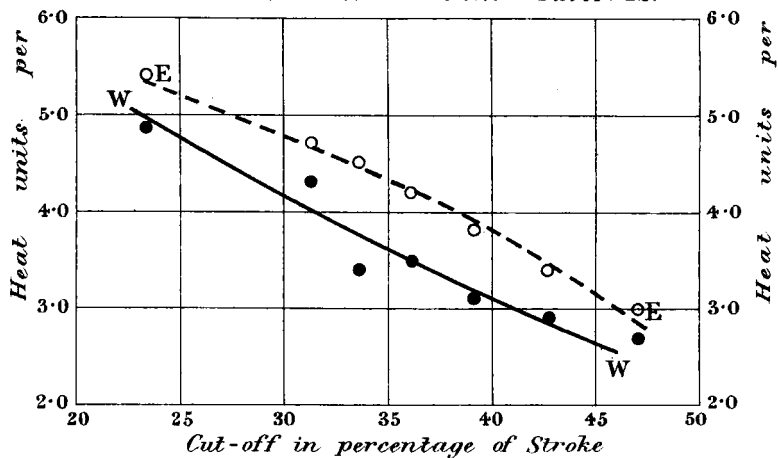


Fig. 53. *Constant Density of Steam. Varying Cut-off.*

● ● ● ● Observed results. ○ ○ ○ ○ Calculated results.

See Mr Willans' Table IV under Table 12.



# CONDENSATION AND RE-EVAPORATION. *Plate 133.*

*Variations in Internal Capacity of Boiler according to varying action of furnace.*

