Capt. Sankey. what absolute thermal efficiency did, as mentioned on the first page of the Paper. The standard thermal efficiency was useful for quite a different purpose, and the standard engine discussed in the Paper had reference only to steam-engines; but a gas-engine could be compared with its $\theta\ \phi$ diagram, as shown in *Fig. 1*, in an exactly similar manner, and the standard thermal efficiency of a gas-engine obtained. That there ought to be two thermal efficiencies, one to compare the absolute conversion into work by an engine, and the other to ascertain the degree of perfection under the conditions in which the engine was placed, Mr. Beaumont appeared to be in agreement with the Paper. He had laid on the Table a few copies of the $\theta\,\phi$ chart, which was a graphic representation of the properties of steam. This chart showed the temperatures, pressures, and volumes of saturated steam and also the volumes of 1 lb. of H_2O under various conditions (using that term to mean a mixture of steam and water); also the total heat expressed in British thermal units required to evaporate water at constant pressure from 32° F.

Correspondence.

Prof. Dwelshauvers-Dery. Professor V. Dwelshauvers-Dery remarked that the ideal steam-engine should have cylinder-walls absolutely impervious to heat; but its cycle would show the breaks due to the exhaust of the working fluid and its replacement in the boiler. There would thus be:—1st, admission at constant pressure p equal to that of the boiler, during which r thermal units per lb. of steam would be furnished, r being the latent heat of the lb. of steam; 2nd, adiabatic expansion prolonged until the pressure became equal to that of the condenser p' (or a higher one as proposed by the Author, but this would complicate the formulas), during which there was condensation, so that the dryness of the steam, which was unity, fell to a value x' which depended upon p'; 3rd, expulsion of the steam at constant pressure p', with consequent negative work taking place during the entire return stroke; 4th, restitution of the lb. of steam in the boiler and elevation of its temperature from that of saturation t', corresponding to p', to that of saturation t, corresponding to the initial pressure p. The quantity of heat expended in this operation was represented by $(q - q')$ thermal units per lb. of water, if by q be represented the heat of the lb. of saturated water at the temperature t, and by q' that of the lb. of water at the temperature t'. It would result that $q + r - q'$

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Prof. Dwelshauvers-Dery.

thermal units would be expended per lb. of steam, or $\lambda - q'$ thermal units, where λ is the total heat of the lb. of saturated steam.

The ratio of the heat equivalent of the work obtained to the total heat expended $(\lambda - q')$ represented the maximum efficiency of the real steam-engine, and its expression was very simple. The heat equivalent of the work done during admission was expressed by $A\,p\,u$. The heat equivalent of the work of the adiabatic expansion was equal to the difference between the internal heat of the lb. of the working fluid at the commencement and at the end of the expansion, or to $(q' + \rho) - (q' + x'\rho')$, where ρ was the internal latent heat of the lb. of saturated steam. If the notation u were employed in the same sense as above, the negative work for the expulsion of the steam was equivalent to $A\,p'\,u'\,x'$. Thus the calorific equivalent of the work was

$$A p u + q + \rho - q' - x'\,(\rho' + A\,p'\,u') = \lambda - q' - x'\,r'.$$

The efficiency was therefore given by the expression

$$\frac{\lambda - q' - x'\,r'}{\lambda - q'} = 1 - x'\,\frac{r'}{\lambda - q'}.$$

The value of u' was easily calculated by means of the adiabatic equation, by using steam Tables in which the entropy of the water and of the steam was calculated beforehand; ϕ being the entropy of the water and T the absolute temperature :—

$$\phi + \frac{r}{T} = \phi' + x'\,\frac{r'}{T'},$$

$$x' = \frac{\phi + \frac{r}{T} - \phi'}{\frac{r'}{T'}}.$$

The values of ϕ, ϕ', $\frac{r}{T}$, $\frac{r'}{T'}$, were found in the Tables opposite the pressures p and p' respectively.

Prof. Hearson.

Professor **Hearson** remarked that the Author, after comparing the various proposed standards, had wisely rejected the ideally perfect engine of the Carnot cycle in favour of that of the Clausius cycle in which the feed-water was raised to the temperature of the boiler by heat provided from the source. He had not, however, given a sufficiently forcible reason for its rejection in saying that it required a dynamical feed-heater, and by merely adding that steam-engines were not so fitted. The advantages of compressing

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Prof. Hearson. the exhaust water and pumping it back to the boiler had been so much enlarged upon, that expectations had been raised that a not inconsiderable saving would result from this process. A few years ago most extravagant pretentions to a high rate of efficiency had been advanced in favour of the Marchant engine, in which a show of carrying out this compression was made, and the success of the pretention was largely due to the false hopes which had been created as to the economy which was due to the process. Those hopes still remained in the minds of many who desired to have a recognition of them in the adoption of the Carnot cycle for the standard engine. It was therefore important to show that those expectations were falsely grounded, and that there were good economic reasons why engines were not fitted with dynamical feed-heaters, and probably never would be.

