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STEAM ENGINE EFFICIENCY,

BY

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INTRODUCTION.

IN making a comparison between Nature's perfect engine and the steam engine of to-day, it will be necessary to come to some definite understanding as to what we exactly mean when speaking of what we call the "steam engine." In a general way the steam engine consists of different adaptions of cylinder and piston, connecting rod and crank, &c., to the various needs of the marine engineer, the miller, the manufacturer, the traveller, &c. Its function remains the same through its various forms, viz.: to do that which would primarily be accomplished by manual or animal labour. In James Watt's time, the horse was the chief labourer in this country, and he appropriately measured the power exerted by his engine by that which would be performed by a number of horses, and took as the unit of power the work performed by one horse; hence the term *horse-power*. I do not need to tell you that the engine is as incapable of work as a dead horse, and that we require, not only our boiler and a supply of water, but also a certain amount of energy to be applied thereto, before we can consider ourselves fully equipped for the performance of work. This energy we apply in the form of heat, and it matters not how the heat is got or communicated to the water, so long as it is communicated.

As we apply more and more heat to the boiler, the water gets hotter, until at a temperature definitely fixed by the pressure it passes into steam. As we further increase the supply of heat more steam is formed, but it will be no hotter than the water. Let us take a practical example of getting steam at a certain pressure. The pressure is an important factor; you can have as much steam as you like, but if the pressure function is not sufficient to move the piston it is of no use for our purpose. Let the pressure required in this example be 165 lbs., and the temperature of the water supply be 60°. We apply heat energy to the water, which will get hotter and hotter until it arrives at 366°. Now all this expenditure of heat in raising the temperature of the water is still heat energy transferred to the water, and no transformation has yet taken place, and so long as our expenditure of heat remains as heat in the water our engine is still useless and unable to deal with it. As we apply more heat, however, the water gets no hotter, as the heat we are applying disappears as heat; steam is formed, our piston begins to move, and we observe that our engine is now endowed with possibilities. (We can mark also that for a definite amount of heat supplied we get a definite amount of steam formed.) We have seen, then, that while the heat remained as heat in the hot water it was of no use, and neither was the heat in the steam which was no hotter than the water; therefore it must have been the heat which disappeared which has given to our engine its first impulse to movement. Let us endeavour to see what has come over this heat which we say has disappeared. We know that when energy in one form (such as heat) disappears, it has been converted into some other form. We have a great many instruments for measuring energy in its various forms—thermometers, galvanometers, electrometers, &c. Let us try our instrument for measuring energy in the work form, and we shall find that it is the one required for this case.

Our engine itself is the instrument, and it can measure some of the work, and were it perfect it would measure all the work. For the exact amount of heat which disappeared the engine would give out an equivalent amount of energy—what we in practice call I.H.P. I shall go more fully into this in describing Nature's perfect engine; meantime, I wish you to bear in mind where the transformation of energy or conversion of heat into work took place. It took place when the water passed into steam in the boiler and the work was supplied direct to the piston in the steam, and our engine merely *transmitted* the work supplied to it. Now the engine I have been speaking of may either be single, compound, triple, or quadruple, and the point I wish to make is that the energy contained in the steam supplied to the piston is energy in the work form. The piston, piston rod, connecting rod, crank, and shaft conjointly transmit this work. The main steam pipe which leads the steam to the cylinder on the one side of the engine corresponds to the shaft bearings which guide the shaft to the propeller on the other—they are both means whereby the medium containing the work energy is applied. When we desire to measure the work our engine is performing we can either measure the steam applied to the piston, by means of our indicator, or the work leaving our engine by the shaft. There is always a transformation of energy in the conveyance of work. This is well illustrated by the friction of the steam passing through the steam pipe and by the shaft revolving in its bearings—in both cases the transformation is the same, viz. : the conversion of work energy into heat energy.

Further than this fact—the transmission of energy in both cases—we know nothing. To assert that the transmission of energy in the steam pipe is molecular, and in the shaft molar, is merely a matter of terms, and of no value whatever. Energy, we know, is not matter, but is always associated with matter. And it is instructive if not educative to look at the condescension of our modern scientists in dealing with the ideas of Newton, Watt, Carnot, &c., who regarded the different manifestations of energy as forms of imponderable matter, when these very scientists themselves employ an unknown and almost incomprehensible form of matter to bring their various theories into line. I think I have now clearly enunciated my view of the steam engine, and stated what I consider to be its sole function, viz. : to transmit the work supplied by the steam. I have also endeavoured to show that the conversion of heat into work takes place in the boiler, and that the exact quantity of heat that is so transformed is what you will all recognise under the name of "latent heat."

I shall now let the thermodynamists state their case, and try to find from their statements and laws where the conversion of heat into work takes place.

EXTRACTS FROM PROFESSOR COTTERILL'S BOOK ON "THE STEAM ENGINE."

"The object of the book being to study the process of the conversion of heat into work in steam engines, all questions relating to steam boilers, or to the strength and efficiency of the mechanism, or to the adaptation of the engine to the work it has to do, are excluded. Important as these questions are, they are quite independent of the efficiency of the engine, considered as a heat engine, that is to say, a machine for the conversion of heat into work."

"A first important step is made by showing that no better result will be obtained by the use of any other machinery than the ordinary piston and cylinder, or by using many cylinders instead of one, provided that the steam be supplied with heat in the same way."

"When the temperature of a body remains constant during the application of heat, that heat is said to be 'latent.' So long as heat was supposed to be a material substance, such an expression as the 'latent heat of steam' was strictly appropriate ; but if used now, it must be distinctly understood that a part of the heat is latent, not in the steam, but in external bodies in the form of mechanical energy. In this work the term will only be used in the phrase 'latent heat of evaporation,' which has the well-understood conventional meaning defined in Art. 4."

EXTRACTS FROM DR. THURSTON'S BOOK ON "HEAT AS A FORM OF ENERGY."

"A steam engine has been seen to be simply a machine contrived for the purpose of converting the energy of heat motion into mechanical power, and applying that power to useful work."

"Knowing the constitution of the various forms of matter and their differences of molecular relation, and knowing the principles of thermodynamic transformation and applying them to the case in which a substance of known constitution is made the working fluid of a heat engine, we can readily trace the changes which occur in the latter and perceive just how the operation of the engine leads to the production of power, and in what ways the energy supplied in the form of heat is distributed ; and, also, what proportion is available for such purposes, and what is the efficiency of the ideal engine of the prescribed form."

"But the power of the engine lies, not in the steam, but in the heat energy of which the steam is simply the vehicle ; not in the molecules of the fluid, but in the 'living force,' as the older physicists used to call it, of the swing and whirl of the particles in their minute orbits ; not in matter, but in the motion of matter."

"In later forms of engine the steam is introduced into the first cylinder at so high a pressure and temperature that three successive expansions are profitably adopted, and, in some cases, even four. Whatever the form of engine, however, the power of its moving pistons is due wholly to the energy of impact of the less than microscopic molecules of the working fluid, striking repeatedly their millions of blows upon the retreating surface of the piston, and thus surrendering, at each contact, a part of their moving power."

"The power of the steam engine is derived directly from the steam boiler. The boiler of the steam engine is an apparatus designed for the production of heat by the combustion of fuel, and its reception, as in a reservoir, for utilisation, later, in the steam engine, the steam being simply the recipient and storage mechanism, and the vehicle of transmission to the machine in which transformation and application took place."

"Thus the operation of heat storage in the boiler consists of the transfer of a part of the heat as sensible heat, unchanged in its character and method of manifestation, and largely, also, in the transformation of heat into work, and its storage as 'latent' heat, as it is called, without producing any effect upon the temperature of the mass."

"The dynamical effects of heat are, in cases of transfer and of transformation—

"1. Variation of temperature—*i.e.*, of sensible heat energy, or of the energy of molecular vibrations."

"2. Performance of internal work—*i.e.* (*a*), molecular work, which is generally considered to include the preceding; (*b*) intramolecular work—work done by molecular, cohesive, or other forces of attraction; (*c*) interatomic work, or similar work done within the molecules and against the forces of chemical affinity."

"3. External work—*i.e.*, work done against forces acting upon the mass from without."

"The effect of adding heat energy to any substance is thus seen to be, usually, one of simple transfer of a part, and of transformation into other forms of energy of the rest. It heats the body to a higher temperature, and it expands it against internal forces and against external pressures; the first being a case of simple transfer without alteration of method or motion, the second and third being cases of transformation into the potential energy of so-called 'latent' heat, the transformation of heat energy into work, internal and external. The first action is one of increasing intensity of agitation of molecules; the others are of a somewhat similar nature to that observed in the expansion of the steam behind the piston of a steam engine, doing work by conversion of one form of energy into another. The first produces accelaration of velocities of vibration of the constituent particles without change of relative intramolecular distances; the others cause separation of particle from particle, overcoming molecular resistances to separation, without affecting their rates of vibration. The first is a case of increasing actual energy of molecules; the others are the conversion of such energy into work. The first produces increase of sensible heat; the others are illustrations of, in the old and incorrect phraseology of Dr. Black, 'heat becoming latent.' The real nature of 'latent' heat can now be readily seen, and the distinction between that and 'sensible' heat appreciated.

When heat becomes 'latent,' it no longer exists, as Black and his contemporaries supposed, still heat but concealed, to reappear later as sensible heat ; but it has actually ceased to be heat ; it has been converted into some form of potential energy by the performance of work. It illustrates the case of the suspended weight, which, by its descent to the ground, may be made to reproduce the energy which formerly carried it up. It is the consideration of such changes as these and their effects in application to various purposes, useful or other, that constitutes the province and purpose of the science of thermodynamics."

"The vehicle of transfer of the energy of heat from point to point and from body to body is always, when actual contact does not take place, the luminiferous ether ; and this wonderful medium is as essential to the operation of the steam or of the gas engine as to the workings of the solar and stellar systems, to the functions of the universe. It is always on this extraordinary mass, pervading all matter and extending throughout the whole visible universe, that the ceaselessly circulating streams and cycles of radiant energy, upon which we rely for light, for heat, for power, and for life, and every action of transfer of heat in the heat-engine, depend. This mass of imponderable and immeasurable substance, extending into infinity but needing no confining wall ; a mass isolable in space and giving bounds and margin to our perhaps minute portion of infinity ; a solvent for the universe having equal density at centre and at circumference ; a medium of intangible density in which floats, on the forces of gravitation and of mightiest law, all the solar and the stellar aggregations that the telescope can detect or the mind of man conceive ; isolated, necessarily if not co-extensive with God's work, by a wall of space of absolute vacuity across which, very possibly, not a light ray, not a beam of heat, nor the most minute portion of energy capable of appealing to the senses or the physical tests of the human body or the human mind, even, can pass ; a magic, infinite sphere separating the outer space from this wide island universe, and taking its course in the greater and grander infinity beyond, according to laws of which the mind of man has neither knowledge nor conception: this ether is the essential physical element of the whole mechanism, tangible and intangible, of all heat engines, of the steam engine and its related transformers of energy, as of the mechanism of the universe. Every cubic mile of sunlight, according to Sir William Thomson, conveys to us about 12,000 foot-pounds of energy, one-third of a horse-power of energy per minute, and the immeasurable space comprehended within the domain of the luminiferous ether thus stores infinity of energy, some small part of which, some infinitesimal part of which, only, is transformed for the use and preservation of mankind."

"Clausius makes use, in the series of papers which followed during the succeeding year, of two principles, on which are based a very large part of his, at times, somewhat obscure treatment of the subject. The first is simply that of the equivalence of heat and mechanical energy, which is now universally taken as the first law of thermodynamics; the second is the statement that a reversible engine produces as high efficiency as can any form of heat engine whatever, working between the same limits of temperature, a principle which is often given as a second law of thermodynamics. He based his proof upon the principle adopted by Carnot, and already given, only changing the method to make it agree with the later doctrine of equivalence of heat and mechanical energy. He starts with the 'axiom' that 'it is impossible for a self-acting machine, unaided by any external agency, to convey heat from any body to another at a higher temperature.' This statement was modified by Thomson to read, 'It is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects.' The second law of thermodynamics is also sometimes taken as simply the expression of the principle of absolute temperatures. But it is obvious that a law of thermodynamics is not a statement of simple fact, but must be one of the relations of phenomena, and that the second law should be the statement of the second most important principle involved in the construction of the science. Such a law was first stated by Rankine, who makes the second law to be, in substance, that the total action of any quantity of heat in causing transformation of the one form of energy into the other is the sum of the effects of all its parts, and, in another form, the enunciation asserts that heat, as energy, is homogeneous, and that every one of the infinite number of equal parts into which any given quantity of it may be divided will have precisely the same action and the same effect, under given conditions as, will every other. This statement, under whatever form it may appear, is evidently a true statement of law, and, as is used by Rankine in the development of the general equation of thermodynamics together with the first law, it may be taken as a proper expression of the real second law of thermodynamics. It should be said, however, that a large proportion of later writers on the subject follow the other usage."

I trust you are satisfied with the selection of thermodynamic evidence which I have presented to you, and that you recognise in it the type of instruction which figures in our text-books of to-day. I shall now traverse a few of the points in which I differ from this accepted teaching, and I shall leave to you the task of deciding whether the conclusions arrived at are more in harmony with the views of the thermodynamists or with the teachings of your experience.

First. (*a*) The steam engine is a machine for transforming heat into work. (*b*) The steam engine is a machine for transmitting work.

Second. (*a*) The steam boiler is the vessel in which water and luminiferous ether increase the rate of motion. (*b*) The steam boiler is the vessel in which steam is generated from water.

Third. (*a*) The furnace is where the fuel increases its rate of motion in contact with luminiferous ether, and where the innumerable concussions of the molecules produce heat. (*b*) The furnace is where the fuel is burned, and when burning transforms its energy into heat.

Fourth. (*a*) The transmission of heat to water is an increasing of the molecular vibrations. (*b*) The transmission of heat to water is simply a raising of the temperature.

Fifth. (*a*) The heat disappearing in water is an evidence of internal work—molecular motion of various kinds. (*b*) The heat disappearing in water converts the water into steam.

Sixth. (*a*) The passing of water into steam is a change in the constitution of water, viz., into small particles. (*b*) The passing of water into steam is simply a transformation of heat into work.

Seventh. (*a*) The amount of steam formed is the number of water molecules in motion and applied to the engine piston. (*b*) The amount of steam formed is the amount of work supplied to the engine piston.

The working material employed by the thermodynamists for transmitting the energy from the fuel to the piston is the luminiferous ether mixed with molecules and atoms. As the boiler received the energy in the form of material moving or matter in motion, and it is carried all through the different materials as motion and leaves the steam engine by the shaft as motion, I fail altogether to make out any transformation of energy. From the statements and theories of the thermodynamists we gather that these are merely changes of rate and direction of motion, and a transmission of the same form of energy throughout.

On considering the statements I have made, you will observe that none of them are new; they are merely statements of your every-day experience. Regarding the transmission and nature of energy you might expect that I would have some theory, but all I can say is that I know nothing of it, save its manifestations in various forms in the physical world.

When I speak of energy in any form, I mean that it manifests itself in some body or material in a manner to which we give various names, according to the character of the manifestation, such as heat energy or work energy. And it is with these two forms that I wish particularly to deal to-night.

Heat energy, like all other forms of energy, is comparative, and we detect it by its transmission, which is accomplished in two ways, viz.: by conduction, as from one end of a metal bar to the other; or by radiation, as from one body to another of lower temperature at a distance. In my view, the study of heat should have for its object the effects of heat on matter rather than the attempt to explain what heat is. The transformation that takes place when a body is heated; what form the heat energy takes when it disappears or becomes, as we say, "latent"; the making of comparative measurements of equal masses of material energised: these are the problems that seem most in need of solution. The thermodynamists, however, prefer to theorise about the nature of energy. They tell us it is not a material substance; but it is the motion of material substance, and when they find it can be transmitted through space entirely devoid of matter, they invent a specially-constructed medium for its transmission—a medium with all the qualities of matter, but which we are not permitted to call matter, viz.: ether. They endeavour also to prove that heat radiated from a luminous hot body has a different effect on matter from the heat radiated from what is called a "black" hot body, and that all the luminous hot bodies on the earth give out "black" heat, while the sun supplies us with luminous heat; and this they can analyse and arrange in the spectrum as they please. Surely it must be plain that these operations are simple transformations of energy. The points, then, I specially want to emphasise are these: (1) that bodies are endowed with heat energy when they are capable of giving out heat to other bodies, and the passage of heat from one body to another is the transmission of energy; (2) when heat disappears and becomes latent, it has been transformed into some other form of energy.

We may define ENERGY IN THE WORK FORM *as—That form of energy capable of being transmitted by matter in motion.*

It is the only form of energy which is transmitted by the movement of material.

Work energy can only be transmitted by the motion of bodies. Every body endowed with work energy must transmit any given portion of its energy by its movements.

The only material known to transmit the work energy with which it is endowed is recognisable by our senses, and forms part of the earth's mass.

It is conclusive proof that the energy of steam is in the work form if we can transmit the energy in any of our machines for dealing with work ; and we find from experience that in order to get the steam back to water we must either transmit it in the work form in some sort of engine, and if our engine will not transmit all the work, we shall still have what remains in the form of steam. By no process yet discovered can we change steam into water except by transmission of work, or by transforming the work back again into heat energy.

Now, for a moment, let us take the water stored up in the mill dam, which possesses, we all admit, a certain amount of stored-up or potential energy. We can transmit this work from the mill dam through the steam engine in a fairly satisfactory manner by simply making the slide valve suitable for admitting and exhausting water. The energy supplied to our engine from the mill dam would be the height of the fall and the quantity of water, *i.e.*, the pressure and the volume. This we would take as the expenditure, and would measure the work applied in the cylinder and transmitted by the shaft by the same indicators.

Now, when we use steam in our engine, we still measure the work transmitted by the same means and in the same manner, and make our statement of results in work units or indicated horse power. From the foregoing comparison of our steam engine working with water under pressure and with steam under pressure, it is evident that in both cases the energy moving the piston is the same, and is expressed by the product of pressure and volume. Therefore, I conclude that the energy in both cases is energy in the same form, and the operations in both cases are identical, viz., a transmission of energy. In the case of the water, the expenditure of energy is as the volume and pressure of the water supplied, and in the case of the steam, it is measured by the amount of heat that disappeared or became latent when the steam was formed from the water. In the efficiency diagrams before you I have therefore used this quantity as the actual efficiency.

The work supply of all steam engines must necessarily be burdened with the expenditure of the heat supply necessary to raise the temperature of the water from the temperature of the exhaust; but in compound engines this expenditure may be reduced to a very small amount.

STEAM ENGINE EFFICIENCY.