The $\theta\phi$ diagram of the Carnot cycle, *Fig. 2*, page 190, showed that by expending an amount of mechanical energy, K, on the pumps which compressed the water from the exhaust-pressure and temperature to the pressure and temperature of evaporation, the expenditure of an amount of heat was avoided which was represented by M + K, a quantity actually expended in the Clausius cycle, *Fig. 2*, and in ordinary engines. The numerical value of the ratio $\frac{K}{M + K}$, or, the ratio of the heat utilized to the heat expended in this portion of the cycle, was 0·10 for 60 lbs. per square inch, and increased to 0·15 for 200 lbs. per square inch steam, the exhaust-pressure being taken at 4 lbs. per square inch in each case. Because these fractions were less than the efficiency-fractions of the corresponding ideal Carnot engines, heating the feed-water by the source of heat was condemned. But, if the process of pumping back the exhaust steam into the boiler were performed by an actual steam-engine, it would have to be done at the expense of some of the mechanical energy developed by that engine, the efficiency of which was much less than that of a Carnot ideal engine. Probably the highest actual duty which had ever been accomplished by the best devised pumping-engine had not exceeded a quantity equivalent to 7½ per cent. of the heat expended, and to obtain the equivalent of 5 per cent. was considered not a bad performance. The pumping of a mixture of steam and water under gradually increasing pressure and diminishing volume would probably be performed much less efficiently. Thus, if at the rates mentioned, mechanical energy was expended in saving heat, and the heat so saved was employed in working the pumps, there would be a dead loss of at least half the mechanical energy expended.

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Prof. Hearson.

Without being further influenced in the same direction by considerations of the cost of the pumping machinery and its upkeep, the futility of this portion of the Carnot cycle was demonstrated.

As to the relative merits of adopting for the expansion line the adiabatic curve, the saturation curve, or the $p v$ = constant curve, it might be observed that in ordinary engines, in which a very short space of time was taken for one stroke, the mass of the actual steam in the cylinder at the commencement of the expansion did really undergo adiabatic expansion, with the formation of a suspended mist, although contemporaneously a film of water was evaporated from the surface of the cylinder, producing a mixture, the resultant curve for which was approximately $p v$ = constant. The circumstances to which the initial condensation and re-evaporation were due, and which prevented the expansion from being adiabatic were undesirable. By superheating the steam, by steam-jacketing the cylinders, and by limiting the range of expansion in any one cylinder by using a series of cylinders, their wasteful influence was minimised. In order that the standard engine should be free from this blemish, the adiabatic curve must be adopted for the line of expansion. If either of the other curves were adopted, the falling off from perfection due to the conductivity of the metal of the cylinder would be condoned to a degree, the exact amount of which might not be realised.

With regard to the limits which should be adopted in estimating the efficiency of the standard engine, he thought that in these respects, as in the form of the expansion curve, no fault whatever in the design and construction of the engine apparatus should be condoned. An unimpeachable standard would then be provided. He would adopt, as the superior limit, the pressure and temperature of the steam in the boiler, and for the inferior limit the temperature in the condenser, or the temperature corresponding to the atmospheric pressure, in the case of a non-condensing engine. Having thus provided a standard, which was perfect within its limitations, it would be necessary to determine a scale of comparison in order that the relative efficiencies of two engines of different types, or in which the range of pressure and temperature was different, might be justly weighed, the scale being adjusted to give an advantage to an engine in which an attempt was made to utilize a large range, as compared with one in which the range was smaller.

Instead of arbitrarily assuming a terminal pressure in the standard engine, such as 0·15 of an atmosphere above the pressure corresponding to the exhaust temperature, as suggested in the

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Prof. Hearson. Paper, it was probable that differences of opinion on this score could be more readily compromised by considering the adjustment which should be made for variety of range apart from the estimation of the standard itself. The adjustment could be effected by the addition of a bonus to the absolute efficiency of an engine, before ascertaining the relative efficiency. It would probably not be difficult for a representative Committee to agree to a tabulated scale of bonus to be added, whereby the performance of engines of different types could be justly compared. If the first apportionment should prove, on experience, to be not perfectly equitable, or the progress of engineering science should cause a modification to be desirable, the change could be made without tampering with the integrity of the standard engine. A comparison of the actual engine with the ideal standard engine would show the total shortcomings of the engine, and the tabulated bonus would express how much of that deficiency was, under the circumstances, excusable.

Prof. Jacobus. Professor D. S. Jacobus, of Hoboken, New Jersey, considered it was ably shown in the Paper that the $\theta \phi$ diagram possessed great advantages in solving a certain class of problem, and in the present case by selecting the proper lines from the $\theta \phi$ chart, given in the Appendix, the theoretical efficiency of an engine could be determined much more readily than by constructing the $p v$ diagram and deriving the heat quantities by analytical means. The employment in an investigation of a "standard ideal engine," in which the expansion was carried to the point where the minimum friction was equal to the forward pressure measured on the combined diagram, appeared to be advisable. Doubtless the adoption of the efficiency of this standard ideal engine as a standard of comparison would do much to render engine tests more readily comparable. The number of heat-units per HP. hour, with the ratio of this quantity to the heat-units for the standard engine, supplied all the necessary data from a thermodynamic standpoint. He thought, however, that what the Author called a "type standard" also formed a valuable basis of comparison. In many cases the pressure at the end of expansion in the low-pressure cylinder was governed by the conditions under which the engine worked, as well as by the vacuum in the condenser. Thus, in the case of marine engines the terminal pressure could not be reduced below that at which the engine gave a sufficiently uniform rotative effort. Again, in direct-acting steam-pumps the conditions limited the ratio of expansion. It was desirable to show how nearly the distribution of steam, as shown by the indicator cards, approached the best theoretical distribution for the conditions under which

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the engine worked, and a type-standard might be adopted to give this ratio. Prof. Jacobus.

The most useful measure of the efficiency of distribution from the standpoint of the steam-engine designer was obtained by comparing the area of the actual combined diagrams with that of a theoretical diagram, cutting off in the high-pressure cylinder at the same fraction of the stroke as in the actual engine, and following the law $p\,v =$ constant. A general practice in designing engines was to make use of such a simple theoretical diagram, and to multiply its area by a factor to allow for the difference which experience showed to exist between the theoretical and the actual areas of the combined cards for the class of engine under consideration. It was his custom to give this factor in reports of engine tests, and to plot the actual and theoretical diagrams on each other, so that the losses due to wire-drawing and condensation, or re-evaporation, were at once apparent. This factor, together with the percentage of water not accounted for at cut-off, measured the relative efficiency of engines of the same class.