FROM an extensive series of experiments carried out on a large number of compound engines of the triple and quadruple types, during which the water of condensation was measured and the temperatures carefully noted, the information so obtained was compared with the indicated horse-power developed. The results arrived at pointed out the important fact that in all engines of a given type, and working with the same pressures, the quantities of steam used were practically identical, provided they were steam-tight, and the slide valves were so set as to get the full benefit of the steam pressure on the pistons. It was easy to make a definite comparison of the performances by comparing the heat used in a minute, say, with the power developed, and stating the results in the usual form of heat units used per minute per indicated horse-power. Had I tabulated and given you the results of those various experiments, such information would, no doubt, have been interesting to all of you; but beyond this, I am afraid, it could have served no good purpose, but, on the contrary, would probably have diverted your attention from the main object of this paper to side issues. I have, therefore, selected, for the purpose of illustration, a typical case, where the experiments were carried out by one of yourselves, Mr. Alex. Dalrymple, chief engineer of the s.s. "Indramayo." In order to render my explanation of the methods I am now about to propose as clear as possible, it occurred to me, during the progress of the investigations, that the data and results might, with advantage, be put into a tabulated form; all the quantities involved being arranged as nearly as possible in accordance with their natural sequence. The demonstration then takes the form of a minute description and explanation on the quantities contained in each line and column, accompanied by sufficient numerical examples of the working out of each step.

The information which it is the object of this paper to convey to you is not only of great scientific interest in itself, but what is of far more consequence to you and your employers—the ship-owners—it is of much practical value, and will, I venture to hope, lead to less of the valuable energy stored up in our coal being wasted in the steam engine.

The first line contains the pressures of steam in the boilers during the trials, together with the initial pressures on the various pistons, as measured from the cards then taken. The difference between the boiler pressure and the initial pressure on the high-pressure piston appeared to be very small, so that for the sake of simplicity of treatment they are taken as being equal. The boiler pressure steadily remained 1 lb. greater in the first case than in the second. The initial pressure on the mid-pressure piston was the same in both cases. That on the low-pressure piston was 2 lbs. less in the first case than in the second. The pressures in the condenser were practically the same in both cases; being, if anything, slightly greater in the second than in the first case.

On the second line is shown the exhaust pressures. It will be noticed that the "drop" between the high-pressure and mid-pressure engines is 3 lbs., and that between the mid-pressure and the low-pressure engines is 1 lb.

Line (3) contains the ranges of pressure through which the engines work. They are simply the differences between the number on lines (1) and (2); but, being important factors in the calculations to be gone into later on, they are here placed on a line by themselves.

Lines (4), (5), (6), and (7) contain the data from which the quantities on line (8) are calculated. The different distribution of the power given out by the compound engine, as shown in the two cases on this line (8), has an important bearing on what follows; but the discussion of this connection is deferred for the present.

Line (9) contains the principal temperatures whose values are required in the calculations.

Line (10) shows the ranges of temperature in the respective cylinders. These quantities, when viewed in relation to those on line (3), are not without interest. We come now to some important items in our table. Line (11) contains that portion of the energy supply to the engines and condenser, which has been transformed from heat into work. The *engine*, by means of which this transformation is brought about, is the *water*. The major portion of the transformation takes place in the boiler; and for each lb. of the material supplied to the high-pressure engine, 858 heat units have been expended in bringing about this transformation. But although the engine can only deal with this work in the steam or latent heat, as it is termed, nevertheless it is usually, debited with the entire heat expenditure, and accordingly expected to deal with it. Line (12) contains the other portions of these expenditures—the sensible heats. They certainly represent so much heat energy supplied by the fuel; but this part of the outlay, it must be carefully borne in mind, is spent on the water; not on the steam. Steam supplied from a boiler is the same in quality whatever the expenditure of heat may be, provided the pressure is the same. Again it is well to remember that a boiler, to use the term in the limited sense in which it is understood in common parlance, is not the only place about an engine where steam is generated. The heat engine (water), to which allusion has already been made, always works when and where the conditions are favourable. It is this principle which enables us to write down an energy expenditure to the credit of each individual engine in the series, whether the transformation from water to steam has taken place wholly in the boiler, or partly in the boiler and partly in the cylinder, or cylinders, through which the material (H_2 O) has passed on its way to the engine we are considering. Thus the energy supply to the high-pressure engine is made up of 858 heat units in the form of work or steam; but before any of this 1 lb. of material could be put into the form of steam, 145 heat units in the first case, and 237 in the second, had to be transmitted as pure heat, from the burning fuel in the furnace to the water in the boiler. The common practice then is to add these two quantities—the latent and sensible heats, as they are termed—and take the sum as the total heat in the steam *from* the temperature of feed supply *at* the temperature of evaporation. That is to say that—

$H_1 = 858 + 145 = 1003$ heat units in the first case, and

$H_1 = 858 + 237 = 1095$ heat units in the second.

This leads at once to the consideration of an important question—namely, the efficiency of a steam engine. Remembering that every cylinder of a compound engine is a simple engine (see the writer's pamphlet on "Terrestrial Energy"), it will considerably simplify matters to be guided by this fact when examining the point at issue. For example, let us consider the performance and treatment of the high-pressure engine in the two cases given in the table. If we, for the time being, neglect the small difference of initial pressure in the two cases, it is evident that the amount of work which one pound of the steam will transmit to the piston during its passage through this engine must be the same in both cases, other things being equal. Calling this transmitted work w heat units per lb., we have the

Efficiency of high-pressure engine $= \frac{w}{1003}$, in the first case, and $= \frac{w}{1095}$, in the second.

On comparing these two efficiencies of the same engine, we find that the first one is

$$\frac{\frac{w}{1003}}{\frac{w}{1095}} = \frac{1095}{1003} = 1{\cdot}09172 \text{ times}$$

greater than the second; and yet the efficiency of the engine, as a machine for transmitting work, is the same in both cases, because *it transmits equal quantities of work from equal quantities of steam.* This consideration clearly indicates that the expression that is used for representing the efficiency of a steam engine is a highly elastic one; and that for a given quality of steam, worked through a given range of pressure, in a given engine, the expression is not, as is commonly supposed, a simple, but a compound one. It is the product of two factors, one of which is constant, while the other one admits of variation. But this idea can best be exhibited, in the first instance at least, by means of general symbols.

Let L_1 stand for the latent heat of the steam at the temperature, T_1, and T_2, T_3 stand for the temperature of exhaust and feed supply to the boiler respectively; then, as before, we write the

$$\text{Efficiency} = \frac{w}{L_1 + (T_1 - T_3)}.$$

But this is exactly the same thing as saying that the

$$\text{Efficiency} = \left(\frac{w}{L_1}\right) \times \left\{\frac{L_1}{L_1 + (T_1 - T_3)}\right\}.$$

where the first factor is constant, and the second one is variable. Under the conditions assumed, the first factor cannot be interfered with, but the other one may. The factor, $\frac{w}{L_1}$, is the efficiency proper of the engine as a transmitter of work; and the other factor, $\frac{L_1}{L_1 + (T_1 - T_3)}$, is what is put down on the table as the "Expenditure Efficiency" (line 17). Now, since the question of steam engine efficiency turns, not upon how much of the energy in the steam is transmitted, but upon how much is paid for the steam from which this portion of work has been abstracted, it necessarily follows that improvement can only be effected by raising the expenditure efficiency.

In no case can the expenditure efficiency of any actual engine approach unity; since each engine must, in order to perform work, receive its steam at a higher pressure than that at which it exhausts

("Terrestrial Energy"). But for every simple engine there is a possible maximum expenditure efficiency, and if this be attained, other things considered, the engine is as efficient as it can be. To attain this, its feed water must be returned at the temperature of its exhaust ("Terrestrial Energy"). In the general case, already considered, the possible maximum expenditure efficiency $= \dfrac{L_1}{L_1 + (T_1 - T_2)}$;

and this is greater than $\dfrac{L_1}{L_1 + (T_1 - T_3)}$,

so long as T_3 is less than T_2.

If we would improve our engine then, so as to economise fuel, we must aim at making the differences between the exhaust and feed-water temperatures as small as possible.

When we come now to view the compound engine in the light of this knowledge, we see at once what the possibilities of the system are. When we thus take a rational view of it, and find that it is simply two or more simple engines linked together, we see how the definition of a compound engine as given in orthodox treatises on thermodynamics, might be extended a little, to include more than the threadbare statement that "compounding is simply an ingenious device for carrying out a greater range of expansion, with a small variation of stresses"; and, finally, we know *why* the compound engine can be made more economical than a simple one working through the same range of pressure. We can now extend our statement as to the efficiency of a simple steam engine to that of a compound engine by adding that, as the efficiency of the whole depends upon the efficiencies of its parts, so must the efficiency of the compound system depend upon the efficiencies of the individual engines composing it, so that if we would improve the whole we must begin by improving its parts.

We shall now see what practice has to say to this, and for this purpose we shall again refer to the table (lines 11, 12, and 13).

Take the second case first. Here all the engines return their feed-water to the boiler at the same temperature—that of the condenser. The consequence is, that for each lb. of steam supplied to the high-pressure engine, 1095 heat units are paid for it. Now, if we denote by w_1, w_2, and w_3, the heat equivalents of the work transmitted by the respective engines, per lb. of the material passing through them, then the efficiency of the high-pressure engine is $E_1 = \frac{w_1}{1095}$,

Had this engine worked under the same conditions as it would have worked as an isolated simple engine, it would have returned its feed-water at a temperature of 298° instead of 126°. The expenditure would then have been$=858+363—298=923$ units per lb. The engine would have transmitted the same amount of work from the same quantity of steam, but with an efficiency$=\frac{w_1}{923}$, as against $\frac{w_1}{1092}$, which shows that there is the possibility of reducing the expenditure by $1095—923=172$ heat units per lb. of steam supply, thus raising the efficiency of the engine by $\frac{172}{1095} \times 100 = 15{\cdot}7\%$.

We see here, as before, that improvement can only be effected on the expenditure side of the account. Line (17), which contains the expenditure efficiences—these numbers being the ratios obtained by dividing the quantities on line (11) by those on line (13)—shows that the engine we are considering, when working under the conditions peculiar to this case, has the lowest expenditure efficiency in the table, it being only 0·78356, as compared with 0·85543, that of the same engine when subject to the conditions implied in the first case.

The next engine for consideration is the mid-pressure or second of the series. This engine is supplied with the exhaust steam from the one preceding it, the cylinder of which, together with the receiver, discharge, to all intents and purposes, the function of a boiler to the second engine. The difference between the initial and the exhaust temperatures experienced in the high-pressure cylinder, and the consequent reduction of pressure during exhaust, supply the material, and bring about the conditions favourable to the working of the heat engine (water) in effecting a re-transformation of heat into work. This process is known as re-evaporation in the cylinder. The receiver, then, becomes the steam space, from which the second engine draws its supply. The temperature of the steam supplied to the second engine is 298° (line 9), and the latent heat of 1 lb. of it is = 904 ; the feed-water is returned at a temperature of 218° in the first case, and 126° in the second, so that the total heat in 1 lb. of steam supply in the two cases is

$904 + 298 - 218 = 984$, and

$904 + 298 - 126 = 1076$ heat units, respectively. The numbers given in the table (933·6 and 1025·9—line 13) as the total expenditures for this engine, are, of necessity, less than those just calculated, on account of the energy which has been transmitted from the steam in the previous cylinder. An approximate method of calculating the quantities on line (13) will be fully explained and illustrated by examples later on. In the meantime, we shall use them without troubling ourselves as to how they are found. For equal quantities of steam passing through the mid-pressure engine, the work which will be transmitted from it does not differ much in the two cases (the small difference arising from the slightly greater range in the second case than in the first) ; but the expenditure is 933·5 heat units in the first case, and 1025·9 in the second, for this same quantity. The efficiency of the engine, then, under these different circumstances, would be $\left(\frac{1025{\cdot}9 - 933{\cdot}6}{1025{\cdot}9}\right) \times 100 = 9\%$, nearly, higher in the first case. But the reason for the higher efficiency is to be sought for in the fact that the expenditure efficiency (line 17) is 0·91431 in the one case, and only 0·83234 in the other.

As for the low-pressure engine, the conditions under which it returns its feed-water are practically the same in both cases, as is seen on the expenditure efficiency line, where the difference is small, but on the right side, in the first case. The difference arises from the fact that the range of pressure is greater by 2 lbs. in the second case than in the first—the initial pressures being 24 and 22 lbs. abs., whilst the exhaust pressure is the same in both. The effect, then, of supplying this engine with steam at a higher pressure, while its exhaust temperature and that of its feed-water remain the same, is to make it less efficient ; and the element of inefficiency increases as the initial pressure increases. We shall, however, return to this point again, after we have investigated a method for obtaining an approximate measure of the work done by steam in an engine.

The next quantity we come to in the table is the energy supply to the condenser ; but as a full discussion of it involves much that follows, it will more naturally come in for consideration at a later stage. In the meantime, we dismiss it with the remark, that it is much greater in the second case than in the first, and is, therefore, so much more energy thrown away, as is also the opportunity for utilising it.

Seeing that this method of examining the credit account of a compound engine, although strictly logical in character, differs somewhat from that hitherto taught, and will, therefore, be new to most of you, it may be well, before passing on, just to retrace our steps a little and see what information we have obtained thereby.

We have seen that when the system is worked as in the second case, the low-pressure, or last engine in the group, is the only one that enjoys anything like immunity from the evils inherent in such a defective arrangement. It is practically as efficient as it can be, so far as its expenditure is concerned, because it is working under conditions as favourable, or nearly so, as it would have done had it been supplied with steam at the same pressure directly from a boiler instead of from the cylinder of a previous engine. But this freedom from the defects of the arrangement, it is evident, is more the result of necessity than of intelligent design. The defects of such an arrangement are very apparent in the cases of the high-pressure and mid-pressure engines. These engines are saddled with a burden of inefficiency which would be, practically, a vanishing quantity were they isolated. They are made to suffer, as it were, on account of their connection with a system which, when properly understood, is seen to be a hybrid arrangement in the absence of facilities for allowing each individual engine to return its own feed-water under, at least, as favourable conditions as those accidentally enjoyed by the low-pressure engine.

In the first case tabulated, we find traces of the fact that the orthodox course of matters has been interfered with, the result being, as there shown, that the mid-pressure engine is placed on a much better footing in this respect, and, incidentally, so is the high-pressure engine. That this step, though not quite exhausting the possibilities of improvement in the system, is in the right direction, will be made sufficiently manifest by an inspection of the numbers on line (35). Those quantities on the compound engine column of that line are taken from Mr. Dalrymple's own table of results; whilst those on the other columns are the results of roughly dividing out the totals to the respective engines in proportion to their share of the total transmitted work. The totals show that for each indicated horse-power given out by the compound engine, 252·8 heat units of an expenditure are required per minute in the first, and 273·6 in the second case. In other words, by raising the expenditure efficiency of the mid-pressure engine 9%, and consequently that of the high-pressure engine by 8·3%, the actual efficiency of the compound engine is raised $\left(\frac{273{\cdot}6 - 252{\cdot}8}{273.6}\right) \times 100 = 7{\cdot}6\%$.

On line (14), the expenditure credited in each individual instance, as already valued on line (13), is reduced to unity. Line (15) contains that fraction of the expenditure which has undergone transformation from the heat into the work form. Line (16) contains the remaining portion of the expenditure as credited, but which is simply so much heat transmitted, per unit expenditure, to the water from which the steam is formed ; and, therefore, gives a measure of the drag on the respective engines. Line (15) is, of course, numerically identical with line (17) ; but to prevent confusion of ideas, and also to exhibit, clearly, the important proportions the quantities on lines (14) and (15) bear to one another and to the whole, an extra line is added.

Up till now we have treated one phase only of the problem of steam engine efficiency. We have examined the question purely as an expenditure one, without troubling ourselves as to the behaviour of the steam in the engines. During the foregoing investigation, however, we have seen that the question of steam engine efficiency is not, "How much work can be got out of a given expenditure of heat ?" but that it naturally resolves itself into—(*a*) "How much is paid for the steam ?" and (*b*) "How much of the work in the steam does the engine transmit ?"

Now nothing can be more obvious than that the efficiency of a steam engine (to use the term in its ordinary sense), depends on two elements which are absolutely independent of each other. Or, to use the language of the mathematician, the efficiency of a steam engine is a function of two independent variables ; these variables being the answers to the questions (*a*) and (*b*). An injudicious outlay will render the best of engines uneconomical, whilst a bad engine may waste for more than is saved by a minimised expenditure.

We have attempted to give an answer to the first question, or rather, to show how many answers may be given to it, and have roughly traced the effects on the economy of the engine. We shall now take up the second question, and try to furnish, at least, an approximate answer to it also.

If we take the usual expression for the efficiency of an engine,

$$E = \frac{W}{L_1 + (T_1 - T_2)},$$

where w = the thermal equivalent of the work done; L_1 = the latent heat at temperature, T_1; and T_2 is the temperature of the exhaust, which for the present is supposed also to be the temperature of the feed. Supposing this latter assumption to hold all through, then it is evident that if the interval of pressure be taken at 1 lb., the work done without expansion will = $144 \times V_1 \times 1$ foot-lbs. per lb. of steam of volume, V_1 cubit feet. Dividing by 772 to reduce it to heat units, we get

$$W = \frac{144 \times V_1}{772}.$$

Under these circumstances the difference between T_1 and T_2 will become very small, and may, therefore, be neglected in comparison with L_1: then

$$E = \frac{144 \times V}{772 \times L} \text{..............} (A.)$$

The suffixes are suppressed as they are no longer required. Formula (A) is perfectly general, and is "The Efficiency Without Expansion" for any pressure; V and L being the volume and latent heat of 1 lb. of the steam corresponding to that pressure.

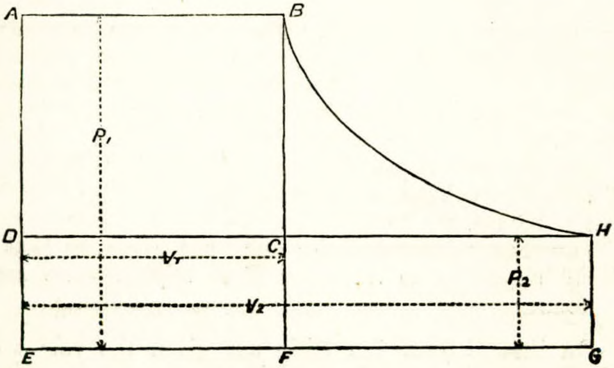
On the accompanying diagrams will be found the values of E for all pressures from 1 lb. up to 250 lbs. per square inch (absolute). They have been calculated for the purpose of facilitating the solution of practical problems on the work done by steam in the cylinder of an engine. On the low-pressure diagram the values of E are given for every 1 lb. up to 25 lbs. On the intermediate-pressure diagram they are given for every 5 lbs. up to 125 lbs., and on the high-pressure one for every 10 lbs. up to 250 lbs. In the latter two cases the average "differences for one" are given, so that a fairly approximate value for E at any pressure may be found.

On line (18) of the table are given the values of E corresponding to the initial pressures of the steam as supplied to the respective engines.

How these factors are to be applied to practical calculations will now be explained. But at the same time, it will be necessary to show upon what ground the proposal for the application rests; and in order to render a fair comparison possible between the merits of the simple formula now to be proposed and those of the well-known expression hitherto used for the same purpose, recourse must be had to general symbols.

Let p_1 = initial pressure of steam (abs.).
p_2 = final ,, ,, ,, ,,
p = any intermediate pressure between p, and p_2
Let V_1 = volume of 1 lb. of steam at p_1 (in cubit feet).
V_2 and V = volumes corresponding to p_2 and p, respectively.

Also, let $d\,v$ stand for any infinitesimally small variation of volume, at a point on the expansion curve whose co-ordinates are p and V. If the ideal indicator diagram of the work done by 1 lb. of steam worked between the pressures p_1 and p_2 be drawn, we get a figure somewhat as follows:—



The rectangle, D E G H, being work done against the back-pressure, p_2, is discounted; the remainder of the area, then, represents the work actually transmitted to the piston. Calling W the work done, then

$$\begin{aligned} \mathrm{V} &= \text{area A B H D.} \\ &= \text{area A B C D} + \text{area B H C.} \end{aligned}$$

Now, $$\begin{aligned} \text{area A B C D} &= \text{A B} \times \text{A D.} \\ &= \mathrm{V}_1 \times (p_1 - p_2), \end{aligned}$$

and, $$\text{area B H C} = \int_{\mathrm{V}_1}^{\mathrm{V}_2} (p - p_2)\, d\,\mathrm{V}.$$

Or, since p_2 is constant—

$$\text{area B H C} = \int_{\mathrm{V}_1}^{\mathrm{V}_2} p\, d\,\mathrm{V} - p_2 \times (\mathrm{V}_2 - \mathrm{V}_1).$$

$$\therefore \mathrm{W} = \mathrm{V}_1 \times (p_1 - p_2) + \left\{ \int_{\mathrm{V}_1}^{\mathrm{V}_2} p\, d\,\mathrm{V} - p_2 \times (\mathrm{V}_2 - \mathrm{V}_1) \right\}.$$

$$\text{or } \mathrm{W} = \mathrm{V}_1 \times (p_1 - p_2) + \int_{\mathrm{V}_1}^{\mathrm{V}_2} (p - p)\, d\,\mathrm{V} \quad \ldots\ldots\ldots\ldots \quad \text{(B)}$$

Now it is evident from an inspection of the figure, and also from the consideration of the positions of B on the ideal diagrams corresponding to the cut-offs adopted in marine engines, that the area B H C is always some fraction of the area A B C D. Stated roughly, the proportion may be taken as varying from 0·2 to 0·8.

Anyone possessing the most elementary knowledge of arithmetic is able to calculate the first term in the above expression for W, that is the area A B C D; but the same cannot be said about the other term (area B H C). The integration of the area B H C has exercised the ingenuity of the two most eminent writers on the thermodynamics of the steam engine. Rankine and Clausius, independently, and about the same time, succeeded in effecting the integration, *approximately.* It may be of some interest to those of you who have not had the opportunity of examining for yourselves the writings of those authors, or who may not have sufficient acquaintance with mathematical language to follow their investigations, to learn something about the nature of the assumptions which each found it necessary to make in order to obtain a solution of this problem.

Both Rankine and Clausius assume the truth of the conversion of energy. The particular case of this general principle which refers to the convertibility of heat into work, is called by Rankine the First Law of Thermodynamics; by Clausius, the First Main Principle. Both seem to have felt the necessity for yet another law, hence the manufacture of one. Rankine assumes that if the absolute temperature of a uniformly hot body, and also the total actual heat in that body, be each broken up into equal little bits, the effect of each of those fragments in causing work to be done is the same. He calls this the Second Law of Thermodynamics. Clausius goes about the business more scientifically. He conceives the existence of a substance which he calls a Perfect Gas; writes down the characteristic equations of this substance; combines this with the equation embodying the First Main Principle; and with characteristic analytical skill deduces an expression; generalises it; then labels it the Second Main Principle. Lastly, both writers implicitly assume, although they do not seem to attach much importance to this assumption, that the material of which the cylinder and piston is made, cannot be heated or cooled, and is a perfect non-conductor of heat.

Setting out with the assumption that the steam engine was a machine for *transforming* heat into work (that is a *heat engine*), they found, after constructing their equations, in conformity with that view, the result to be rather a heterogeneous mixture of pressures, volumes, latent heats, and temperatures. The result was, of course, that no solution could be obtained in the absence of more experimental data or more laws. The former were not at hand, so a law was created.

By means of a corollary to this law, the pressures and volumes were eliminated from the equations, and then a solution became possible. The resulting formula was very gratifying to the thermodynamic school, because it may be expressed entirely in terms of the absolute temperatures between which the engine works.

The formula thus deduced for calculating the area A B H D of the ideal diagram is for initially dry steam—

$$W=772\times\left\{L_1+T_1-T_2-T_2\times\left(\frac{L_1}{T_1}+\log.\frac{T_1}{T_2}\right)\right\}.$$

This is the form in which it was given by Rankine.

Clausius, however, took the more general case, by supposing the heat supply to the engine to be partly steam and partly hot water. Let 1 lb. of the material be made up of x lbs. of steam and $(1-x)$ lbs. of water ; then the equation becomes

$$W=772\times\left\{x\times L_1+T_1-T_2-T_2\times\left(\frac{x\times L_1}{T_1}+\log.\frac{T_1}{T_2}\right)\right\}.$$

When the difference between T_1 and T_2 is not great, the hyperbolic logarithm of $\frac{T_1}{T_2}$ is usually replaced, by an approximate expression, $\frac{2\times(T_1-T_2)}{T_1+T_2}$.

Making this substitution and reducing, we get Rankine's formula—

$$W=772\times\left\{\frac{T_1-T_2}{T_1+T_2}+\frac{L_1}{T_1}\right\}\times(T_1-T_2)\ldots\ldots\ldots\ldots(1)$$

Treating that of Clausius in the same way, we have

$$W=772\times\left\{\frac{T_1-T_2}{T_1+T_2}+\frac{x\times L_1}{T_1}\right\}\times(T_1-T_2)\ldots\ldots\ldots(2)$$

By writing for L_1 its value $1437-{\cdot}7\times T_1$, in formula (1), we get that form of it well known to marine engineers, namely—

$$W=772\times\left\{\frac{T_1-T_2}{T_1+T_2}+\frac{1437\cdot}{T_1}-{\cdot}7\right\}\times(T_1-T_2)\ldots\ldots\ldots(3)$$

Formula (3), although the one most commonly used, is not adapted for the calculation of the work done by the same quantity of material passing successively through two or more cylinders, as in the compound or triple-expansion engines, unless the whole system be considered as one large engine. But this, we know, is a highly erroneous proceeding, and is sure to give equally erroneous results.

If, however, it be desired to calculate the work done by the separate engines, then formula (2) is the one which must be used. When the value of x is known to begin with, W may be calculated for the first engine. From the value of W thus determined, together with the "total heat" supplied to this engine, x for the second engine may be found, and so on. The process thus indicated is rather complicated, and involves considerable labour, and more knowledge of algebraical operations than most practical engineers possess. We have no wish either to occupy your time or our space by needless calculations, which anyone may verify for himself from the data given on the accompanying table; but we have carefully worked out the necessary calculations just mentioned, using the data given with the second case on the table, where the whole quantity of material passes through each engine in succession. The following are the results arrived at:—

For the first, or high-pressure engine—

$$\frac{\text{Work calculated by formula}}{\text{Work transmitted by engine}} = 1{\cdot}3.$$

For the second, or mid-pressure engine—

$$\frac{\text{Work calculated by formula}}{\text{Work transmitted by engine}} = 1{\cdot}5.$$

For the third, or low-pressure engine—

$$\frac{\text{Work calculated by formula}}{\text{Work transmitted by engine}} = 1{\cdot}8.$$

These results sufficiently speak for themselves. No wonder that the performance of an ordinary steam engine, with its cast-iron cylinder, and its cast-iron or steel piston, should fall short of that of the ideal "heat engine," with its piston and cylinder constructed of material which has no existence outside the thermodynamic mind; and which, moreover, required the creation of a special law to explain its behaviour.

Since the time when that formula first saw light, there have been many carefully carried out experiments on steam engines, and much valuable information gained thereby. No matter how contradictory some of the results so obtained may be, there is one fact more or less established by all, and that is, that there is more steam passing through the engine than is accounted for on the indicator cards. Recent writers on the thermodynamics of the steam engine have taken notice of this; it may be discovered in their works by the name of the "missing quantity."

In no instance do we find any of those writers attempting to modify the formula so as to come nearer the truth, or in any way attempting to make use of the large mass of experimental data now at hand to construct another one, at least approximately accurate, and moderately simple; one that would be of some service to the practical engineer, and, at the same time, not too difficult to apply. What although it be empirical, so long as it is simple and fairly truthful? The most valuable formulas the engineer possesses are empirical. Take, for example, Regnault's simple formula for the latent heat in steam: the engineer, by the use of a thermometer, and by performing a simple sum in arithmetic, can tell, in a few seconds, how much energy is in his steam. Examples like this might be multiplied indefinitely; but that is foreign to the object of this paper, which is an attempt to provide the engineer with a simple method whereby he may, with no other further information outside of what he gets from his indicator and thermometer, and the application of a little arithmetic, be able to arrive at an approximate estimate of some things he would like to know.

Another fact which comes out very strikingly, more especially in marine engine practice (which alone concerns us), is that the actual indicator diagram bears very little resemblance to its prototype the ideal one. This is not of very general importance; but as it has some little connection with what follows, it is well to mention it here.

If we reproduce here, for the sake of reference and comparison, the formulas, (B) and (2),

$$W = V_1 \times (p_1 - p_2) + \int_{V_1}^{V_2} (p - p_2)\, d\,V, \text{.........................} (B),$$

$$W = 772 \times \left\{ \frac{T_1 - T_2}{T_1 + T_2} + \frac{x \times L_1}{T_1} \right\} \times (T_1 - T_2), \text{............} (2),$$

we have, then, two expressions for the area, A B H D, of the ideal diagram. The first one gives the value of W in terms of the quantities with which the engineer is most familiar. But before he can apply it, the second term must be evaluated.

This is effected by assuming that the equation of the expansive curve on the ideal diagram is of the form,

$$p\,V^n = \text{a constant.}$$

The integration is then accomplished by expressing p in terms of V by means of this equation. When this is done and a little reduction made, equation (B) becomes

$$W = V_1 \times (p_1 - p_2) + \left\{ \frac{p_1 V_1}{n-1} \times \left(1 - \left[\frac{p_2}{p_1}\right]^{\frac{n-1}{n}} \right) - p_2 \left(V_2 - V_1 \right) \right\} \text{....} (C).$$

The term in the large brackets still represents the area B H C, and, as is easily seen, is an exceedingly complex expression, and very difficult to apply. If n were constant, matters would be a little simplified; but it is not so. When the general value of n is deduced from equation (2), with the help of a few minor assumptions, it is found not only to vary with each particular case, but to have a different value for each point on the same curve, and differs according to the wetness or dryness of the steam. Many mean values have been proposed for the index n, varying from 0·8 to 1·135. Zeuner has examined a large number of cases, and concludes, therefrom, that a fairly approximate value for n is given by the formula,

$$n = 1{\cdot}035 + \frac{x}{10},$$

where x is the weight of "dry" steam per lb. of the initial supply.

But even admitting a knowledge of the true value of n, we have seen that the formula, as it stands, does not in any sense, represent facts. It appears to come nearer the truth the higher the pressures; but this is appearance only. The real reason lies in the fact that high-pressure steam is much more efficient as a motive power than an examination of the formula would lead one to anticipate. If, then, formula (C) is to be of any use for the requirements of the engineer, it must either be reconstructed or considerably modified; and if, in effecting the necessary modification, the formula can, at the same time, be simplified, "the end will justify the means."

Now, by a careful analysis of the imformation obtained from the series of experiments with compound marine engines, already referred to at the commencement of this paper, it is found that the work *theoretically* gained by expansion is, in practice, lost by condensation. That is to say, if we take the area, A B H D, of the ideal indicator diagram to represent the total theoretical amount of work which could be obtained from 1 lb. of steam worked expansively between the pressures p_1 and p_2, theory says that the gain due to expansion is represented by the area B H C; but experiment shows that this gain is neutralized by losses, principally due to condensation; and that if the engine be steam-tight, and the valve set so as to maintain the full steam pressure during admission, the one becomes almost an exact measure of the other.

This, then, provides us not only with a clue to the nature, but also with the measure, of the correction that is necessary to render formula (C) a more truthful symbolical statement of the quantitative effect of steam worked in a metal cylinder.

Quantitatively speaking, then, we have

$$\left\{ \frac{p_1\ V_1}{n - 1} \left(1 - \left[\frac{p_2}{p_1} \right]^{\frac{n-1}{n}} \right) - p_2\,(\mathrm{V}_2\ \mathrm{V}_1) \right\} = 0, \text{ and}$$

therefore, $\mathrm{W} = \mathrm{V}_1 \times (p_1 - p_2)$……………………(D).

This virtually amounts to the same thing as saying that the area of the actual indicator card is equal to the area A B C D of the theoretical diagram. Qualitatively speaking, this result has already been shadowed forth in the propositions bearing on the subject on pp. 7 and 8 of "Terrestrial Energy." The substance of those propositions is that only a portion of the steam entering the cylinder of an engine is shown on the indicator cards. That what is shown on the cards performs the theoretically possible amount of work. That the difference between the total quantity entering the engine and that accounted for by the cards, is proportional to the difference of the initial and exhaust temperatures taken in conjunction with the weight of steam used per unit of time, and the extent of the surface to which the steam is exposed.

For a given range of temperature, and a given area of surface, it is evident that the percentage of condensation, arising from the abstraction of heat by the surface exposed, will vary inversely as the weight of steam admitted. For a given weight of steam, the percentage of condensation will vary conjointly with the area of surface exposed, and the difference of temperatures. The time of contact being considered unity all through, such as, for instance when the variations here discussed are those occuring during the passage of steam through a compound engine. The re-evaporation during exhaust is a transformation of heat into work, but the water deposited on the metal of the cylinder during admission is the engine, and the heat in the metal, due to initial condensation, is the source, from which that heat engine draws its supply. When the engine has been at work for some time, and attained its normal conditions, the re-evaporations is a fair measure of the previous condensation. But this is not all the condensation that takes place in the cylinder. When the steam expands and transmits its work to the piston, an amount of condensation, equivalent to the work done, must take place. Hence, if we suppose there to be no external supply of heat, we see that all the energy in the steam, minus the transmitted work, is (neglecting the small effects of conduction and radiation) exhausted as latent heat.

We see, then, why it is that, in a multiple-cylinder engine, where decreasing ranges of pressure are accompanied by increasing falls of temperature, and where a diminishing quantity of actual steam is exposed to an increasing area of metal surface, the results should differ from those calculated for an hypothetical engine, with its cylinder made of imaginary material, and also why it is that the differences should get wider as we descend the scale.

We have no intention of propounding any theory to explain these phenomena. We simply accept them as facts, and content ourselves by trying to get some measure of them. In a rough sort of way this has been accomplished, with the result as already stated.

It only remains now to illustrate the application of the deduction to the solution of practical problems. For this purpose we shall take the data and results of Mr. Dalrymple's tests, given on the accompanying table. When the pressures are per square inch, equation (D) becomes $W = 144 \times V_1 \times (p_1 - p_2)$. But by equation (A)

$$E = \frac{144 \times V_1}{772 \times L_1}$$

Substituting, we get

$$\left.\begin{aligned} W &= 772 \times E \times L_1 \times (p_1 - p_2).\ \text{ft.—lbs.} \\ &= E \times L_1 \times (p_1 - p_2).\ \text{heat units.} \end{aligned}\right\} \cdots\cdots\cdots (E).$$

Now, E and L_1 may be obtained from the diagrams, and the conditions of the problem will supply the remaining factor. Formula (E) as it stands gives the work transmitted by the engine per lb. of steam passing into it. Since this transmission can only take place from the energy in the steam (the latent heat), and is independent of what has been paid for it (the total heat), we get, by dividing out L_1, the actual efficiency of the engine as a transmitter of work—

$$\frac{W}{L_1} = E \times (p_1 - p_2) \cdots\cdots\cdots\cdots (F).$$

If it be required to know what fraction of the work in the steam is transmitted by the engine, (F) is the formula to use; but if it be required to compare this with the price paid for it, then, as already explained, this expression must be multiplied by the expenditure efficiency. When this is done, the result is the ordinary expression used for the efficiency of an engine—

$$\frac{W}{L_1} \times \frac{L_1}{L + T_1 - T_3} = \frac{W}{L_1 + T_1 - T_3}.$$

when T_3 is the temperature of the feed-water.

This formula is of little use to the engineer, who, with only that information which he obtains from the indicator and the thermometer, has not sufficient data to apply it. To be able to do so, it would be necessary to measure the feed-water accurately, and to know the state of the steam as to its "wetness." But, as was stated at the outset, it is found that all engines working under the same conditions as to pressure, &c., practically use the same quantities of steam. If, then, we consider the formula (F), not in the narrow sense as the efficiency of the engine only, but as representing that fraction of the total energy supply which the engine transmits, and consider the energy supply to be unity when the feed-water is supplied to the boiler at the temperature of the hot-well, we have all the materials for solving problems without troubling ourselves about the state of the steam, or how much of it is passing into the engines. This method enables us to discount all considerations but the transmission of energy, and being of real value to the practical engineer, will be explained as simply and as clearly as possibly in the examples that follow. Take the second case first; it is rather simpler to deal with than the other.

On line (18) we have the efficiency without expansion (which we shall always denote by E) for 1 lb. of difference at 159 lbs. abs. (the initial pressure in the high-pressure cylinder)—

$$E = 0{\cdot}000609.$$

The range of pressure $(p_1 - p_2)$, (line 3), is 91.

Hence the work—

$$E \times (p_1 - p_2) = 0{\cdot}000609 \times 91 = 0{\cdot}05542.$$

In the same way, the values of $E \times (p_1 - p_2)$ for the mid-pressure and the low-pressure engines are calculated and given on line (19). The energy supply to the first engine is taken as unity, so that 0·05542 stands for that engine's share of the transmitted work; and, therefore, the energy supply to the second engine = 1—0·05542,
= 0·94458.