Such a determination of the efficiency of distribution, together with the absolute thermal efficiency of the actual engine, and the comparison with the ideal engine, recommended by the Author, would give the most important data in an engine trial, and a uniform adoption of this method would greatly facilitate the comparison of different tests.

Mr. Luther. Mr. G. LUTHER, of Brunswick, observed that in all known forms of heat-motors, the heat developed by the fuel was not received, in accordance with the Carnot cycle, at the highest temperature, but while the temperature of the working fluid was rising. This theoretically incorrect reception of the heat was to be regarded as the chief reason why attempts at perfect conversion of the heat of the fuel into mechanical work had hitherto proved unsuccessful.

Mr. Northcott. Mr. W. H. NORTHCOTT agreed with the Author in thinking that it was desirable to establish a common standard of reference wherewith actual results might be compared, and that two standards—an absolute one and a relative one—were necessary. In regard to both standards, however, there was room for considerable difference of opinion. The user of a steam-engine naturally thought mainly, if not wholly, of the cost of the useful work, taking into account not only the coal bill, but the first cost of machinery, the cost of labour and maintenance, and depreciation charges, &c. The only standard of efficiency from the commercial point of view was, therefore, that of the cost of the work done. The scientific investigator would no doubt advocate a standard based upon a

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Mr. Northcott. theoretical ideal, conceivable but impossible. The engine-maker would again express a preference for a standard with which his own engines might be most advantageously compared. Even in regard to the engine-factor itself there were difficulties, a point with which the Author had not dealt. Generally speaking, whether the absolute or the relative efficiency was obtained, and whatever might be the standard adopted, the brake HP., or its equivalent, should be employed, and not the indicated HP. Unfortunately, however, the former could not always be ascertained, and it was necessary to fall back upon the latter. This might introduce errors of considerable magnitude, owing to faults in the indicator cards, brought about by defects in the indicators themselves. With very high-speed engines indicator diagrams were extremely doubtful even when taken with care. As before the steam could do useful work it must drive the engine against its own frictional resistance, it appeared only reasonable that the steam should be credited with this work. The result, however, was the approximate dynamic efficiency of the steam—not of the steam-engine—and the efficiency was generally perhaps overstated. The internal engine friction no doubt diminished the cylinder condensation at the expense of the useful work. Under any circumstances the I.HP. might mislead, under some circumstances it might be quite delusive.

The useful mode of expressing engine efficiency employed largely in connection with pumping-engines was not mentioned by the Author. Here the efficiency was expressed in foot-lbs. of water raised per bushel or per pound of coal. An engine raising 1,000,000 foot-lbs. per pound of coal was doing good "duty," and with coal of standard quality assumed, this mode of expressing the engine efficiency was simple, serviceable, and instructive. It would be easy enough to separate the engine performance from the boiler performance, and the efficiency on any other basis could be deduced readily from the "duty." A duty of 1,000,000 foot-lbs. per pound of coal of 14,000 units represented an absolute efficiency of the whole apparatus of $\frac{1,000,000}{772 \times 14,000} = 0 \cdot 0925$, and an absolute engine efficiency of probably $\frac{1,000,000}{772 \times 10,000} = 0 \cdot 1295$. The Cornish efficiency showed exactly what the engine was doing, and in that respect had an advantage over an efficiency based either upon the Carnot cycle engine or any other ideal conception. The latter might be more scientific, but the usefulness of a rule often varied inversely with its scientific pretensions. The expression

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Mr. Northcott.

of the results of a test in terms of heat expended for I.HP. hour, a method advocated by Mr. Mair-Rumley, was approved by the Author. This method was due to Rankine, and Mr. Northcott had himself published a series of comparative engine-results so expressed in 1876 or before. The heat expended per HP. hour might vary between 10,000 or 15,000 for first-rate engines, up to 100,000 for some of the no-flywheel pumping-engines. These figures were somewhat large for convenient comparison, and he would suggest expressing engine efficiencies in foot-lbs. of work per heat-unit expended. For a good engine the indicated work per unit of heat expended would be about 115 foot-lbs. for the entire process, or about 140 foot-lbs. per unit admitted to the cylinder. The Carnot cycle standard appeared to be at least as good as any. It was considered unsuitable by the Author because "the Carnot cycle was an ideal incapable of realization." But this was the case with every ideal. In this respect he saw little difference between the Carnot-cycle engine and the Rankine steam-engine of maximum efficiency. Both were practically unrealizable, and, moreover, the peculiar difference between the two standards might be removed by conceivable means. The nearer the standard was to the actual result the easier it would be to detect accidental and other errors, and this was the only advantage possessed by the Clausius standard over the Carnot-cycle standard. If the latter was rejected as unsuitable because unrealizable, it would logically follow that the best standard was the one nearest realization. This would, he thought, be the constant saturation standard used by Professor Osborne Reynolds and Mr. Davey. When an engine was furnished with a jacket to promote constant saturation, it did not appear unreasonable that its efficiency should be referred to a saturation standard. On the whole, however, the Carnot cycle standard appeared to be fairly unobjectionable. It was easily calculated, it applied to all types of heat-engines, it required fewer arbitrary assumptions than any other proposed ideal standard, and it was the most scientific.

Prof. Peabody.