From this the second engine transmits a portion
= 0·05320 × 0·94458,
= 0·05025.
The work supply to the third engine
= 1 — 0·05542 — 0·05025,
= 0·94458 — 0·05025,
= 0·89433,
from which it transmits its share
= 0·06540 × 0·89433,
= 0·05849,
so that the energy exhausted into the condenser
= 0·89433 — 0·05849,
= 0·83584.

The total work transmitted by the compound engine is the sum of these quantities calculated for the separate engines,
= 0·05542 + 0·05025 + 0·05849,
= 0·16416.

The results thus calculated are all given on the table. The numbers on line (20) give the quantity of material passing through the engines. We call it H_2O, as it may be partly water. It is unity for each engine in this case, as the whole quantity passes through each in succession. Line (21) gives the work supply to each engine ; and line (23) the portion of the total transmitted by each, and by all.

If all the energy possessed by the steam could be taken out of it, one indicated horse-power would require heat units equivalent to 33,000 ft. — lbs. = $\frac{33000}{772} = 42{\cdot}75$ per minute ; but if only a fraction of this energy be transmitted, we must divide 42·75 by the fraction in order to arrive at the expenditure per indicated horse-power, thus—

Heat units per minute per indicated horse-power is for—

$$\text{High-pressure engine} = \frac{42{\cdot}75}{0{\cdot}05542} = 771{\cdot}39.$$

$$\text{Mid-pressure engine} = \frac{42{\cdot}75}{0{\cdot}05025} = 850{\cdot}74.$$

$$\text{Low-pressure engine} = \frac{42{\cdot}75}{0{\cdot}05849} = 730{\cdot}89.$$

$$\text{Compound engine} = \frac{42{\cdot}75}{0{\cdot}16416} = 260{\cdot}41.$$

These results are given on line (34) ; and on line (35) the measured values are given for comparison.

It will be seen that the calculated results differ slightly from those obtained by measurement ; but this is principally due to irregularities in the distribution of the steam during the periods of admission.

The aggregate result obtained by measurement was 273·6 heat units per minute per indicated horse-power. Hence calculation differs from measurement by $\left(\frac{273{\cdot}6 - 260{\cdot}41}{273{\cdot}6}\right) \times 100 = 4{\cdot}8\%$.

Line (36) contains these results expressed in terms of the steam used per hour per indicated horse-power. They are calculated on the assumption that the steam supplied from the boiler contains no suspended moisture. The total expenditure per lb. will in that case be = 1095 heat units, so that the compound engine will require $\frac{260{\cdot}41 \times 60}{1095} = 14{\cdot}26$ lbs. of steam per hour per indicated horse-power. By measurement it used 15·02 lbs. (line 37). The other quantities given on this line have been proportioned out to the respective engines according to the power given out by each.

We shall now take up the other case given on the table.

On line (18), under the high-pressure engine, we have E=0·000606.
From line (3) $(p^1 - p_2) = 92$ lbs. Hence, when energy supply is taken as unity, the transmitted work by the high pressure engine=0·000606×92
=0·05575.
The work supply to the second engine is, therefore,
=1—0·05575
=0·94425.

From lines (3) and (18) we get $(p_1 - p_2) = 42$ lbs., and E = 0·00133 ∴ E × $(p_1 - p_2)$ = 0·00133×42= 0·05586. The mid-pressure engine, therefore, transmits a portion of the work supply=0·05586×0·94425 =0·05275; and exhausts the remainder—
= 1 — 0·05575 — 0·05275,
= 0·94425 — 0·05275,
= 0·89150.

At this stage of the operations, part of the steam supply is abstracted from the low-pressure receiver, sufficient in quantity to heat the feed-water returning from the condenser, and thus allow the mid-pressure engine to return its feed a little nearer the temperature of its exhaust than formerly. The temperature of the water coming from the condenser (the feed-heater for the low-pressure engine)=126° F., and its temperature on leaving the feed-heater was observed to be 218° F. The temperature of the steam in the low-pressure receiver was=233° F., and its latent heat=950 units per lb.

Let n stand for the weight of steam thus abstracted from each lb. supplied to the low-pressure receiver. The remainder $(1 - n)$ lbs., passes into the low-pressure engine, thence into the condenser, and back to the heater, where its temperature is raised from 125° to 218° = 92°. The heat thus absorbed $= 92 \times (1 - n)$ units. The total heat in 1 lb. of steam at 233°, measured from 218°, is $= 950 + 233 - 218 = 965$ units. Therefore, on the assumption that the loss of heat on the one hand is equal to the gain on the other, we get the following equation for finding n:—

$$
\begin{aligned}
& 965 \times n = 92 \times (1 - n), \\
& \qquad\quad\; = 92 - 92 \times n, \\
\text{or,}\quad & 1057 \times n = 92, \\
\therefore\quad & n = \frac{92}{1057} = 0{\cdot}08704 \text{ lbs.}
\end{aligned}
$$

The work supply to the low-pressure engine is therefore

$$
\begin{aligned}
&= 0{\cdot}89150 - 0{\cdot}08704, \\
&= 0{\cdot}80446,
\end{aligned}
$$

from which it transmits a portion

$$
\begin{aligned}
&= 0{\cdot}06282 \times 0{\cdot}80446, \\
&= 0{\cdot}05054,
\end{aligned}
$$

and exhausts to the condenser the remainder,

$$
\begin{aligned}
&= 0{\cdot}80446 - 0{\cdot}05054, \\
&= 0{\cdot}75392.
\end{aligned}
$$

Adding these results, we get the total fraction of work transmitted by the compound engine from the energy supply from the boiler,

$$
\begin{aligned}
&= 0{\cdot}05575 + 0{\cdot}05275 + 0{\cdot}05054, \\
&= 0{\cdot}15904,
\end{aligned}
$$

as given on line (22) of the table.

The immediate effect, then, of allowing the mid-pressure engine to return its feed at a higher temperature than formerly is to reduce the total transmitted work by $0{\cdot}16416 - 0{\cdot}15904 = 0{\cdot}00512$ units per lb. But if the energy supply from the boiler be unity when the feed-water is supplied to it at 126°, involving an expenditure = 1095 heat units, it is evident that for the same supply of heat from the fuel, when the feed-water is supplied to the boiler at 218° instead of 126°, and only requiring 1003 heat units to heat and evaporate 1 lb. of it, the energy supply will be increased in the ratio $\frac{1095}{1003}=1\cdot09172=1+$the increment.

In the former case we had unity supply of material passing through each engine in succession and thence into the condenser. In this case, before taking into account the above increment, it is unity to the high-pressure and to the mid-pressure engines, and to the heater, but $1-0\cdot09704=0\cdot91296$ to the low-pressure engine and to the condenser. To get the incremental quantity of material, the incremental work supply, and also the incremental transmitted work, it is only necessary to multiply the quantities on lines (20), (21), and (22) by 0·09172. This has been done and the results given on lines (23), (24), and (25). Then by adding lines (20) and (23); lines (21) and (24); and lines (22) and (25), we get the totals given on lines (26), (27), and (28).

It will be seen that the work now transmitted by each engine is:

0·06086 by the high-pressure engine.
0·05760 ,, mid-pressure engine.
0·05518 ,, low-pressure engine.

The total for the compound engine being

$$=0\cdot06086+0\cdot05760+0\cdot05518,$$
$$=0\cdot17364.$$

The fraction actually transmitted by the engine was $=0\cdot16910$.

Expressed in heat units per minute, the calculation gives,

$$\frac{42\cdot75}{0\cdot17364}=246\cdot19 \text{ per indicated horse-power.}$$

The actual quantity used was, in this case, found to be = 252·80 per indicated horse-power. The difference between calculation and measurement is, therefore, $= 252\cdot8-246\cdot19$,

$=$ 6·61 heat units per minute per indicated horse-power, or about 3% of the measured quantity. The effect, then, on the economy of the compound engine, of introducing another feed-heater into the system, is to raise the general efficiency $\left(\frac{273{\cdot}6 - 252{\cdot}8}{273{\cdot}6}\right) \times 100 = 7{\cdot}6\%$ on its former actual performance; and $\left(\frac{260{\cdot}41 - 246{\cdot}19}{260{\cdot}41}\right) \times 100 = 5{\cdot}4\%$ on its former performance as deduced by calculation. Considering the importance of the foregoing investigations and experimental results as a contribution to the subject of steam engine efficiency, there appears to be ample justification for pushing the examination one step farther.

We have, all along, laid great stress on the fact that each cylinder of a compound engine is a simple engine. We shall now examine briefly the effect on the general efficiency, of allowing the high-pressure, mid-pressure, and low-pressure engines to work as simple engines of ordinary efficiency.

As before, let the quantity of energy supply which is obtained from a given expenditure of heat units when the feed-water is put into the boiler at the temperature of the condenser be taken as unity; and suppose the conditions to be those given in case first on the table.

$$\text{Work transmitted by high-pressure engine} = 0{\cdot}05575$$
$$\text{Energy exhausted} = 1 - 0{\cdot}05575$$
$$= 0{\cdot}94425.$$

The feed-water returning from the mid-pressure engine is at the temperature of the steam in the low-pressure receiver = 233°, and has to be heated to that of the mid-pressure receiver = 298°. The latent heat at 298° is 904. Let n_1 stand for the weight of steam required to heat $(1 - n_1)$ lbs. of water from 233° to $298° = 65° =$: then

$$904 \times n_1 = 65 \times (1 - n)$$
$$\therefore \qquad n_1 = \frac{65}{969} = 0{\cdot}06708 \text{ lbs.}$$

The weight of material (H_2 O) to the mid-pressure engine $= 1 - 0{\cdot}06708$,
$= 0{\cdot}93292$;

and the work supply (steam or latent heat)

$$=0\cdot93292\times0\cdot94425,$$
$$=0\cdot88691.$$

Work transmitted by the mid-pressure engine

$$=0\cdot05586\times0\cdot88691,$$
$$=0.04954\,;$$

and energy exhausted from

$$=0\cdot88621-0\cdot04954,$$
$$=0\cdot83737.$$

Sufficient steam is here again taken away to heat the returning feed of the low-pressure engine from 126° to $233^\circ=107^\circ$. Let n_2 be the quantity required. The latent heat at 233° is 950 ; and the weight of water returning from the condenser $=(1-n_1-n_2)$ lbs.

$$=(0\cdot93292-n_2)\ \text{,,}$$

Hence, n_2 must be such that

$$950\times n_2=107\times(0\cdot93292-n_2),$$

or

$$n_2=\frac{0\cdot93292\times107}{1057},$$
$$=0\cdot09444\text{ lbs.}$$

The quantity of material to the low-pressure engine is, therefore, $=0\cdot93293-0\cdot09444$

$$=0\cdot83848\,;$$

and the energy supply is

$$=0\cdot83848\times0\cdot83737$$
$$=0\ 73212,$$

from which this engine transmits a quantity

$$=0\cdot06282\times0\cdot70212$$
$$=0\cdot04411.$$

The feed-water now enters the boiler at 298° instead of 126°, involving an expenditure = 923 units instead of 1095 as formerly. Hence the energy supply from an expenditure of 1095 will $=\frac{1095}{923}=1\cdot18634$.

The work transmitted by the compound engine is then $=1\cdot18634\times(0\cdot05575+0\cdot04954+0\cdot04411)$,

$$=1\cdot18634\times0\cdot14940,$$
$$=0\cdot17724$$

The engine will, therefore, transmit work at the rate of $\frac{42\cdot75}{0\cdot17724}=241\cdot19$ heat units of expenditure per minute per indicated horse-power.

Throughout the foregoing investigations, there is one fact which has been fairly well verified, and that is that the higher the pressure between which the engines work, the higher are their actual efficiencies as transmitters of work. If, then, three numbers, *a*, *b*, and *c*, can be obtained such that

Efficiency of the high-pressure engine : efficiency of the mid-pressure engine : efficiency of the low-pressure engine :: *a* : *b* : *c*,

it is evident that the most economical arrangement, so for as the distribution of power is concerned, will be that which most nearly approaches the proportion—

Indicated horse-power of high-pressure engine : indicated horse-power of mid-pressure engine : indicated horse-power of low-pressure engine :: *a* : *b* : *c*.

But in order to get values for *a*, *b*, and *c*, some standard of comparison is necessary. It is not sufficient to know only how much of the energy in the steam *is* transmitted by any one of the engines; but we must know also how much *would* be transmitted by the most perfect engine working under the same conditions as to pressure The ratios, then, of the former to the latter quantities for the several engines will be proportional to *a*, *b*, and *c*. In "Terrestrial Energy," the performance of Nature's perfect engine is investigated, and it is there shown that this engine, working with its perfect and continuous system of feed-heating, has an expenditure efficiency, and also a transmission efficiency, both equal to unity. The expenditure in its boiler is simply the latent heat at the temperature of evaporation (T_1), and its exhaust is zero. The engine works between the absolute temperatures, T_1 and T_2, which are connected by an equation deduced on page 23 of that book. The thermal equivalent of the work transmitted between those two temperatures is the latent heat, L_1; but if the operation were stopped at some temperature higher than T_2, some of the energy in the steam would be exhausted, so that the work done would necessarily be less than L_1. Let T_0 = the temperature of exhaust, and U = the work done between T_1 and T_0; then replacing T_2 in the first equation given on the page just quoted, by T_0, we have

$$U = \left(\frac{T_1 - T_0}{T_1}\right)L_1 + (T_1 - T_0).$$

$$= (L_1 + T_1)\left(\frac{T_1 - T_0}{T_1}\right).$$

Dividing by L_1, the expenditure, we get the

$$\text{Perfect engine efficiency,} = \frac{U}{L_1}$$

$$= \frac{(L_1 + T_1)\ (T_1 - T_0)}{T_1\ L_1}.$$

This is the general equation of the curves of Nature's perfect engine efficiency given on the accompanying diagrams. On these diagrams the origin of each curve is the pressure corresponding to the temperature of the exhaust; ordinates give the initial pressures, and abscissae give the perfect engine efficiency for work transmitted between those two pressures. On line (30) of the table are given the values of these efficiencies, due to the ranges through which the respective engines work. If these quantities be divided into the corresponding quantities on line (19), we get the actual comparative efficiencies of the engines; which ratios are given on line (31).

If we suppose the total indicated horse-power developed by the compound engine to be represented by unity, we get then a very simple method for ascertaining the direction in which economy might be looked for in the distribution of power by adjusting matters so as to get the largest proportionate share out of the best engine, and *vice versâ*. Dividing the actual indicated horse-power of each engine by the total power given out by the compound engine, we get the numbers given on line (33).

Thus in first case given, the total indicated horse-power = 2118, so that the proportional indicated horse-power of—

The high-pressure engine $= \frac{720}{2118} = 0{\cdot}33994.$

„ mid-pressure „ $= \frac{681}{2118} = 0{\cdot}32153.$

„ low-pressure „ $= \frac{717}{2118} = 0{\cdot}33853.$

„ compound „ $= \frac{2118}{2118} = \underline{\underline{\overline{1{\cdot}00000}}}.$

In the second case, the total indicated horse-power $=2148$, and therefore, proportional indicated horse-power of—

The high-pressure engine $= \frac{688}{2148} = 0.32029.$

„ mid-pressure „ $= \frac{627}{2148} = 0{\cdot}29185.$

„ low-pressure „ $= \frac{883}{2148} = 0{\cdot}38786.$

„ compound „ $= \frac{2148}{2148} = \underline{\underline{\overline{1{\cdot}00000}}}.$

If now we take the comparative efficiencies (line 31), and add them, we have

$$\begin{aligned}\text{sum} &= 0{\cdot}37796 + 0{\cdot}36583 + 0{\cdot}31490,\\ &= 1{\cdot}05869 \text{ for the first case, and}\\ \text{sum} &= 0{\cdot}37685 + 0{\cdot}37845 + 0{\cdot}30942,\\ &= 1{\cdot}06472 \text{ for the second case.}\end{aligned}$$

Now, dividing each number by the sum as we have done with the actual powers, we get the following proportional numbers for the first case :—

$\frac{0{\cdot}37796}{1{\cdot}05869} = 0{\cdot}35700$ for high-pressure engine.

$\frac{0{\cdot}36583}{1{\cdot}05869} = 0{\cdot}34555$ „ mid-pressure „

$\frac{0{\cdot}31490}{1{\cdot}05869} = 0{\cdot}29745$ „ low-pressure „

$\frac{1{\cdot}05869}{1{\cdot}05869} = \underline{\underline{\overline{1{\cdot}00000}}}$

For the second case the numbers are—

$\frac{0{\cdot}37685}{1{\cdot}06572}=0{\cdot}35394$ for high-pressure engine.

$\frac{0{\cdot}37845}{1{\cdot}06472}=0{\cdot}35545$,, mid-pressure ,,

$\frac{0{\cdot}30942}{1{\cdot}06472}=0{\cdot}29061$,, low-pressure ,,

$\frac{1{\cdot}06472}{1{\cdot}06472}=\underline{\underline{\overline{1{\cdot}00000}}}$

The ratios just calculated may be taken as the values of *a*, *b*, *c*. Now, writing out the proportions, measured and calculated, we have, in the first case—

Indicated horse-power of the high-pressure engine: indicated horse-power of the mid-pressure engine: indicated horse-power of the low-pressure engine :: 0·33994 : 0·32153 : 0·33853.

Whereas if the indicated horse-power of each engine were proportional to its actual comparative efficiency, we should have—

Indicated horse-power of the high-pressure engine : indicated horse-power of the mid-pressure engine : indicated horse-power of the low-pressure engine :: 0·35700 : 0·34555 : 0·29745.

In the second case, the measured powers are—Indicated horse-power of the high-pressure engine : indicated horse-power of the mid-pressure engine : indicated horse-power of the low-pressure engine :: 0·32029 : 0·29185 : 0·38786 ;

And the calculated—Indicated horse-power of the high-pressure engine : indicated horse-power of the mid-pressure engine : indicated horse-power of the low-pressure engine :: 0·35394 : 0·35545 : 0·29061.

Collecting these results into a form more suitable for examination, we have, for the first case—

Measured I.H.P. of H.P. engine = 0·33994 } ratio =
Calculated ,, ,, ,, = 0·35700 } 0·95221
Measured ,, M.P. ,, = 0·32153 } ratio =
Calculated ,, ,, ,, = 0·34555 } 0·93048
Measured ,, L.P. ,, = 0·33853 } ratio =
Calculated ,, ,, ,, = 0·28745 } 1·13810

For the second case—

Measured I.H.P. of H.P. engine = 0·32029 } ratio =
Calculated ,, ,, ,, = 0·35394 } 0·90492
Measured ,, M.P. ,, = 0·29105 } ratio =
Calculated ,, ,, ,, = 0·35545 } 0·82107
Measured ,, L.P. ,, = 0·38786 } ratio =
Calculated ,, ,, ,, = 0·29061 } 1·33464

The former arrangement of power approaches the calculated proportions more nearly than does the latter. The effect of this better approximation to the theoretical proportions, on the general economy of the compound engine, has been sufficiently made evident in what has gone before.

It must be recollected that when any engine in the series is interfered with, in this respect, such interference affects both terms of the ratios for all the engines in the series; and if the initial pressure of the high-pressure and the exhaust pressure of the low-pressure engines remain constant, the interference, if in the direction we have been considering, tends to reduce the inequality in these terms. Still, the ratios, when calculated for any given state of matters, will always indicate the direction in which improvement is possible. In the cases taken for illustration, the first is rather better than the second; but still there is room for improvement yet, and in the same direction. The low-pressure engine has more than its legitimate share of the power; the other two engines have less. If not only the low-pressure and mid-pressure engines, but the high-pressure engine also, were allowed to work as ordinary simple engines, the general efficiency of each, and, consequently, of all, considered as a compound system, would be raised, and the proportion of power given out by each engine would make a still closer approximation to that deduced by calculation.

During the reading of the foregoing, when page 41 of the original proof was reached, the author suggested that the remaining portion be held as read, and concluded by making the following remarks:—

I shall not prolong my remarks further, as I have already taken up sufficient of your time, and the concluding portion of the paper is of such a nature that it could not be well followed on a mere reading. I wish to say, however, that all standards of efficiency of the steam engine are purely empirical; and this applies also to the diagrams you hold in your hands and to the multipliers represented on the margin as equal to E. Their special claim on your attention is, that they coincide with actual results more closely than those now in use. They are, besides, simpler, and can be used by anyone after going over a numerical example. Printed examples are now in course of preparation, and will be sent to members of the Institute on completion

The mathematical arguments on which they are founded are entirely apart from their usefulness, and are not suited for discussion in public meeting, such as this of our Institute. Any communication on them, however, addressed to me, either personally or through our Hon. Secretary, will have my best attention. I have to thank you for your patient hearing on what I fear has been a rather dry and complicated subject.

STEAM ENGINE EFFICIENCY.

ADJOURNED DISCUSSION, MR. A. BELDAM, PRESIDING.

THE HONORARY SECRETARY.

Previous to entering upon the further discussion of MR. WEIR's Paper, it may be well to make a few comments, and also to refer to the several suggestions and criticisms which have been offered for the Author's consideration, and to which we have received his reply.

The various points and questions introduced into the Paper and the many practical considerations to which it gives rise have naturally provoked a good deal of criticism in respect to the theories advanced by the Author. While Members may differ widely from MR. WEIR in reference to some of the views he has advanced, it is our privilege to do so, and while many may, as individual members, pass independent opinions and judgment on what is at variance with accepted theories, and what may be considered, and may possibly, be proved to be erroneous, we may all glean several grains of good, practical and wholesome thought by careful perusal of the Paper. The publication of this, or any Paper by the Institute, does not imply an acceptance of the views or theories advanced by the Author. Members are invited to read, question, and discuss all Papers, and to weigh the remarks made upon them, bringing independent thought to discriminate, and to judge accordingly, what is most profitable to retain.

Referring to the suggestions and criticism, MR. GRAY considered that the position Mr. WEIR occupied in the foremost rank of modern improvers of the marine engine, entitled him to be listened to as an authority when he addressed us on Steam Engine Efficiency, but it was submitted that he should have before his mind very definitely the distance there was between the generally accepted teaching and his statements, so that he might reduce that distance, perhaps by explaining wherein, and how, these differences in thought were justified.

Passing over suggested alterations in forms of expression, about which there might be expected to be differences in minds, arising from differences in training, it was held that the omission of a copy of the mean indicator diagrams, upon which the experimental deductions had been calculated, detracted very much from the value of the Paper.

It was pointed out that the ratio of the latent heat at the highest temperature to the total expenditure of heat adopted on page 18, as "Expenditure Efficiency," appeared to be an artificial distortion of the hitherto accepted ratio stated on the previous page as "Efficiency," and that no good and sufficient reason was given for creating a difference between "Efficiency" and "Expenditure Efficiency," terms which could only suggest the same idea to the mind of any engineer.

The calculation of the efficiency of each engine, in a series, as if it were not one in a series, appeared likely to lead to confusion of thought; for instance, on page 20, where the increase of efficiency was made out to be 15·7% instead of 18·6%.

It was said that hardly could it be accepted as a defect in the arrangement of the series engine, as stated on pages 22 and 23, that each engine was not "supplied with steam at the same pressure directly from a boiler instead of from the cylinder of a previous engine."

"The efficiency without expansion, for any pressure," on page 25, when extended in the form of its thermodynamical equivalent was, substantially:—

$$E = \frac{144V}{772L} = \frac{dt}{Tdp}$$

It was contended that in this form it could at once be seen that E was made to be a function of the magnitude of the arbitrary fundamental units employed; that "efficiency" must be always a purely numerical ratio, independent of the magnitudes of the fundamental units employed in ascertaining it. It was remarked that perhaps Mr. WEIR was mixing up "duty" and "efficiency" in his expressions, terms that must be held to be quite distinct. What the (A) expression denoted was—the Carnot function for any temperature for the cycle between P and P–1 when the pressure is in pounds per square inch. The utility of this expression was not apparent.

On page 32, there was an expression given for the work done by the engine on the assumption that the expansion curve is of the form

$$PV^n = \text{a constant.}$$

It was also pointed out that this equation had been frequently investigated in all its developments at several of our meetings, and the value of whad been frequently stated to be

$$W = \frac{n}{n-1}(P_1V_1 - P_2V_2),$$

an expression which could scarcely be looked upon as of the exceeding complex nature complained of. Members were reminded that this equation would be found several times in the Paper on Compressed Air, and the discussion on it, and that it was easily derived from the equation of condition given. In the equation (C) the term $V \times (P_1 - P_2)$ ought to be omitted, and the remainder, the complex part, was then equal to W in the simple form given in the Paper referred to. Another peculiarity occurred on page 34, where the Author remarked that to render

(c) a more truthful statement of the quantitative effect of steam worked on a metal cylinder, we must regard these remaining terms=nothing. That is to say, in the value of W in equation (C), the terms V_1 $(P_1 - P_2)$ arose from an error in the integration, and ought to be wiped out, and the rest of the terms make up nothing, so that the conclusion reached in equation (C) was, that in any steam engine the work done under any condition was always just equal to nothing, as the $V_1 \times (P_1 - P_2)$ had no right to be in (C) there was, therefore, no reason why it should appear in (D), which was (C) with the nothing part wiped out.

That on page 45 there was another expression given for the work done. This was stated to be the general equation of the curves of Nature's perfect engine upon which the graphic tables or diagrams had been constructed. The Author had not intimated that he meant this to be quite different from the equations of Clausius, Rankine, and that of the Marine Engineers. To be in accordance with the last, which was an understood approximation to the others, it ought to read, writing it in a form suitable for comparison with the Author's expressions:—

$$U = \left(L_1 + T_1 \times \frac{T_1 - T_0}{T_1 + T_0}\right) \left(\frac{T_1 - T_0}{T_1}\right)$$

instead of $$U = (L_1 + T_1) \frac{T_1 - T_0}{T_1}$$

A numerical example was given thus:—

$$U = \left(861 + 822 \times \frac{822 - 585}{822 + 585}\right) \times \left(\frac{822 - 585}{822}\right) = 287 \cdot 9$$

$$U = (861 + 822) \times \frac{822 - 585}{822} = 484 \cdot 9.$$

The first case being according to previous teaching, the second line in accordance with the Author's formula.

Copies of these comments and objections were distributed along with proof copies of the Paper, and having been desired to consider these in time for the discussion this evening, Mr. Weir's reply is as follows :—

In answer to the first remark, I may say that it was quite unnecessary to bring more definitely before my mind the distance there is between the generally accepted standpoint and my own. No one is better aware of the gulf than myself, and a little perception would have enabled anyone to see that my precise reason for quoting the statements of Professors Cotterill and Thurston was in order to show the distance that existed between our views: and my purpose in this paper has not been to reconcile my views with those of Professors Cotterill and Thurston, but to show how practical results, for which they are unable to account satisfactorily, can be easily and correctly explained by any engineer.

2. On page 14 are given my reasons for not putting in the indicator diagrams. The engines of the s.s. "Indramayo" were used merely as a particular case to show the application of the Nature's Engine diagrams. To reproduce the indicator diagrams might give rise to discussion on Mr. Dalrymple's experiments, which in no way affect the paper.

3. As to the the terms "Efficiency" and "Expenditure Efficiency," I think that a more careful perusal of the paper will show a just and sufficient reason for the distinction made.

4. If the percentage taken exception to in this note be worked out it will be found quite correct. All percentages given in the paper are calculated on the same principle and mean simply so much saving of expenditure. This is made sufficiently clear by the context.

5. The opinion expressed here is the result of a total misapprehension of the whole of that part of the paper to which it refers.

This reply may provoke further comment, as indeed it is desirable that it should.

In the proof copies of the Paper which have been distributed, Mr. Weir has since explained that certain errata appeared, and as some of the Remarks were based upon the formulæ involved, these are here specially noted to prevent misconceptions.

Page 32 Equation C. should read:—

$$W = V_1 \times (p_1 - p_2) + \left\{ \frac{p_1 V_1}{n-1} \times \left(1 - \left[\frac{p_2}{p_1} \right]^{\frac{n-1}{n}} \right) - p_2 (V_2 - V_1) \right\}$$

Page 34 First Equation should read:—

$$\left\{ \frac{p_1 V_1}{n-1} \left(1 - \left[\frac{p_2}{p_1} \right]^{\frac{n-1}{n}} \right) - p_2 (V_2 - V_1) \right\} = 0$$

STEAM ENGINE EFFICIENCY.

Supplementary Paper Read at Cardiff.

In an important subject such as that of this paper, considering the principles involved and the bearing that these have upon modern physics, I have thought it necessary to make a separation into two distinct portions, viz., one dealing with matter of a purely empirical nature; the other with statements having a general bearing on the science of the steam engine, and accepted as general principles. Taking the latter first, we may enumerate them thus:—

1. There is only one quality of steam. It may be superheated, but it cannot be cooled below the temperature due to the pressure.

2. As much work can be got from exhaust steam (see 1) as from steam taken direct from a boiler, provided the pressure is the same.

3. The value of steam is in direct proportion to its pressure.

4. Heat in the engine, unless under the form of mechanical energy (latent heat) of steam, is not only a loss, but is the exact measure of the loss.

5. The whole quantity of steam (shown by the indicator) performs the theoretically possible amount of work, but this quantity does not represent the whole of the steam that enters the cylinders.

6. This difference is due to condensation; but condensation is due to two distinct causes—(1) to work done; (2) to contact with metal. The second is a source of loss, for we have heat appearing (see 4) during condensation, and being absorbed during exhaust in re-evaporation. The amount condensed is equal to the amount absorbed, plus the equivalent of transmitted work.

7. The proportion between the total quantity of steam admitted and that shown on the card depends on the difference of initial and exhaust temperatures, and the weight of steam used per minute taken in relation to the surface exposed.

8. The efficiency of every engine depends on getting the initial or boiler pressure on the piston as near as possible, and returning the feed-water as near the exhaust temperature as possible.

9. Every cylinder of a compound engine is a simple engine.

10. Every steam engine to perform or transmit work must receive steam at a greater pressure than that at which it exhausts; and each simple engine must exhaust, for only a small proportion of the work in the steam can be used, whatever the pressure and expansion may be.

11. All the heat put into the boilers from the fuel (radiation and conduction waste excepted), less that heat which has its equivalent in transmitted work, must be exhausted as the energy (latent heat) of steam.

12. The steam engine is a machine for transmitting work.

13. Heat disappearing in water converts the water into steam, and is a transformation of heat energy into work energy. The engine that performs this transformation is the water, and the efficiency of this engine is absolutely perfect.

The practical application of the foregoing principles to the steam engine (of any form or design), in the present state of our knowledge, can only be empirical; and all the data of which we are in possession is derived solely from experience.

The empirical assumption may be enunciated thus:

The actual work transmitted by an ordinary steam engine bears a constant ratio to the initial volume multiplied by the difference between the initial and exhaust pressures.

In the examples as tabulated (1st table) a slight liberty has been taken, viz., instead of simply taking the initial volume and multiplying it by the difference of pressure and allowing for the transmitted work, E has been taken from the diagrams and the allowance then made for the transmitted work.

There is still another simple application, *i.e.*, to take E from the diagram and make no further allowance for transmitted work. In making a choice between these three ways for application and comparison with the actual engine, to have taken the first, might have led some to think it more than empirical. By adopting the second, which is furthest from truth, because it makes too great an allowance for transmitted work, this surplus allowance would soon have shown up when practically applied, and have led to an investigation into the nature of E. This is a point I should like discussed by scientists, as it is one of the points which has some scientific bearing on the subject; it is, however, of no practical use to the marine engineer.

After giving the merits of the first, careful consideration, I propose to discard it in the meantime, and to advocate the adoption of the method which takes E simply and makes no further allowance for transmitted work than that already taken into account in the construction of E.

This course, I believe, will not interfere with the general bearing of the assumption, and will form a fixed standard of comparison.

When applying the transmitted work formed in this manner, to find the heat units used per minute, and the lbs. of steam used per hour per indicate horse-power, the total heat expended to produce the steam at the initial pressure is to be measured from the temperature of the exhaust. The feed-water should be at the same temperature as the exhaust.

The following are some simple numerical examples illustrative of the methods just indicated :—

To calculate the efficiency of steam at 40 lbs. abs. when worked in a *simple* engine down to 3 lbs. abs.

Initial pressure on piston = 40 lbs. abs.
Final ,, ,, = 3 ,,
Range of ,, ,, = 37 lbs.

At 40 lbs. abs., $E = 0{\cdot}0020687$,
$\therefore$ Efficiency $= 0{\cdot}0020687 \times 37$
$= 0{\cdot}0765$.

To calculate the efficiency of steam at 40 lbs. abs. when worked in a *compound* engine down to 3 lbs. abs.

When the total range of pressure and the number of cylinders through which the steam is to be worked are known, then the portion of that total range which should be allotted to each simple engine in the series may be determined by means of the curves in the Diagrams as follows :—The perfect engine efficiency corresponding to the given total range of pressure is read off the Diagrams; this number is then divided into as many parts as there are cylinders in the system; these parts being proportioned in the same ratios as the desired efficiencies off the steam in the respective cylinders. The ranges of pressure corresponding to these constituent perfect engine efficiencies are those satisfying the required conditions.

If, however, it be desired that the steam shall have its maximum total efficiency for the given systems, then, obviously, matters must be adjusted so as to have *equal* efficiences for the steam worked in each individual simple engine in the series. To secure this, the perfect engine efficiency corresponding to the total range must be divided into as many *equal* parts as there are cylinders.

This latter method will be adopted in what follows, as it is the *best* performance of the steam in each case that is wanted for the purpose of comparison.

Perfect engine efficiency corresponding to range of pressure from 40 lbs. to 3 lbs. abs. = 0·308.

Ranges corresponding to perfect engine efficiencies $=\frac{0{\cdot}308}{2}=0{\cdot}154$ are

40 lbs. to 12·5 lbs. abs., and
12·5 ,, 3·0 ,, therefore

Initial pressure on high-pressure piston = 40·0 lbs. abs.
Final ,, ,, ,, ,, = 12·5 ,,
Range of ,, ,, ,, ,, = 27·5 lbs.

At 40 lbs. abs., E = 0·0020687,
∴ Efficiency of steam at 40 lbs. abs. worked in a simple engine down to 12·5 lbs. abs.
= 0·0020687 × 27·5
= 0.0568.

Initial pressure on low-pressure piston = 12·5 lbs. abs.
Final ,, ,, ,, ,, = 3·0 ,,
Range of ,, ,, ,, ,, = 9·5 lbs.

At 12·5 lbs. abs., E = 0·00592,
∴ Efficiency of steam at 12·5 lbs. abs. worked in a simple engine down to 3 lbs. abs.
= 0·00592 × 9·5
= 0·0562.

Hence total efficiency of steam at 40 lbs. abs. worked in a *compound* engine down to 3 lbs. abs.
= 0·0568 + 0·0562
= 0·1130.

To calculate the efficiency of steam at 40 lbs. abs. when worked in a *triple* engine down to 3 lbs. abs.

Ranges of pressure corresponding to a perfect engine efficiency $=\frac{0{\cdot}308}{3}=0{\cdot}103$ are

40 lbs. to 19 lbs. abs.,
19 ,, 8 ,,
8 ,, 3 ,, therefore

Initial pressure on high-pressure piston = 40 lbs. abs.
Final ,, ,, ,, ,, = 19 ,,
Range of ,, ,, ,, ,, = 21 lbs.

At 40 lbs. abs., E=0.0020687,
∴ Efficiency of steam at 40 lbs. abs. worked in a simple engine down to 19 lbs. abs.
=0·0020687 × 21
=0·0434.

Initial pressure on mid-pressure piston=19 lbs. abs.
Final ,, ,, ,, ,, = 8 ,,
Range of ,, ,, ,, ,, =11 lbs.
At 19 lbs. abs., E=0·0040394,
∴ Efficiency of steam at 19 lbs. abs. worked in a simple engine down to 8 lbs. abs.
=0·0040394 × 11
=0·0444.

Initial pressure on low pressure piston=8 lbs. abs.
Final ,, ,, ,, ,, =3 ,,
Range of ,, ,, ,, ,, =5 lbs.
At 8 lbs. abs., E=0·0088399,
∴ Efficiency of steam at 8 lbs. abs. worked in a simple engine down to 3 lbs. abs.
=0·0088399 × 5
=0·0442.

Hence total efficiency of steam at 40 lbs. abs. worked in a *triple* engine down to 3 lbs. abs.
=0·0434+0·0444+0·0442
=0·1320.

Comparing the efficiencies of steam at 40 lbs. abs. when worked in different types of engines down to 3 lbs. abs.

In a simple engine, total efficiency=0·0765.
,, compound ,, ,, =0·1130.
,, triple ,, ,, =0·1320.

To find the efficiency of steam at 80 lbs. abs. when worked in a *simple* engine down to 3 lbs. abs.

Initial pressure on piston=80 lbs. abs.
Final ,, ,, = 3 ,,
Range of ,, ,, =77 lbs.

At 80 lbs. abs., E=0·0011158,
∴ Efficiency of steam at 80 lbs. abs. worked in a *simple* engine down to 3 lbs. abs.
=0·0011158 × 77
=0·0859.