Professor C. H. Peabody, of Boston, U.S.A., considered that the efficiency of the cycle advocated by the Author was the proper standard with which to compare the efficiency of the actual steam-engine, but that the efficiency of the Carnot cycle should be retained as the absolute standard. The primary reason why a steam-engine could not be made to work on the Carnot cycle was that no method had been devised to transfer heat to the working substance during isothermal expansion, and to withdraw heat during isothermal compression. The secondary reason, namely, that no

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Prof. Peabody. proper non-conducting material of which steam-engine cylinders could be made was available, affected both the Carnot cycle and the proposed standard cycle. It was not impossible that a material might be found which had as little effect on saturated steam as cast iron had on dry air, and which could be used for making or lining steam-engine cylinders. Such a material would allow a close approximation to adiabatic expansion and compression; the admission that such a material might exist was useful, as it gave a concrete conception of the problem under discussion. An engine with a cylinder of such material would correspond exactly with the requirements of the standard cycle, provided that it had valves and passages sufficient to avoid sensible loss of pressure. It would take steam at boiler-pressure, expand it adiabatically, exhaust against the back pressure, and give an adiabatic compression from the back pressure to the boiler-pressure. The exhaust steam could be condensed at the temperature corresponding to the back pressure and returned to the boiler. Each pound of the feed-water would be re-evaporated at the expense of $L_a + \theta_a - \theta_e$ thermal units, which quantity formed the denominator of the expression for the standard efficiency, and represented the heat supplied to the engine per lb. of steam. The numerator of the expression for efficiency represented the heat converted into work per lb. of steam. For the standard efficiency the work per lb. of steam was of course calculated by the aid of proper thermodynamic equations; for the actual engine the indicator-diagram furnished the basis for a like calculation. By such a conception of the problem attention was concentrated on the difference between the actual engine and what might be called the standard engine. That difference for slow engines of good design was due mainly to the energetic action of cast iron on saturated steam, and superheating, jacketing and compounding were so many devices for reducing that action.

In making the report of a thorough test on a steam-engine the efficiency of the Carnot cycle and of the standard cycle ought always to be given, together with the actual thermal efficiency and its ratios to the efficiencies just mentioned. The first ratio showed how far the engine fell short of perfection, and the second showed how near it came to its prototype. The standard back-pressure and the failure to expand down to the back-pressure formed subjects for experiment rather than for discussion. If a standard were agreed upon, probably sooner or later it would be proved by experiment that this standard was wrong, and then the standard itself became useless. The proper temperatures and pressures

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Prof. Peabody.

from which to calculate the standard efficiency were the pressure near the cylinder in the steam-pipe, the terminal pressure in the low-pressure cylinder, and the pressure in the exhaust-pipe.

It was convenient and customary to quote the number of pounds of steam per HP. hour, when stating the results of any steam-engine test; but it must be borne in mind that such a statement was inexact and might be misleading. The method of stating steam-engine performance in thermal units, on the contrary, was simple, exact, and scientific. It might be applied to engines using superheated steam, to engines with steam jackets, and to compound engines; further, it could be used for gas-engines and other heat-engines. If stated in terms of thermal units per HP. per minute the necessity of using large numbers or fractions was avoided. With proper Tables of the properties of saturated steam the calculations involved would be simple and expeditious.

As an illustration of the misconception that might arise from quoting lbs. of steam per HP. hour, he instanced two tests out of several series made on the experimental engine in the laboratory of the Massachusetts Institute of Technology.[1] This engine had three cylinders, 9 inches, 16 inches, and 24 inches diameter, with 30 inches stroke. With steam in the jackets of all three cylinders the engine used 13·7 lbs. of steam per HP.-hour, or 231·7 thermal units per HP. per minute. Without steam in the jackets it used 15·2 lbs. of steam, or 275 thermal units. The actual gain from the use of steam in the jackets was 15 per cent.; while the comparison of the lbs. of steam used indicated only 11 per cent. The efficiency for the test was $42{\cdot}42 \div 231{\cdot}7 = 0{\cdot}183$. The efficiency of an engine with a non-conducting cylinder working on the standard cycle would be 0·222; the efficiency for the Carnot cycle was 0·249. The ratios were:—

$$0{\cdot}183 : 0{\cdot}222 = 0{\cdot}82$$
$$0{\cdot}183 : 0{\cdot}249 = 0{\cdot}74.$$

The discrepancy between the actual and the standard efficiency was largely due to external radiation. A special test showed that 18·6 thermal units were radiated per HP per minute. If radiation could be suppressed, the engine would use 213·1 thermal units per HP. per minute, and would have an efficiency of 0·199, which was 90 per cent. of the standard efficiency, leaving only 10 per cent. to be attributed to condensation and evaporation.

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[1] Transactions of the American Society of Mechanical Engineers, vols. xii., xiv. and xvi.

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Prof. Peabody. The temperature-entropy diagrams showed clearly the nature and the effect of the various elements entering into the problem. Nothing could show more clearly the inadequacy of the other standards that had been proposed, and that were so thoroughly disposed of by the Author, whose diagram for finding the efficiency of the proposed standard cycle was admirable in its simplicity and directness. He could not, however, agree that the calculation of efficiency by proper equations was either difficult or laborious.

Mr. Porter. Mr. CHARLES T. PORTER, of New York, remarked that the questions presented on the trial of a steam-engine appeared to separate themselves naturally into three distinct classes. In order to derive the absolute efficiency, which constituted a class by itself, the engine was charged with the number of thermal units supplied to it, and was credited with the number converted into work. The ratio that the latter bore to the former expressed the value of the engine in the economic scale. On every test of a steam-engine, the primary object must be to ascertain these two amounts with the utmost attainable certainty. This having been done, three questions next presented themselves, and constituted the second class, as follows:—How did the ratio of the heat utilized compare with that in an ideal engine (or an engine reaching the highest ratio attainable), working within the same temperature limits, and with the same number of expansions? How did this ratio compare with those in other engines working under the same limiting conditions? and how did it compare with the ratios reached in engines working under different conditions of heat limits and expansions? All practical questions constituted a third class of two groups; what were the causes of the superiority or the inferiority shown? and by what means could a higher degree of efficiency be attained? Comparison with a standard engine did not appear practical for two reasons:—general agreement was not possible upon the standard engine, and advances in engine performance would probably compel frequent renewal of the standard. These advances might be expected to result from a more distinct realization of the fact, that, in engines working merely saturated steam, the heat for conversion into work was obtained chiefly or wholly (depending on the character of the expansion curve) from steam that was not represented on the diagram. He considered the engine quite distinct from the boiler, as it seemed important that the performance of each should be separately ascertained.

Mr. Schröter. Mr. M. SCHRÖTER, of Munich, agreed with the Author as to the necessity of having a universally adopted standard, so that all

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Mr. Schröter.

figures of thermal efficiency would be directly comparable; but he did not think it urgent to substitute the (so-called) Clausius standard as adopted by the late Mr. Willans. In each class of heat-engine, the cycle of the ideally perfect engine would be to some extent arbitrary, depending on what losses were considered as inherent in the nature of the engine, and those ideally avoidable. Upon two points there was general agreement; namely, that when the temperatures of admission and exhaust were given, the ideal of absolute perfection was the Carnot process; and further, that the omission of the dynamical feed-heater was an unavoidable loss. As regards all other losses, the determination of how far they were avoidable was open to discussion. A standard of comparison ought not to be affected by arbitrary numbers such as that chosen by the Author for the limit of expansion. From the thermo-dynamic point of view it was clear that the available heat would be best utilized by carrying the expansion as far as the back-pressure corresponding to the temperature at which heat was abstracted from the working fluid, and it seemed that the mechanical perfection of the engine was better left out of consideration, the more so as the Author's proposed standard involved calculations of considerable length and complication, and this would be a hindrance to its general introduction. Moreover, if the Clausius-Willans standard were adopted, then some ideal process could be employed for the cold-vapour engines of the compression system, the inversion of the steam-engine (refrigerating engines with ammonia or carbonic acid as a working fluid). With these the suppression of the expansion cylinder might be regarded as an unavoidable loss, just as in the case of the steam-engine, the omission of the dynamical feed-heater was so regarded, and thus the reversibility of the thermo-dynamical process found expression in the choice of the standard heat and cold-engine. This was of so much importance in theory that it was worth the little sacrifice which must be made from the more practical point of view, in considering that the theoretically best terminal-pressure of the expansion was identical with the back-pressure.

Prof. Smith.

Professor Robert H. Smith, wished, with reference to the Author's definition of "standard efficiency" to protest against the common phrase "heat converted into work." Heat was energy; work was not energy, and could not be converted into heat-energy or *vice versâ*. Work was the process of transfer of energy from one mass to another, or of transformation of energy from one form to another form within one mass. He would prefer to confine the use of the word "work" to the transfer only of energy from mass to mass,

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Prof. Smith. and not to transformation. But when the latent (or potential) energy of heat-elasticity of, say, a gas, produced rapid outflow of the gas from the containing vessel, it was so invariably the custom to say that mechanical work had been done in producing the kinetic energy of the outflow that it seemed for the present desirable to include transformations within the meaning of the term "work." It could be said quite properly that heat was spent in doing work. An arbitrary selection was made by the Author of a very few of the many physical and economic conditions which affected steam-engine efficiency, and all other operative conditions were thrown so much into the shade as to make them unworthy of consideration in determining the character of the "ideal" engine, seemingly because they were merely "practical," in spite of their being influential to the extent of reducing "actual" efficiency from 100 per cent. to 50 per cent.

The calculation of the complete thermo-dynamic efficiency necessarily included the actions of furnace, feed-pump, boiler, engine, condenser, and air-pump. It might be very convenient and perfectly scientific to split this whole efficiency into separate factors, one of which, for instance, would deal with the action of the engine alone; but each such separate factor had no reference to any complete thermo-dynamic cycle. Even including the whole of the thermo-dynamic apparatus, it was well known that the cycle of operations was never "complete." The air-pump never delivered the discharge from a surface-condenser at the temperature of the feed. With an injection-condenser the condensed steam was brought more nearly to the primal condition of the feed; but still not wholly so, and in both cases a considerable amount of the working fluid was discharged in the form of low-pressure steam. In non-condensing engines the bulk of it was discharged in this form, mixed with only a small volume of water in the form of cloud. It ought to be recognised that these thermo-dynamic operations were essentially and necessarily "incomplete," that was to say, not represented by a "complete cycle"; and that they involved waste thermo-dynamic quantities beyond what was usually termed the "waste" or "discharge" heat.