To find the efficiency of steam at 80 lbs. abs. when worked in a *compound* engine down to 3 lbs. abs.

Perfect engine efficiency corresponding to range of pressure from 80 lbs. to 3 lbs. abs.=0·415.

Ranges of pressure corresponding to perfect engine efficiency $=\frac{0·415}{2}=0·208$ are

80 lbs. to 20 lbs. abs., and
20 ,, 3 ,, therefore

Initial pressure on high-pressure piston=80 lbs. abs.
Final ,, ,, ,, ,, =20 ,,
Range of ,, ,, ,, ,, =60 lbs.

At 80 lbs. abs., E=0·0011158,
∴ Efficiency of steam at 80 lbs. abs. worked in a simple engine down to 20 lbs. abs.
=0·0011158 × 60
=0·0669.

Initial pressure on low-pressure piston=20 lbs. abs.
Final ,, ,, ,, ,, = 3 ,,
Range of ,, ,, ,, ,, =17 lbs.

At 20 lbs. abs., E=0·0038605,
∴ Efficiency of steam at 20 lbs. abs. worked in a simple engine down to 3 lbs. abs.
=0·00386051 × 7
=0·0656.

Hence total efficiency of steam at 80 lbs. abs. worked in a *compound* engine down to 3 lbs. abs.
=0·0669+0·0656
=0·1325.

To find the efficiency of steam at 80 lbs. abs. when worked in a *triple* engine down to 3 lbs. abs.

Ranges of pressure corresponding to perfect engine efficiency $=\frac{0{\cdot}414}{3}=0{\cdot}138$ are

80 lbs. to 32 lbs. abs.,
32 „ 11 „
11 „ 3 „ therefore

Initial pressure on high-pressure piston = 80 lbs. abs.
Final „ „ „ „ = 32 „
Range of „ „ „ „ = 48 lbs.

At 80 lbs. abs., E = 0·0011158,
∴ Efficiency of steam at 80 lbs. abs. worked in a simple engine down to 32 lbs. abs.

$$=0{\cdot}0011158\times48$$
$$=0{\cdot}0535.$$

Initial pressure on mid-pressure piston = 32 lbs. abs.
Final „ „ „ „ = 11 „
Range of „ „ „ „ = 21 lbs.

At 32 lbs. abs., E = 0·0025392,
∴ Efficiency of steam at 32 lbs. abs. worked in a simple engine down to 11 lbs. abs.

$$=0{\cdot}0025392\times21$$
$$=0.0533.$$

Initial pressure on low-pressure piston = 11 lbs. abs.
Final „ „ „ „ = 3 „
Range of „ „ „ „ = 8 lbs.

At 11 lbs. abs., E = 0·0066226,
∴ Efficiency of steam at 11 lbs. abs. worked in a simple engine down to 3 lbs. abs.

$$=0{\cdot}0066226\times8$$
$$=0{\cdot}0530.$$

Hence, total efficiency of steam at 80 lbs. abs. worked in a *triple* engine down to 3 lbs. abs.

$$=0{\cdot}0535+0{\cdot}0533+0{\cdot}0533$$
$$=0{\cdot}1598.$$

Comparing the efficiencies of steam at 80 lbs. abs. when worked in different types of engines down to 3 lbs. abs.

In a simple engine, total efficiency = 0·0859.
„ compound „ „ = 0·1325.
„ triple „ „ = 0·1598.

To find the efficiency of steam at 160 lbs. abs. when worked in a *simple* engine down to 3 lbs. abs.

Initial pressure on piston = 160 lbs. abs.
Final „ „ = 3 „
Range of „ „ = 157 lbs.

At 160 lbs. abs., E = 0·0006066,
∴ Efficiency of steam at 160 lbs. abs. worked in a *simple* engine down to 3 lbs. abs.

$$= 0{\cdot}0006066 \times 157$$
$$= 0{\cdot}0952.$$

To find the efficiency of steam at 160 lbs. abs. when worked in a *compound* engine down to 3 lbs. abs.

Perfect engine efficiency corresponding to range of pressure from 160 lbs. to 3 lbs. abs. = 0·536.

Ranges corresponding to perfect engine efficiency $= \frac{0{\cdot}536}{2} = 0{\cdot}268$ are

160 lbs to 35 lbs. abs., and
35 „ 3 „ therefore

Initial pressure on high-pressure piston = 160 lbs. abs.
Final „ „ „ „ = 35 „
Range of „ „ „ „ = 125 lbs.

At 160 lbs. abs., E = 0·0006066,
∴ Efficiency of steam at 160 lbs. abs. worked in a simple engine down to 35 lbs. abs.

$$= 0{\cdot}0006066 \times 125$$
$$= 0{\cdot}0758.$$

Initial pressure on low-pressure piston = 35 lbs. abs.
Final „ „ „ „ = 3 „
Range of „ „ „ „ = 32 lbs.

At 35 lbs. abs., $E=0{\cdot}0023325$,
$\therefore$ Efficiency of steam at 35 lbs. abs. worked in a simple engine down to 3 lbs. abs.

$$=0{\cdot}0023325\times32$$
$$=0{\cdot}0746.$$

Hence, total efficiency of steam at 160 lbs. abs. worked in a *compound* engine down to 3 lbs. abs.

$$=0{\cdot}0758+0{\cdot}0746$$
$$=0{\cdot}1504.$$

To find the efficiency of steam at 160 lbs. abs. when worked in a *triple* engine down to 3 lbs. abs.

Ranges of pressure corresponding to perfect engine efficiency $=\frac{0{\cdot}536}{3}=0{\cdot}179$ are

160 lbs. to 55 lbs. abs.,
55 „ 15 „ and
15 „ 3 „ therefore

Initial pressure on high-pressure piston = 160 lbs. abs.
Final „ „ „ „ = 55 „
Range of „ „ „ „ = 105 lbs.

At 160 lbs. abs., $E=0{\cdot}0006066$,
$\therefore$ Efficiency of steam at 160 lbs. abs. worked in a simple engine down to 55 lbs. abs.

$$=0{\cdot}0006066\times105$$
$$=0{\cdot}0637.$$

Initial pressure on mid-pressure piston = 55 lbs. abs.
Final „ „ „ „ = 15 „
Range of „ „ „ „ = 40 lbs.

At 55 lbs. abs., $E=0{\cdot}0015584$,
$\therefore$ Efficiency of steam at 55 lbs. abs. worked in a simple engine down to 15 lbs. abs.

$$=0{\cdot}0015584\times40$$
$$=0{\cdot}0623.$$

Initial pressure on low-pressure piston = 15 lbs. abs.
Final „ „ „ „ = 3 „
Range of „ „ „ „ = 12 lbs.

At 15 lbs. abs., $E=0{\cdot}0049993$,

∴ Efficiency of steam at 15 lbs. abs. worked in a simple engine down to 3 lbs. abs.

$$=0{\cdot}0049993\times 12$$
$$=\underline{\underline{0{\cdot}0600}}.$$

Hence, total efficiency of steam at 160 lbs. abs. worked in a *triple* engine down to 3 lbs. abs.

$$=0{\cdot}0637+0{\cdot}0623+0{\cdot}0600$$
$$=\underline{\underline{0{\cdot}1860}}.$$

Comparing the efficiencies of steam at 160 lbs. abs. when worked in different types of engines down to 3 lbs. abs.

In a simple engine, total efficiency $=0{\cdot}0952$.
„ compound „ „ $=0{\cdot}1504$.
„ triple „ „ $=0{\cdot}1660$.

To put these results into a concrete form it is only necessary to remember that the expenditure of heat must be calculated for each simple engine individually, and should be measured from the initial and exhaust pressures. The expenditure is, therefore, made up of the difference between the initial and exhaust temperatures, added to the latent heat at the initial temperature. This is the minimum expenditure; but if the actual expenditure, which will always be greater, is known, then it must be taken instead of the minimum.

The minimum expenditure between 40 lbs. abs. and 3 lbs. abs. $=1052$;

∴ Steam required by a simple engine working through this range $=\dfrac{2565}{0{\cdot}0765\times 1052}=\dfrac{2565}{80{\cdot}47}=\underline{\underline{32}}$ lbs. per hour per indicated horse-power.

Heat efficiency (rate of expenditure)

$=\dfrac{42{\cdot}75}{0{\cdot}0765}=\underline{\underline{558{\cdot}8}}$ heat units per minute per indicated horse-power.

For compound engine working from 40 lbs. abs. down to 3 lbs. abs. minimum expenditures are:—995 for the high-pressure engine, and 1032 for the low-pressure engine;

∴ Steam required by high-pressure engine $=\frac{2565}{0\cdot0568\times995}=\frac{2565}{56\cdot5}=\underline{\underline{45\cdot3}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for high-pressure engine $=\frac{42\cdot75}{0\cdot0568}=\underline{\underline{752\cdot6}}$ heat units per minute per indicated horse-power.

Steam required by low-pressure engine $=\frac{2565}{0\cdot0562\times1032}=\frac{2565}{58}=\underline{\underline{44\cdot2}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for low-pressure engine. $=\frac{42\cdot75}{0\cdot0562}=\underline{760\cdot6}$ heat units per minute per indicated horse-power.

Hence, steam required by compound engine $=\frac{2565}{46\cdot5+58}=\frac{2565}{114\cdot5}=22\cdot4$ lbs. per hour per indicated horse-power.

Total heat efficiency $=\frac{114\cdot5}{105\cdot2}=\underline{\underline{0\cdot1088}}$.

Rate of expenditure for compound engine $=\frac{42\cdot75}{0\cdot1088}=\underline{393}$ heat units per minute per indicated horse-power.

For triple engine working from 40 lbs. abs. down to 3 lbs. abs., minimum expenditures are :—

For high-pressure engine = 968 units per lb.
,, mid-pressure ,, = 997 ,, ,,
,, low-pressure ,, = 1028 ,, ,,

Steam required by high-pressure engine $=\frac{2565}{0\cdot0434\times968}=\frac{2565}{42}=\underline{\underline{61}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for high-pressure engine $=\frac{42\cdot75}{0\cdot0434}=\underline{\underline{985}}$ heat units per minute per indicated horse-power.

Steam required by mid-pressure engine $=\frac{2565}{0\cdot0444\times997}=\frac{2565}{44\cdot26}=\underline{\underline{58}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for mid-pressure engine

$=\frac{42\cdot75}{0\cdot0444}=\underline{962}$ heat units per minute per indicated horse-power.

Steam required by low-pressure engine

$=\frac{2565}{0\cdot0442\times1028}=\frac{2565}{45\cdot44}=\underline{\underline{56\cdot4}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for low-pressure engine

$=\frac{42\cdot75}{0\cdot0442}=\underline{967}$ heat units per minute per indicated horse-power.

Hence, steam required by triple engine

$=\frac{2565}{42+44\cdot26+45\cdot44}=\frac{2565}{131\cdot7}=\underline{\underline{19\cdot4}}$ lbs. per hour per indicated horse-power.

Total heat efficiency $=\frac{131\cdot7}{1052}=\underline{\underline{0\cdot1251}}.$

Rate of expenditure for triple engine

$=\frac{42\cdot75}{0\cdot1251}=\underline{\underline{341\cdot7}}$ heat units per minute per indicated horse-power.

Collecting these results for steam at 40 lbs. abs., worked in engines of different types, down to 3 lbs. abs.

Steam required per hour per indicated horse-power:—

By simple engine (40 to 3) = 32·0 lbs.
,, compound ,, ,, = 22·4 ,,
,, triple ,, ,, = 19·4 ,,

Heat efficiency—

For simple engine (40 to 3) = 0·0765.
,, compound ,, ,, = 0·1088.
,, triple ,, ,, = 0·1251.

Rate of expenditure per minute per indicated horse-power—

For simple engine (40 to 3) = 558·8 units.
,, compound ,, ,, = 393·0 ,,
,, triple ,, ,, = 341·7 ,,

Minimum expenditure between 83 lbs. abs. and 3 lbs. abs. = 1065 heat units per lb;

$\therefore$ Steam required by simple engine

$=\dfrac{2565}{0{\cdot}0859\times1065}=\dfrac{2565}{91{\cdot}48}=\underline{\underline{28}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for simple engine

$=\dfrac{42{\cdot}75}{0{\cdot}0859}=\underline{\underline{497{\cdot}6}}$ heat units per minute per indicated horse-power.

For compound engine, working from 80 lbs. abs. down to 3 lbs. abs.. minimum expenditures are:—

For high-pressure engine = 978 units per lb.
,, low-pressure ,, = 1040 ,, ,,

$\therefore$ Steam required by high-pressure engine

$=\dfrac{2565}{0{\cdot}0669\times978}=\dfrac{2565}{65{\cdot}42}=\underline{\underline{39{\cdot}2}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for high-pressure engine

$=\dfrac{42{\cdot}75}{0{\cdot}0669}=\underline{\underline{639}}$ heat units per minute per indicated horse-power.

Steam required by low-pressure engine

$=\dfrac{2565}{0{\cdot}0656\times1040}=\dfrac{2565}{68{\cdot}22}=\underline{\underline{37{\cdot}6}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for low-pressure engine

$=\dfrac{42{\cdot}75}{0{\cdot}0656}=\underline{651{\cdot}6}$ heat units per minute per indicated horse-power.

Hence, steam required by compound engine

$=\dfrac{2565}{65{\cdot}42+68{\cdot}22}=\dfrac{2565}{133{\cdot}64}=\underline{19{\cdot}1}$ lbs. per hour per indicated horse-power.

Total heat efficiency $=\dfrac{133{\cdot}64}{1065}=0{\cdot}1254.$

Rate of expenditure for compound engine

$=\dfrac{42{\cdot}75}{0{\cdot}1254}=\underline{\underline{340{\cdot}9}}$ heat units per minute per indicated norse-power.

For triple engine working between 80 lbs. abs. and 3 lbs. abs., minimum expenditures are:—

For high-pressure engine = 952 heat units per lb.
,, mid-pressure ,, = 992 ,, ,,
,, low-pressure ,, = 1031 ,, ,,

∴ Steam required by high-pressure engine $=\frac{2565}{0\cdot0535\times952}=\frac{2565}{51}=\underline{50\cdot3}$ lbs. per hour per indicated horse-power.

Rate of expenditure for high-pressure engine. $=\frac{42\cdot75}{0\cdot0535}=\underline{799}$ heat units per minute per indicated horse-power.

Steam required by mid-pressure engine $=\frac{2565}{0\cdot0533\times992}=\frac{2565}{52\cdot87}=\underline{48\cdot5}$ lbs. per hour per indicated horse-power.

Rate of expenditure for mid-pressure engine. $=\frac{42\cdot75}{0\cdot0533}=\underline{802}$ heat units per minute per indicated horse-power.

Steam required by low-pressure engine $=\frac{2565}{0\cdot0530\times1031}=\frac{2565}{54\cdot64}=\underline{46\cdot9}$ lbs. per hour per indicated horse-power.

Rate of expenditure per low-pressure engine $=\frac{42\cdot75}{0\cdot0530}=\underline{806}$ heat units per minute per indicated horse-power.

Hence, steam required by triple engine $=\frac{2565}{51\times52\cdot87+54\cdot64}=\frac{2565}{158\cdot51}=\underline{16.18}$ lbs. per hour per indicated horse-power.

$$\text{Total heat efficiency}=\frac{158\cdot51}{1065}=\underline{0\cdot1488}.$$

Rate of expenditure for triple engine $=\frac{42\cdot75}{0\cdot1488}=\underline{287\cdot3}$ heat units per minute per indicated horse-power.

Collecting results for steam at 80 lbs. abs. worked in engines of different types down to 3 lbs. abs.

Steam required per hour per indicated horse-power—
By simple engine (80 to 3) = 28·00 lbs.
,, compound ,, ,, = 19·10 ,,
,, triple ,, ,, = 16·18 ,,

Heat efficiency—

For simple engine (80 to 3) = 0·0859.
,, compound ,, ,, = 0·1254.
,, triple ,, ,, = 0·1488.

Rate of expenditure per minute per indicated horse-power—

For simple engine (80 to 3) = 497·6 units.
,, compound ,, ,, = 340·9 ,,
,, triple ,, ,, = 287·3 ,,

Minimum expenditure between 160 lbs. abs. and 3 lbs. abs. = 1080 heat units per lb.;

∴ Steam required by a simple engine working through this range $= \frac{0{\cdot}0952 \times 1080}{2565} = \frac{2565}{102{\cdot}8} = \underline{\underline{25}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for simple engine $= \frac{42{\cdot}75}{0{\cdot}0952} = \underline{\underline{449}} =$ heat units per minute per indicated horse power.

For compound engine working from 160 lbs. to 3 lbs. abs., the minimum expenditures are—

For high-pressure engine = 962 heat units per lb.
,, low-pressure ,, = 1050 ,, ,,

∴ Steam required by high-pressure engine $= \frac{2565}{0{\cdot}0758 \times 962} = \frac{2565}{73} = \underline{35{\cdot}1}$ lbs. per hour per indicated horse-power.

Rate of expenditure for high-pressure engine $= \frac{42{\cdot}75}{0{\cdot}0758} = \underline{\underline{564}}$ heat units per minute per indicated horse-power.

Steam required by low-pressure engine $= \frac{2565}{0{\cdot}0746 \times 1050} = \frac{2565}{78{\cdot}3} = \underline{\underline{32{\cdot}7}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for low-pressure engine $= \frac{42{\cdot}75}{0{\cdot}0746} = 573$ heat units per minute per indicated horse-power.

Hence, steam required by compound engine

$=\frac{2565}{73+78\cdot3}=\frac{2565}{151\cdot3}=\underline{\underline{16\cdot9}}$ lbs. per hour per indicated horse-power.

$$\text{Total heat efficiency}=\frac{151\cdot3}{1080}=\underline{\underline{0\cdot1400}}.$$

Rate of expenditure for compound engine

$=\frac{42\cdot75}{0\cdot1400}=\underline{\underline{305\cdot3}}$ heat units per minute per indicated horse-power.

For triple engine working between 160 lbs. and 3 lbs. abs., the minimum expenditures are—

For high-pressure engine = 934 heat units per lb.
„ mid-pressure „ = 986 „ „
„ low-pressure „ = 1036 „ „

∴ Steam required by high-pressure engine

$=\frac{2565}{0\cdot0637\times934}=\frac{2565}{59\cdot5}=43\cdot1$ lbs. per hour per indicated horse-power.

Rate of expenditure for high-pressure engine

$=\frac{42\cdot75}{0\cdot0637}=\underline{671}$ heat units per minute per indicated horse-power.

Steam required by mid-pressure engine

$=\frac{2565}{0\cdot062\times986}=\frac{2565}{61\cdot42}=\underline{41\cdot7}$ lbs. per hour per indicated horse-power.

Rate of expenditure for mid-pressure engine

$=\frac{42\cdot75}{0\cdot0623}=\underline{\underline{686}}$ heat units per minute per indicated horse-power.

Steam required by low-pressure engine

$=\frac{2565}{0\cdot0600\times1036}=\frac{2565}{62\cdot16}=\underline{\underline{41\cdot7}}$ lbs. per hour per indicated horse-power.

Rate of expenditure for low-pressure engine

$=\frac{42\cdot75}{0\cdot0600}=\underline{\underline{712\cdot5}}$ heat units per minute per indicated horse-power.

Hence, steam required by triple engine

$$=\frac{2565}{59{\cdot}5+61{\cdot}42+62{\cdot}16}=\frac{2565}{183{\cdot}08}=\underline{\underline{14{\cdot}01}}\text{ lbs. per}$$

hour per indicated horse-power.

$$\text{Total heat efficiency}=\frac{183{\cdot}08}{1080}=\underline{\underline{01695.}}$$

Rate of expenditure for triple engine

$$=\frac{42{\cdot}75}{0{\cdot}1695}=\underline{\underline{252{\cdot}2}}\text{ heat units per minute per indi-}$$

cated horse-power.

Collecting results for steam at 160 lbs. abs. worked in different types of engines down to 3 lbs. abs.

Steam required per hour per indicated horse-power—
By simple engine (160 to 3)=25·00 lbs.
,, compound ,, ,, =16·90 ,,
,, triple ,, ,, =14·01 ,,

Heat efficiency—
For simple engine (160 to 3)=0·0952.
,, compound ,, ,, =0·1400.
,, triple ,, ,, =0·1695.

Rate of expenditure per minute per indicated horse-power.
For simple engine (160 to 3)=449·0 units.
,, compound ,, ,, =305·3 ,,
,, triple ,, ,, =252·2 ,,

If, in the case of the triple engine, working between the pressures 160 and 3 lbs. abs., the feed-water be supplied to the boiler from the condenser at 90° F. instead of 141°, as previously assumed, then the expenditure of heat in the boiler will be increased from 1080 to $1080+(141-90)=1080+51=1131$ units per lb. of steam. This will in no way affect the steam efficiency nor its complement—the steam required per hour per indicated horse-power—but it will diminish the heat efficiency and raise the rate of expenditure to an extent which is determined as follows:—

$$\text{Heat efficiency}=\frac{1080}{1131}\times 0{\cdot}1695=\underline{\underline{0{\cdot}1618.}}$$

$$\text{Rate of expenditure}=\frac{42{\cdot}75}{0{\cdot}1618}=\underline{\underline{264{\cdot}2}}\text{ heat units per}$$

minute per indicated horse-power.

If, together with this state of matters, a heater were set to work between the mid-pressure and low-pressure engines, from which the feed was supplied to the boiler at 212° F., this would cause a reduction of $212^\circ - 90^\circ = 122$ units in the expenditure necessary to produce 1lb. of steam in the boiler, so that an expenditure of 1131, which formerly produced 1 lb., will now produce $\left(1+\frac{122}{1131-122}\right) = \left(1+\frac{122}{1009}\right)$ lbs. of steam.

The increment of work done by the high pressure

$$\text{engine} = \frac{122}{1009} \times 59{\cdot}50 = \underline{7{\cdot}19} \text{ units, and}$$

increment done by the mid-pressure engine

$$= \frac{122}{1009} \times 61{\cdot}42 = \underline{7{\cdot}42} \text{ units.}$$

Hence, total work transmitted by the respective engines, per an expenditure of 1131 units, is—

$59{\cdot}50 + 7{\cdot}19 = 66{\cdot}69$ units by high-pressure engine.
$61{\cdot}42 + 7{\cdot}42 = 68{\cdot}84$ „ mid-pressure „
$62{\cdot}16 + 0{\cdot}00 = \underline{62{\cdot}16}$ „ low-pressure „
Total $= \underline{\underline{197{\cdot}69}}$ „ triple „

$$\therefore \text{Heat efficiency} = \frac{197{\cdot}69}{1131} = \underline{\underline{0{\cdot}1748}}.$$

$$\text{Rate of expenditure} = \frac{42{\cdot}75}{0{\cdot}1748} = \underline{\underline{244{\cdot}5}} \text{ heat units per}$$

minute per indicated horse-power.

Total thermal equivalent of work transmitted by triple engine per 1 lb. of steam from boiler

$$= \frac{1009}{1131} \times 197{\cdot}69 = \underline{\underline{176{\cdot}36}} \text{ units.}$$

$$\therefore \text{Steam from boiler} = \frac{2565}{176{\cdot}36} = \underline{\underline{14{\cdot}54}} \text{ lbs. per hour per}$$

indicated horse-power.

If the heater be placed between the high-pressure and mid-pressure engines, through which the feed-water passes on its way from the hotwell to the boiler, and, in doing so, becomes heated from 90° F. to 262°, exhaust pressures. This can only be approximately obtained from the ordinary indicator card. To obtain this definitely it will be necessary to fit the indicator with pipe connections to the slide valve casing, and to the receiver into which the engine exhausts, in the case of the high-pressure and mid-pressure engines, and to the condenser in the case of the low-pressure engine.

The indicator cards will have the initial and exhaust pressure drawn as shown on the cards. On the high-pressure card draw the boiler pressure line on the top, and on the bottom draw a line to represent mean exhaust pressure. The range of pressure with which this engine works will be represented by the distance between the boiler line and the exhaust lines. The mean initial and exhaust lines are treated in the same manner for the other engines as shown. By this means we shall not only get the proper initial and exhaust pressures, but we shall also be able to find and make allowance for errors between the indicators, as each indicator draws two lines which show the same pressure, viz., the atmosphere line in common and the exhaust line of the first engine is the same as the initial of the next engine. From the point of cut-off on the card continue the expansion curve until it cuts the initial pressure line. On the top of the high-pressure card we have a space between the initial pressure line and the boiler pressure line; the area of this will be a measure of the loss by resistance in the steam pipe; and the space between the initial pressure line and the top of diagram proper (transmitted work) will give the loss by the side valve during admission, and the area of the space between the card and the exhaust line below the card will be the loss during exhaust. The initial and exhaust lines in the other cards drawn by the indicator will likewise show the losses from the slide valve. It is scarcely necessary to point out the importance of this information to the engineer and the shipowner. It will show distinctly and truthfully a good valve arrangement from a bad one. The shipowner will be enabled to see what losses are taking place and how they may, in most cases, be made less; and to the engineer it will point the way to improve his engine.

EXAMPLE.

Full area of high-pressure card (measured from casing pressure) = 5·13 square inches.

Full area of high-pressure card (measured from boiler pressure) = 5·56 square inches.

Actual area of high-pressure card = 4·80 square inches.

$$\because \quad \frac{\text{Full card (casing)}}{\text{Full card (boiler)}} = \frac{5{\cdot}13}{5{\cdot}56} = 0{\cdot}922.$$

Loss due to main steam pipe = 7·8%.

$$\frac{\text{Actual card}}{\text{Full card (casing)}} = \frac{4{\cdot}80}{5{\cdot}13} = 0{\cdot}935.$$

Loss due to high-pressure slide valve, steam ports, &c. 6·5%.

$$\frac{\text{Actual card}}{\text{Full card (boiler)}} = \frac{4{\cdot}80}{5{\cdot}56} = 0{\cdot}863.$$

$\because$ Total loss (measured from boiler pressure) = 13·7%.

Full area of mid-pressure card = 5·05 square inches.
Actual " " " = 4·90 " "

$$\because \quad \frac{\text{Actual card}}{\text{Full card}} = \frac{4{\cdot}90}{5{\cdot}05} = 0{\cdot}970.$$

$\because$ Loss due to mid-pressure slide, valve, &c. = 3%.

Full area of low-pressure card = 4·69 square inches.
Actual " " " = 4·11 " "

$$\because \quad \frac{\text{Actual card}}{\text{Full card}} = \frac{4{\cdot}11}{4{\cdot}69} = 0{\cdot}876.$$

Loss due to low-pressure slide valve, &c. = 12·4%.

Boiler pressure = 175 lbs. abs.
High pressure mean exhaust " = 73 " "
" range of " = 102 "

At 175 lbs abs., E. = 0·0005605.

∵ Theoretical efficiency of steam at 175 lbs. abs., worked down to 73 lbs. abs.
= 0·0005605 × 102 = 0·0572.

Actual efficiency = 0·863 × 0·0572.
= 0·0494.

Total heat in 1 lb. of steam at 175 lbs. abs. (measured from high-pressure exhaust pressure) = 918 units.

∵ Thermal equivalent of work transmitted to piston of high-pressure engine = 0·0494 × 918 = 25·34 heat units per lb. of steam supply.

Initial pressure on mid-pressure piston = 73 lbs. abs.
Exhaust ,, ,, ,, = 20 ,, ,,
Range of ,, ,, ,, = 53 ,,

At 73 lbs. abs., E = 0·001211.

Theoretical efficiency of steam at 73 lbs. abs. worked down to 20 lbs. abs.
= 0·001211 × 53 = 0·0642.

Actual efficiency = 0·970 × 0·0642.
= 0·0623.

Total heat in 1 lb. of steam at 73 lbs. abs. (measured from mid-pressure exhaust) = 977 units.

∵ Thermal equivalent of work transmitted to mid-pressure piston = 0·0623 × 977 = 60·86 heat units per lb. of steam supply.

Initial pressure on low-pressure piston = 20 lbs. abs.
Exhaust ,, ,, ,, = 3 ,, ,,
Range of ,, ,, ,, = 17 ,, ,,

At 20 lbs. abs., E = 0·0038605.

Theoretical efficiency of steam at 20 lbs. abs. worked down to 3 lbs. abs.
= 0·0038605 × 17 = 0·0656.

Actual efficiency = 0·876 × 0·0656.
= 0·0574.

Total heat in 1 lb. of steam at 20 lbs. abs. (measured from low-pressure exhaust) = 1040 units.

∵ Thermal equivalent of work transmitted to low-pressure piston $= 0{\cdot}0574 \times 1040 = \underline{\underline{59{\cdot}69}}$ heat units per lb. of steam supply.

∵ Work transmitted per lb. of steam supply, by the respective engines is:

	45·34	units by	high-pressure engine
	60·86	,,	mid-pressure ,,
	59·69	,,	low-pressure ,,
Total =	165·89	,,	triple ,,

∵ Steam supply from boiler $= \frac{2565}{165{\cdot}89} = \underline{\underline{15{\cdot}46}}$ lbs. per hour per indicated horse-power.

Minimum expenditure possible in this case $= \underline{\underline{1082}}$ heat units per lb. of steam.

This gives a maximum—

$$\text{Heat efficiency} = \frac{165{\cdot}89}{1082} = \underline{\underline{0{\cdot}1532}}.$$

And a minimum—

$$\text{Rate of expenditure} = \frac{42{\cdot}75}{0{\cdot}1532} = \underline{\underline{279}} \text{ heat units per}$$

minute per indicated horse-power.

A point of much importance in connection with the discussion of steam engine efficiency is the relation between the back-pressure on the low-pressure piston and the pressure in the condenser. With the condensing apparatus in good condition, the pressure in the condenser may be kept nearly constant, while the piston speed may vary; but, if the object be to work the engine economically, this is not a condition of things to be aimed at.

The back-pressure on the low-pressure piston does not depend on the pressure in the condenser alone, but increases and decreases with the piston speed, other things equal. If the flow of steam from the cylinder into the condenser was not hindered by friction and other obstructive causes (see page 97), the maximum rate of discharge would be attained when the difference of those pressures was equal to 58 per cent. of the back-pressure on the low-pressure piston, the velocity of flow would be a maximum. It is evident, then, that in this ideal state of things, it would not only be useless, but worse than useless to have a pressure in the condenser lower than this. In practice, a *free* flow between the cylinder and condenser has no existence. The circumstances under which the actual flow takes place, are such as to necessitate some modifiation of the relations just stated. The amount and nature of the modification, however, can only be determined by observation. From actual observation, together with careful measurement of those quantities on indicator diagrams, upon which the necessary lines were drawn simultaneously by the same instrument, it would appear that the facts of the case are fairly well represented, if the per centages be taken at 30 per cent. and 70 per cent. respectively. Hence, whatever the back-pressure on the low-pressure piston may be, it will be found that no appreciable reduction of it will be effected by increasing the difference between it and the condenser pressure beyond 30 per cent. of the former. Although such an increase has no effect on the efficiency of the steam, it has a direct effect in reducing the heat efficiency, by increasing the expenditure. A simple example will illustrate this point.

Suppose a case where the piston speed may be at the rate of 90 revolutions at one time, and 140 at another. At the lower speed, the back-pressure will$=4$ lbs. abs. (say). The condenser pressure should than be about 70 per cent. of 4 lbs.$=0{\cdot}7\times4=2{\cdot}8$ lbs. abs.

At the higher speed, the back-pressure will not be much short of 7 ibs. abs. Then, a vacuum equivalent to $0{\cdot}7+7=4{\cdot}9=5$ lbs. abs. in the condenser will be amply sufficient, and more than this will do more harm than good. The temperature corresponding to 2·8 lbs. is 139° F., whilst that corresponding to 5 lbs. abs. is 162° F. Now, to retain the lower pressure in the condenser, while the higher pressure would be just as effective, will involve an unnecessary increase of expenditure$=162-139=23$ heat units per lb. of feed-water.

SUMMARY.—The steam efficiency, or available work per lb. of steam, is a simple constant ratio depending only on the pressure and type of engine, provided there were no losses due to steam pipes and slide valves. But in practice there always will be some such losses, which, however, may be measured by the indicator, as already explained and illustrated.

The steam per hour per indicated horse-power for a simple engine, is a simple constant quantity depending on the steam efficiency.

For a compound engine, it is a compound quantity, depending on the steam efficiency of each simple engine sn the system; and when the feed is heated by any other exhaust besides that of the low-pressure engine, this quantity assumes a more complex character.

It must be carefully borne in mind that, in all the cases tabulated, it means so much steam leaving the boiler per hour per indicated horse-power. The heat efficiency is a quantity which admits of considerable variation. It depends on the efficiency of the condensing apparatus, such as, for example, the efficiency of the air-pump. The maximum values possible for each case are given on Table II. In practice, they are always less than these, and may be much less, the difference being largely due to the *efficiency of the engineer*. This point has already been made plain in what has gone before.

The heat units per minute per indicated horse-power (rate of expenditure) is simply another way of expressing the heat efficiency; this time in a form more familiar to engineers.

TABLE II.

RANGE OF PRESSURE.		SIMPLE ENGINE.	COMPOUND ENGINE.	TRIPLE ENGINE.				
		Minimum Expenditure	Minimum Expenditure	Minimum Expenditure	Feed Temp. =92° F.	Heater between M.P. and L.P.	Heater between H.P. and M.P.	Both Heaters on.
40 to 3 lbs. abs.	Steam efficiency - - -	0·0765	0·1130	0·1320	—	—	—	—
,, ,,	Do., per hour per indicated horse-power - - (lbs.)	32·0000	22·4000	19·4000	—	—	—	—
,, ,,	Heat efficiency - - -	0·0765	0·1088	0·1251	—	—	—	—
,, ,,	Do., per minute per indicated horse-power (B.T.U.) -	558·8000	393·0000	341·7000	—	—	—	—
80 to 3 lbs. abs.	Steam efficiency - - -	0·0859	0·1325	0·1598	—	—	—	—
,, ,,	Do., per hour per indicated horse-power - - (lbs.)	28·0000	19·1000	16·1800	—	—	—	—
,, ,,	Heat efficiency - - -	0·0859	0·1254	0·1488	—	—	—	—
,, ,,	Do., per minute per indicated horse-power (B.T.U.) - -	497·6000	340·9000	287·3000	—	—	—	—
160 to 3 lbs. abs.	Steam efficiency - - -	0·0952	0·1504	0·1860	0·1860	0·1860	0·1860	0·1860
,, ,,	Do., per hour per indicated horse-power - - (lbs.)	25·0000	16·9000	14·0100	14·0100	14·5400	15·6100	15·0300
,, ,,	Heat efficiency - - -	0·0952	0·1400	0·1695	0·1618	0·1748	0·1713	0·1780
,, ,,	Do., per minute per indicated horse-power (B.T.U.) - -	449·0000	305 3000	252·2000	264·2000	244·5000	249·5600	240·0000

"IRON" September 18th, 1891.

The opening meeting of the Autumn Session of the Institute of Marine Engineers, was held in the hall of the Society of Arts, John Street, Adelphi, on September 8th, when a paper on "Steam Engine Efficiency," by Mr. James Weir (of Glasgow) was read.

The meeting was presided over by Mr. G. W. Manuel (past president). In the introductory portion of his paper, the author quoted from the writings and opinions of several standard authors on the steam engine, and proceeded to point out wherein he greatly differed from their generally accepted theories. He then enunciated his own views in reference to the economy of the steam engine, pointing out the losses and shadowing forth a possible remedy, illustrating this by means of a table constructed from data supplied by experiments.

Mr. J. Macfarlane Gray objected to the way in which the formulæ were introduced in the paper, and pointed out the inconsistencies and want of discrimination manifested by the author in the placing of his own rendering of the formulæ. Mr. Gray held that Mr. Weir was entirely at variance with known and accepted teaching, and quite wrong in the position he had taken up.

Professor Elliot spoke warmly of the services rendered by Mr. Weir to the engineering world, and indicated in the course of his remarks that he himself had been impelled to consider the question brought forward by Mr. Weir quite recently, and although he agreed to a considerable extent with the remarks made by Mr Gray, he considered that a very valuable service had been rendered by Mr. Weir in contributing such a paper and opening up the discussion on a question which might possibly prove to be a very important one in reference to the steam engine.

The Chairman then gave a few remarks and notes from results of trials he had himself made in the direction indicated by the author of the paper, after which Mr. Weir replied. He thanked Mr. Gray and Professor Elliot for their comments, and courted remarks by correspondence, which should have his best attention and reply. Mr. Gray then gave a brief description of the principle of feed heating discovered and acted upon by Mr. Weir in his feed heater, proving that feed heating is economy, and is not, as some have attempted to prove, "robbing Peter to pay Paul."

"The Mechanical World" Sept. 18th, 1891.

THE THEORY OF THE STEAM ENGINE.

On the 8th instant, a somewhat remarkable paper, by Mr. James Weir, of Glasgow, on "Steam Engine Efficiency" was read before the Institute of Marine Engineers. The paper had been looked forward to with much interest, as it was understood that Mr. Weir would attack some of the generally accepted principles of thermo-dynamics.