He could find no justification for assuming the Carnot cycle, or the "isothermal-adiabatic," or "two-temperature two-entropy" cycle, as the ideally perfect one; or that the aim of engine-makers ought to be to approximate as closely as possible to the Carnot cycle. The consideration of the Carnot cycle had been of immense importance in the elucidation of the true laws of thermo-dynamics and in helping towards a true conception of

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Prof. Smith.

thermo-dynamic efficiency, but no evidence had been produced that even Carnot himself ever considered this cycle to have any great further importance. If the efficiency of thermo-dynamic engines were limited by considerations of temperature alone, then no doubt the Carnot cycle, which gave the maximum possible efficiency under the sole condition of prescribed temperature limits, would be of supreme importance, and it would then be the endeavour of all engine-makers and users to approximate as closely as possible to it. But pressure-limits were of equal, if not greater, importance because of considerations of strength and stiffness. Volume limits, that was limiting grades of expansion, were of very essential importance because the increasing bulk per HP. of the motor machinery accompanying greater expansion not only increased the weight and therefore the prime cost of the material spent in building the engine, but increased also the prime cost in machining, and the general costs of maintenance; and, moreover, increasing expansion decreased the mechanical efficiency by diminishing the uniformity of the driving effort. This last, at any rate, reached a maximum with one certain grade of expansion depending on the speed and rate of reciprocation of the parts, beyond which further expansion would not be desirable if mechanical efficiency alone were to be considered. Calculations of the best ratio of expansion based on a comparison of the cost of increasing bulk with the saving in steam and fuel, had often been made, and this particular item influenced the design of steam-engines to a greater extent than was generally appreciated. The most economical exhaust-pressure appeared hitherto to have received little attention; perhaps because if a condenser was to be used at all, the extra cost for making it and the air-pump larger and more efficient was small compared with the greater advantage obtained in steam-consumption. But even here the same considerations of cost were practically operative in determining limits. Thus, for instance, the extra cost of reducing the back-pressure from 3 lbs. per square inch absolute to 2 lbs. or 1½ lb. per square inch was not generally found to be justified by the advantage gained, this extra cost being very greatly more than was involved in reducing it from say 7 lbs. to 6 lbs. or 5½ lbs. per square inch.

Temperature limits operated in two ways. First, high steam-temperature involved correspondingly great chimney-waste of heat (although this extra waste was perhaps not serious as compared with the increased steam-efficiency), and also slower conduction of heat through the boiler heating surface. The slower conduction was accompanied by decreased boiler horse-power.

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Prof. Smith. Secondly, the keeping of working surfaces in good condition became rapidly more difficult and costly as the steam-temperature rose above certain limits related to the evaporative qualities of the lubricants used.

Admitting the fundamental importance of the Carnot cycle reasoning for the theoretical purpose of establishing primary thermo-dynamic laws, it should not be forgotten that this reasoning has absolutely no direct bearing upon practical problems, because it had involved infinitely slow conduction of heat to and from the working substance, and therefore zero HP. In fact, the Carnot process could not be carried out consistently with the development of any HP. at all in the boiler and engine. This did not mean that an isothermal-adiabatic indicator diagram necessarily meant zero HP. The reasoning, whereby Carnot did so much towards establishing correct scientific thermo-dynamic principles, did not lie in the use of this particular kind of indicator diagram, but depended on the use of "infinitely small" conductive differences or falls of temperature, involving "infinitely" slow rates of conduction. Such conditions of working were infinitely remote from those of any possible practical process.

If the upper and lower pressure limits were alone of importance in restricting the working of a pressure thermo-dynamic engine, then to obtain maximum thermo-dynamic efficiency the whole of the conductive heat-supply ought to be at the upper limit of permissible pressure, and the exhaust of the working fluid ought to take place wholly at the lowest permissible pressure. If temperature limits were alone operative, the whole supply of heat should be at the highest temperature allowed, and the whole exhaust of heat at the lowest allowed. If both temperature and pressure limits be imposed, then the maximum efficiency possible under the given conditions would be obtained if the conductive heat-supply were given at the upper limit of permissible pressure until the upper limit of temperature was reached and continued at this upper limit of temperature (with falling pressure) until the whole heat allowed per lb. of steam had been so supplied.

In either case, after the supply of the heat allowed per lb. had been finished, adiabatic expansion should be continued (in order to obtain maximum efficiency) until the limiting volume imposed by conditions other than those of thermal efficiency had been reached. Temperature limits probably received more consideration than pressure limits—first, because in the thermo-dynamic theory of an "elementary engine" the mathematical expression for the thermal efficiency took a simpler form when given in terms of

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Prof. Smith.

temperature than in other terms, and secondly, because so long as the evaporation of water into steam was alone considered, the isothermal line was coincident with the isobaric line and the identity had prevented engineers recognising the impracticability of working along an isothermal *per se*. But now that the advantages of superheating steam were being more generally recognised, it was never attempted to superheat along an isothermal. The invariable method was to superheat along an isobaric, maintaining the same pressure as that used for evaporation. It was true that Rankine many years ago set forth the advantages obtainable from superheating by wire-drawing at the throttle-valve and the slide-valve ports; but this method was only tolerated in so far as it was found practically unavoidable. The general rule for the mode of conducting heat so as to obtain the highest thermo-dynamic efficiency was to select that method which, among those permitted by other necessary limiting conditions, increased by the largest additional amount the latent (or potential) elastic energy of the working substance.

Prof. Thurston.

Professor R. H. THURSTON was greatly interested in the subject of the Paper, and had already given it very close consideration.[1] He had endeavoured to ascertain what process could be practically applied to realize with exactness the idea of Rankine, who sought to identify that ratio of expansion at which the steam-engine would give the required amount of power at minimum annual total running cost, inclusive of interest, &c. That method, when applied to current practice, proved a failure in consequence, as he had discovered, of the fact that the influence of the extra thermodynamic wastes of the machine were not taken into account. The later attempts to follow Rankine's methods were fatally invalidated, both by this neglect and, even more seriously, by the fact that these who sought to apply the system to modern forms of engines, apparently without suspecting a vital difference between the two cases, endeavouring to ascertain what adjustment of the expansion-gear would correspond to the requirement of securing the highest possible return from a stated engine already constructed and in operation. The results were found, in many cases, to be contradictory of experience, and widely erroneous solutions of Rankine's, "the designer's," problem. Other problems, which he had been accustomed to call the "Owner's problems," were: (*a*) To ascertain what, with an engine of given dimensions, would be the

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[1] "The Several Efficiencies of the Steam-Engine," Transactions of the American Society of Mechanical Engineers, 1882; Journal of the Franklin Institute, 1882; "Manual of the Steam-Engine," vol. i. chap. vii.

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Prof. Thurston. best ratio of expansion, and what the best amount of power to be delivered, highest financial returns being demanded. (*b*) The adjustment of cut-off and power at which a limit would be found in the securing of satisfactory profit. These were entirely distinct forms of the problem from those which confronted the designer seeking to properly proportion an engine for a stated amount of power, and then led, if correctly solved, to radically different solutions, giving results which would be absurd as solutions of the designer's problem.

He saw no objection to using as the standard the absolute efficiency. He would obtain the ratio of the heat transformed, and usefully applied, to the total quantity of heat furnished the engine, in the unit of time, measuring both in the same way, either in thermal or dynamic units, in either calories or foot-pounds, and would take this efficiency as the recorded measure of value of the machine as a thermo-dynamic apparatus. Measured by this standard, one engine had an efficiency, in a correct sense, of 5 per cent.; another gave 20 per cent., as did actually the Milwaukee steam-pumping engine, which was, at the time of its formal trial, the most remarkable engine, in this respect, probably, in the world.[1]

The engine-cycle of highest efficiency, and of absolutely defined value, and which should therefore serve as a standard, both for these reasons, and because it was the perfect limit toward which all work of the engineer was expected to constantly approximate, although never by any possibility to fully attain, was, of course, the Carnot cycle. This seemed the more suitable from the fact that it was a form of cycle which, thermal wastes aside, could be produced in the actual engine, and he had devised a number of methods of securing such adjustments of mechanisms as would, in an engine composed of non-conducting substances, actually give such a cycle. In this case, with complete adiabatic expansion and compression, the maximum possible efficiency of heat-conversion was attained. The comparison of the efficiency of any actual engine with the efficiency of the corresponding Carnot cycle afforded an absolutely accurate and scientifically exact means of securing a measure of the value of the former.

Still another standard, frequently adopted in America in place of either of the above, which he was accustomed to place beside the others, was the Rankine cycle, which differed from the Carnot cycle in the fact that no clearance or compression was assumed,

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[1] "Maximum Contemporary Economy of the Steam-Engine," Transactions of the American Society of Mechanical Engineers, vol. xv. No. dlxxii., p. 313.

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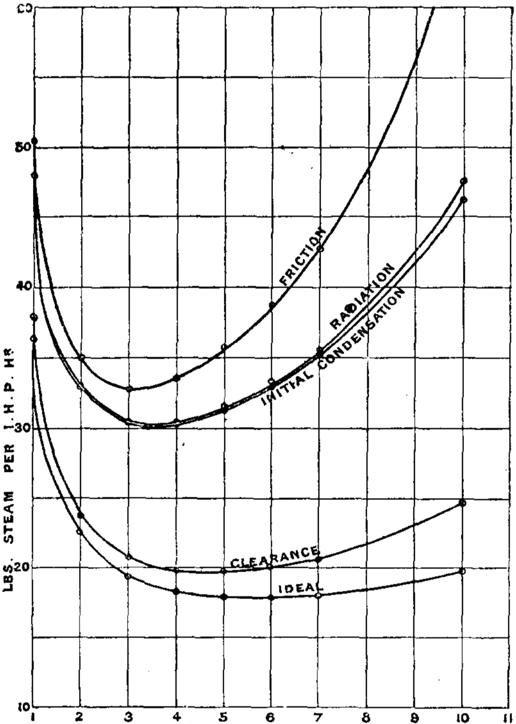
Prof. Thurston.

and also in terminating the expansion-line at the same point with the actual engine under comparison.

The selection of a standard thus became easy; it depended simply upon the purpose sought to be accomplished by the engineer. If the aim was to ascertain what part of the work-equivalent of the energy supplied was utilized, in any case, then an unapproachable ideal of unit efficiency became properly and naturally the standard. If the desire was to ascertain how nearly the engine tested approached an ideal, conceivable but, however closely approachable, never actually attainable, the proper and natural standard to be taken for the case was the Carnot cycle. If, finally, the purpose was to show how closely a certain engine approached the ideal engine of Rankine, one free from all extra thermo-dynamic wastes, and having a similar steam-distribution to that of the actual case, then the efficiency of the Rankine cycle

Fig. 21.



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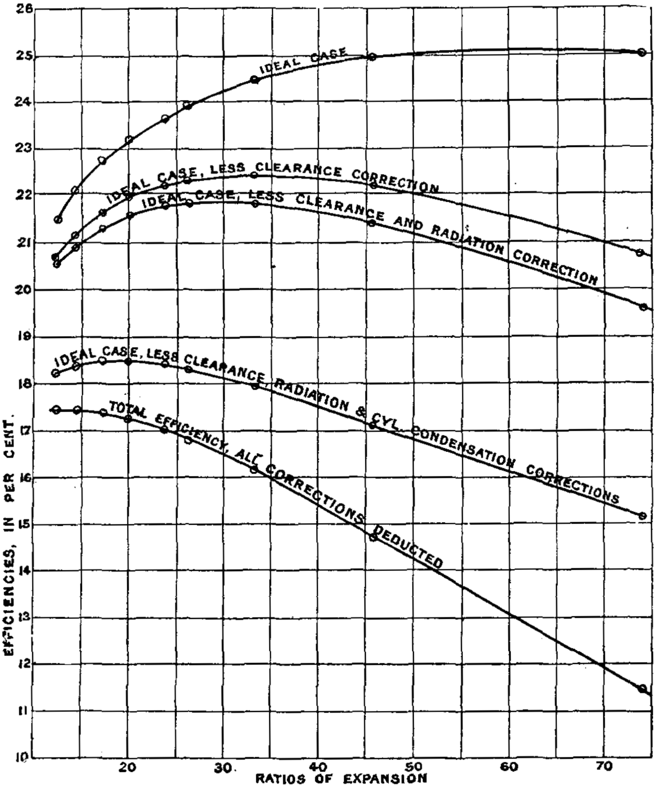
Prof. Thurston.

was taken as the only proper and natural standard. He saw no reason why, for these several purposes, each of these standards should not be strictly defined for use in the particular case, each which it best suited; precisely as the mile, the yard, the foot, or the inch were used as standards of measure.

The employment of such a variety of standards, even in the same work, was often desirable and justifiable, and he had frequently placed such a series in a report to meet the requirements of various readers.[1]

Fig. 22.



As a standard with which to compare the outcome of the numerous tests of all kinds reported by the engineer for miscellaneous purposes, he inclined to the adoption of the Carnot cycle; but he saw no reason why the absolute efficiency should

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[1] Transactions of the American Society of Mechanical Engineers, vol. xv. p. 338.

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Prof. Thurston

not constitute the ultimate reference. The Author's proposed standard of comparison was, in fact, the Carnot cycle, with a conventional displacement of the back-pressure line, and with the introduction of the Rankine idea, no clearance and no compression. He, however, preferred the Carnot or the Rankine, unmodified but precisely defined as to limits. There would seem to be, however, no serious objection to the statement, where it proved for any reasons desirable, of a series of efficiencies, measured against appropriate standards. The restriction to a minimum necessary number, and those of the highest and simplest forms was, nevertheless, most desirable. All measured efficiencies should ultimately give the measure of energy required in heat supplied, rather than in weight of steam, where both were not given.

In the graphical representation of the quantities which determined useful and wasteful expenditures and ideal or real efficiencies, he had for many years been accustomed to employ a system illustrated in *Fig. 21*, which showed the variation of useful and wasted energies of a common Corliss mill-engine of about 200 rated HP., and of 18 inches diameter, and 42 inches stroke of piston, making 85 revolutions per minute, with 100 lbs. per square inch steam-pressure. The economy of the machine was here gauged by the amount of steam consumed, and the various items of total expenditure were given in superposed curves; the magnitude of the ordinate intercepted between each and the next lower curve measuring that particular item indicated in the legend on the curve referred to. The expenditures of a well-known pumping-engine of high efficiency, made up on an absolute efficiency-scale, were shown in *Fig. 22*. The pistons were 18 inches, 32 inches, and 48 inches diameter, with a stroke of 36 inches; it was rated at a capacity of 5,000,000 foot-lbs. in twenty-four hours, and a duty was guaranteed by its builders of 120,000,000 foot-lbs. per 1,000 lbs. of steam supplied from the boilers. Its actual performance was a duty of 128,108,123, foot-lbs. on 100 lbs. of dry coal, for a period of nine months. The diagrams showed clearly the manner in which its various wastes varied with varying conditions of operation as computed by securing from an actual trial, the constants for use in well-established formulas for wastes, and the exact formulas of thermo-dynamics so far as regarded the ideal case.

He esteemed it a privilege to express his appreciation of the elaborate and interesting work of the Author, and to compliment him on the skill with which he had employed a system of graphical illustration, the uses of which could not yet be confidently foretold. It was now many years since Professor J. Willard Gibbs

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Prof. Thurston. in his first Paper, detailed the nature of this thermo-dynamic diagram. To Mr. MacFarlane Gray and the Author was due the distinction of having accomplished much in its adaptation to the discussion of important problems of the steam-engine.

Mr. Wilkinson. Mr. H. D. WILKINSON asked whether the Author's statement, that an engine working with saturated steam returned a greater percentage of the heat-units in effective work than one working with superheated steam, was to be applied generally, or whether he had in mind a particular case of an engine working under some limited conditions.

Capt. Sankey. Captain SANKEY, in reply to the Correspondence, was glad to observe that so many of the correspondents expressed themselves clearly on the advantage there would be in establishing a recognised standard of comparison for thermal efficiency, but pointed out that there was wide disagreement amongst them as to what this standard should be. For instance, Professor Smith remarked (p. 234), "He could find no justification for assuming the 'Carnot' cycle . . . . as the ideally perfect one; or that the aim of enginemakers ought to be to approximate as closely as possible to the Carnot cycle;" whereas Professor Thurston took the opposite view and stated (p. 238), "The engine cycle of highest efficiency . . . . the perfect limit toward which all work of the engineer was expected to constantly approximate . . . . was, of course, the Carnot cycle." A number of arrangements devised by Professor Thurston would, in an engine composed of non-conducting substances, actually give a Carnot cycle; but Professor Smith remarked (p. 236) that "the Carnot process could not be carried out consistently with the development of any HP. at all in the boiler and engine." Many other points were raised in the correspondence to which he would liked to have replied, and there were also many suggestions in respect of the standard of comparison to which he would have referred had he not thought it best to refrain from doing so, seeing that the whole question was now under discussion by a Committee appointed by the Institution; doubtless the various suggestions would be considered by the Committee. He was obliged to Mr. Wilkinson for his question, because he believed there had been some misunderstanding as to his statement at p. 206. That statement has reference only to the standards of comparison when supplied with the same number of heat-units per lb., as was again pointed out at p. 214. It did not follow that an actual engine, using saturated steam, utilized a greater proportion of the heat supplied to it than an engine using superheated steam. As a matter of fact, owing to cylinder condensation, the latter utilized a greater amount than the former.

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