Confidence in the theory of the steam engine has received many rude shocks during the last few years, but, generally speaking, the opposition hitherto appears to have been contented to point out defects in the present theory, without suggesting a better substitute. This charge, however, cannot be laid to Mr. Weir, for in the introductory portion of his paper he not only distinctly controverts many of the tenets of the thermo-dynamist, but at the same time he gives what, from his experiments and observations, he believes to be the more rational exposition of the facts. From the following contrasts it will be seen that Mr. Weir adopts a much more common-sense view of the changes brought about during the conversion of heat into work in the steam engine than the modern views of thermo-dynamics would allow. Below we give in parallel columns, the generally accepted views, and those which Mr. Weir would substitute:—

(1) The steam engine is a machine for transforming heat into work.	(1) The steam engine is a machine for transmitting work.
(2) The steam boiler is the vessel in which water and luminiferous ether increase their rates of motion.	(2) The steam boiler is the vessel in which steam is generated from water.

(3) The furnace is where the fuel increases its rate of motion in contact with luminiferous ether, and where the innumerable concussions of the molecules produce heat.	(3) The furnace is where the fuel is burned, and when burning transforms its energy into heat.
(4) The transmission of heat to water is an increasing of the molecular vibrations.	(4) The transmission of heat to water is simply a raising of the temperature.
(5) The heat disappearing in water is an evidence of internal work molecular motion of various kinds.	(5) The heat disappearing in water converts the water into steam.
(6) The passing of water into steam is a change in the constitution of water, viz., into small particles.	(6) The passing of water into steam is simply a transformation of heat into work.
(7) The amount of steam formed is the number of water molecules in motion and applied to the engine piston.	(7) The amount of steam formed is the amount of work supplied to the engine piston.

Of the foregoing statements, the first, sixth, and seventh are the most important. It will be seen that Mr. Weir flatly refuses to recognise the steam engine as a machine for converting heat into work, for, according to his view, the engine only *transmits* work, which work (from 6) is brought into existence by the conversion of water into steam. From (6) and (7) we are led to infer that Mr. Weir regards steam as work, from which we suppose it follows that a vessel containing steam should be said to contain *work*. But work is usually regarded as the result of resistance overcome by the action of force, a definition which distinctly implies that motion takes place. In the face of this we fail to see that Mr. Weir is justified in making the sweeping assertion that the generation of steam is concomitant with the transformation of heat into work. We are much more inclined to regard the change of water into steam as a transformation of heat into "work-energy," which Mr. Weir, later on in his paper, defines as "that form of energy capable of being transmitted by matter in motion."

According to this view, water is, by the application of heat, endowed with energy, which energy has the power to do work through the medium of the steam engine, There are many other points in Mr. Weir's disquisition which invite discussion, and to which we hope to return on a future occasion.

MR. GEO. CLEGHORN.

(MEMBER).

In this paper we have an abundance of matter for discussion, not only because Mr. Weir's methods of dealing with his subject are new, but because some of his conclusions have an appearance of being out of harmony with the teaching of the day.

We may rest assured that a man in Mr. Weir's position would not commit himself to a public expression of opinions which are unusual, unless he was prepared to support them by powerful reasoning, and if we are to derive any advantage from this paper we must be prepared to extend to it that impartial consideration which alone will enable us to see the matter from the writer's point of view.

We have been told to-night that before a young man reads this paper he should go up for examination and get a license, in this suggestion, and in Mr. Weir's treatment of steam-engine efficiency, we have examples of conditions of thought which have existed in all generations.

Men think in advance (rightly or wrongly) and assert their right of drawing their own conclusions, whilst other men with every good intention would throttle advanced thought, and as it were put on the brake, both sides are useful and necessary in their way, and together increase our knowledge and separate truth from error.

In the introduction to this paper Mr. Weir has commented on that curious substance, the luminiferous ether. It would have been to our advantage if he had given us his views on this point instead of using it as a missile at the heads of thermo-dynamists. It will be noticed that Mr. Weir does not deny the existence of the ether, he only goes out of his way to remind us that some of the writers who are loudest in their condemnation of Dr. Black, and those of his contemporaries who held the theory of caloric, have themselves, in common with others, adopted the idea of the ether in order to bring their ideas into line.

Now, whilst Mr. Weir is doubtless correct in what he says, in this connection, his remarks do not convey to the mind the important place which the ether occupies in the economy of nature. The ether has not been invented, to bring any ideas into line; its existence has been gradually brought to our knowledge.

We can call to mind how the planet Neptune made its existence known to us by the effect it had upon its surroundings, this effect was the first step in the discovery of a world, it is the same with the ether, we are only becoming alive to its existence. I hope Mr. Weir's remarks will call out some information on this important subject, one thing which must be allowed is that the ether is some form of matter.

Passing from this we come to what Mr. Weir seems to have constituted the front of his position; that is, that the steam-engine only transmits work. That the transformation of heat into work takes place when the water passes into steam. It appears to me that this conclusion is quite legitimate, although it has an appearance of being out of touch.

It might be said, that so long as we are satisfied that somewhere in our system there is a transformation of heat into work, it is a matter of little practical importance at which point the transformation takes place.

Mr. Weir, seems to have considered the question to be one of first importance, and if we take it at even its least value it may be said to be a question of some interest and likely to repay us for any consideration we may give to it.

It has been assumed and generally accepted that all bodies are built up of infinitely minute particles of matter which have been called molecules, with a given specimen of matter the mass of the molecule is a fixed quantity. To avoid further introduction of the ether, I may explain, that in using the word molecule, the image

I desire to convey to your minds, is that of a small but perfect island afloat in an environment of the ether; also that a molecule in its motion, causes a disturbance of the ether, similar in many, if not in all respects, to the disturbance set up in the air when a body passes through it.

Heat is the evidence of a continual movement of these molecules. When matter has been set in motion it is in such a condition that we describe it as having momentum. I would define heat as being an evidence of molecular momentum, due to the particular motion which a molecule receives whilst it is under the power of the laws of inter-molecular attractions, and which it may retain after it has passed beyond the control of those laws; temperature is an indication of the intensity of this molecular momentum, and as the mass of a molecule is constant, temperature may be taken as a measure of the velocity of the motion which a molecule receives whilst under the control of the laws referred to.

Active energy is matter in motion, or momentum, and I have no doubt that the laws that control its communication from one body to another also control its communication as heat from one molecule to another.

Potential energy, may be defined as being matter brought into such a condition that by the operation of any natural law we can endow it with momentum.

Pressure, I would define as a latent momentum and when we impart motion to a body or a molecule, or when we cause any variation in whatever motion they may already possess, we have done work. Work may be defined as overcoming Inertia by utilising any available supply of energy. These definitions are the impressions I receive from some of the common words used by Mr. Weir, and by their aid it may be shown that he is quite correct when he says, the transformation of heat into work takes place when the water passes into steam, and that what takes place after this is simply a transmission of work.

Take a marine engine for example. At one end of our system we have the furnace, at the other end the propeller, the work to be done is to pump a stream of water aft or forward as we may desire, the energy available is of a potential form ; by taking advantage of the law of chemical affinity we commence by doing work, and we continue doing work right through; but, there is this distinction that up to the point where the water passes into steam our work has been a transmission of heat, or molecular momentum.

When a molecule of water passes into steam it has passed from the control of the inter-molecular attractions, because that control has for the time being been overcome by the power of a new law, and the molecule has become a separate body in space ; by the expenditure of heat it has received an accession of momentum due to a motion of translation similar to that of a projectile.

This is the transformation of heat into work. The molecule is now endowed with potential energy, and by the operation of a natural law we can utilise its latent power, and it is this latent momentum or pressure (not heat) that is transmitted to the water at the stern of the ship.

This, I apprehend, explains Mr. Weir's remarks about heat energy. Heat energy is molecular momentum, work energy is the latent momentum of independent molecules or bodies.

Leaving the introduction and coming to the paper proper we have on every page an evidence of diligent work, it must have taken Mr. Weir a long time to gather this together for us, and he deserves our best thanks for having taken such a duty upon himself.

One cannot enter at once upon an investigation of his methods, the paper requires time for study and I confess that at present I do not understand Mr. Weir on many of the points upon which he touches, and can only venture upon a few general remarks.

There is not the slightest doubt that it can be shown that an engine fitted with a feed heater as in the example, will have a higher efficiency than the same engine would have without a heater.

In the tabulated results of trials with the heater at work and with the heater shut off, we have in each case the thermal value of the work done, set in comparison with the thermal expenditure. Mr. Weir has adopted a complicated method of deducting these results, it seems to me that a simpler method would have been to find the thermal value of the total work from the combined I.H.P. under each condition and compare it with the thermal expenditure.

In this instance owing to an appearance of error in the mean effective pressure on the pistons we can hardly by any method deduce the relative value of the heater, you will notice that with the heater at work the initial pressure is 160lbs., and with the heater shut off the initial pressure 159lbs., also that the back pressure upon the H. P. piston is the same in both cases, the mean pressure upon the piston is given as 70·15 and 66·92 respectively, we may take it that during these trials the cut off was not altered and that the throttle valve was open to the same extent. Under these conditions if we take the H.P. mean pressure as 70·15 when the heater was at work, a mean pressure of 69·28 might be expected when the heater was shut off, which would give a considerable increase in the thermal value of the work done when working without the heater.

Evidently Mr. Weir has adopted this method of taking each engine of the series separately and deducing the efficiency, that he may work up to his idea of an engine where each cylinder in the series would return its feed at the temperature of the exhaust, this point may be worthy of our consideration.

The arrangement of an engine of this description we might expect to be this, each cylinder or separate engine in the series to have an evaporator and feed pump separate from the others, the evaporator for the

H. P. would be the boiler, the other two evaporators would be, say those of the description made by Mr. Weir, they would have to be enormous in size, the exhaust steam from the H. P. cylinder would be condensed in the I. P. evaporator and expand the greatest part of its heat in evaporating steam for the I. P. cylinder, when the H. P. steam had been condensed it would be returned to the boiler at the temperature of the exhaust, the I. P. exhaust would be treated in the same way in the L. P. evaporator and the condensed steam returned to the I. P. evaporator at the temperature of the I. P. exhaust, the L. P. steam would be sent to the condenser and the feed returned to the evaporator at the temperature of the hot-well, this arrangement would seem to meet Mr. Weir's requirements. If the cylinders were proportioned to work the steam at the pressure given by Mr. Weir, and we take it for granted that there are no losses of heat except in doing work, the efficiency of the system would be ·052 thermal units turned into work per thermal unit expended.

The usual arrangement of a triple engine which Mr. Weir has designated as hybrid, would show ·059 thermal units turned into work, per thermal unit expended, with the feed at a temperature of 126°.

A feed heater does not owe its importance to the amount it increases the efficiency of the engine, it is because it prolongs the life of the boiler, by reducing the variations of temperature in the water, thus it is beneficial and should be fitted to every boiler.

Another point raised in this paper is, that an Indicator diagram does not show the quantity of steam that is passing through the engine. If an indicator is properly fitted and applied, it seems to me that this is one thing it can show, but we cannot expect it to show the quantity of steam that is evaporated in the boiler; this difference is due to the condensation that takes place in the system, and an indicator cannot be expected to show water that may be carried bodily from the H. P. cylinder to the exhaust, for instance.

If the feed water is measured, it will invariably be found greater than the quantity of steam shown on the diagrams of the engine, in this respect the indicator is most useful, if the weight of steam passing through each cylinder of a series be calculated, it will be found to vary in each cylinder as a rule, showing the condensation, re-evaporation, and any leakage that may be going on internally.

MR. J. H. THOMSON

(MEMBER OF COUNCIL).

Seeing that the subject has been so fully discussed from a theoretical point, and as the majority of us have to look at matters in a practical light, I consider we now ought to try and see how the advantages of heating the feed water are obtained, and also what hints we can get for improvement.

At present there are several methods for heating the feed water, one of which is by robbing the low pressure cylinder of about a tenth part of its volume of steam, and mixing it with the feed, a considerable economy of feed is obtained thereby.

Another arrangement is by taking steam direct from the steam pipe before it has done any work ; and by surface heating the feed on its way from the pumps to the boilers, this has been termed by some "robbing Peter to pay Paul." As far as I can learn, this arrangement was originally designed to get over the difficulty with leaky boilers, due to the unequal expansion caused by the feed water entering the boilers at a low temperature, and the singular part is that after many careful trials it has been proved there is a good percentage of saving in fuel by adopting this method.

Another means of heating has been tried with success which neither robs the high nor low pressure cylinders. In the place of the ordinary baffle plates fitted inside the furnace door a chamber is fitted, through which the feed water is passed, and where there are two or more furnaces in a boiler a high temperature is obtained. An important feature in this arrangement is that by having a connection with the bottoms of the boilers, circulation of the water commences as soon as the fire is lighted and an even temperature kept throughout the boilers while steam is being raised, thereby preventing unequal expansion and serious strains; there is also considerable economy in fuel by this system.

It is, I think, proved that by adopting some means of heating the feed water there is a saving of fuel and the life of the boiler is lengthened.

In the first case I referred to, I think it shows us there is something wrong with the low pressure cylinder or the condenser, either the proportions of the receiver or cylinder are at fault, or we are too ambitious to obtain a good vacuum by reducing the temperature of the feed too low, and, by so doing, throwing the heat overboard with the circulating water. The second method also proves that we are far from getting the full power of the steam in passing through the engine; the other system, by utilising the heat which would otherwise pass into the stokehold, helps to keep the stokehold cool, and it can be easily understood how a saving of fuel is effected.

I think there is still a wide field for the young engineer; as the reading and discussion of this paper shews that there are many improvements yet to be made in the steam engine before the full power of the steam is converted into work.

MR. J. HAWTHORN

(MEMBER).

In reading through Mr. Weir's paper one is struck with the amount of mathematics it contains. The theoretical efficiency of an engine is very neatly expressed by a formula given by Mr. Macfarlane Gray, and by his kind permission I will give you a rendering of it.

If H=total heat of evaporation;
then $H=1437+\cdot 3\ A-F$.

If A represents the absolute temperature of the steam, F the absolute temperature of the feed water, and if U=the units of heat turned into work—taking no account of the losses in the engine itself, that is from radiation, condensation, friction of machine, &c.—

Then Mr. Gray puts

$$U=\left(\frac{A-B}{A+B}+\frac{1437}{A}-\cdot 7\right)\left(A-B\right)$$

A as before being the absolute temperature of the steam entering the cylinder,
B being the absolute temperature of the steam leaving the cylinder;
Then $\frac{U}{H}$=theoretical efficiency.

Now this efficiency is a maximum when all the steam enters at the temperature A, and all the steam leaves at a temperature B. (Rankin).

That feed heating is economical, practical results show.

Let us take an example, say, of a triple expansion engine, and take one-tenth of the steam out of the L. P. valve box, the pressure shall be, say, 150lbs. absolute; exhausting at a pressure from L. P. at 7lbs. absolute, take the hot-well at 150° Fahr. without feed heating, then by Mr. Gray's notation or formula H = the total heat of evaporation—in this case=roughly 1073 units, and U=236 units:—

$$\frac{U}{H}=\frac{236}{1073}=\cdot 219 \text{ as the efficiency.}$$

Let us assume that one-tenth of the heat that is in the steam when rejected from the Intermediate cylinder at a pressure say, 15lbs. by gauge, or 30lbs. absolute, be sent to the L. P. to heat up the feed. The units of heat turned into work now, up to the moment it enters the L. P. valve box, is by the above formula—working in this case with the temperature of B as 250° Fahr., that corresponding with 30lbs. absolute, instead of at the 7lbs.,—which we will call $U=122$, and the heat turned into work in the L. P. cylinder without feed heating$=236-122=114$, but by feed heating the units of heat turned into work in the whole engine is 224 units—called U_1—, and of course the L. P. work is diminished by 12 units, there being now only 102 units turned into work in the L. P. cylinder. The feed water becomes enriched not by this 12 units, but by one-tenth of the total heat rejected at the temperature 250° Fahr. or 95 units, so that instead of "robbing Peter to pay Paul" we rob Peter of 12 units of heat and pay Paul 95 units.

So now the total heat supplied to raise the steam is less, being in fact—which we call H_1—978 units instead of as before 1073 units. So that in comparing feed heating with the same engine without feed heating the increase of efficiency is in favour of feed heating

$$\text{by } \frac{U_1}{H_1}-\frac{U}{H}=\frac{224}{978}-\frac{236}{1073}=\cdot229-\cdot219=\cdot01$$

$$=\frac{\cdot01\times 100}{\cdot219}\,\%=\frac{1}{\cdot219}=\text{say } 5\,\%$$

NOTE.—ON TRANSFORMATION DUE TO MECHANICAL DETAILS IN THE STEAM ENGINE.

The unavoidable losses due to the mechanical details in the steam engine, such as the friction of the steam passing through the pipes, valves, cylinder passages, &c., are directly due to a transformation of work into heat. A thorough knowledge of this fact is necessary before the first principles of the steam engine can be comprehended.

On page 12 the definition of energy in the work form is given, also a statement, viz.:—"By no process yet discovered can we change steam into water, except by transmission of work or by transforming the work (latent heat) again into heat energy." For example, when our steam engine is at work, say, propelling a ship, the steam passes from the boiler to the engine. Some of the work (energy) in the steam is used in propelling the steam through the pipes, valves, &c. The amount of this work (energy) used depends on the velocity of the steam, this again depending on the sizes of the pipes and passages.

Now, carefully examine the state of the steam while in motion, and compare it with its original condition, *i.e.*, before it left the boiler. While in the boiler, all the energy in the steam could be measured by the pressure function, and so long as the steam remained at rest in the boiler, its quantity and quality would be constant, and would remain so for ever.

The proper designation for steam at rest would thus be work (energy) in the *potential state*, *i.e.*, a state capable of transmitting energy.

It must be quite apparent to all that the work (energy) could, by no means yet conceived, leave the boiler if the outside pressure was equal to the inside one. Equally clear it must be that we could not get the work (energy) out of the boiler except by the steam, and it could not get out if the outside pressure was greater than the inside one. It will now be easily seen that to obtain work (energy) transmitted from the boiler to the engine, the vehicle which carries it is a material substance, and to move that substance, (H_2O) work must be expended. Now, the work expended in moving the mass is still work (energy), but in the *kinetic state*, and, when projected into a steam engine cylinder, appears as heat. We have thus our original amount of energy in two distinct forms, their relative quantities depending on the velocity of the steam along the passages. The effect of this in a steam engine is readily seen, for, when we increase the velocity, the pressure on the piston is less than we previously had in the boiler. This is simply a gravitation problem, the pressure representing gravity. However, the mass moved is not constant, as it depends on the pressure.

MR. W. H. NORTHCOTT

(VICE-PRESIDENT).

Mr. WEIR's paper is, I think, chiefly valuable for being a bold attempt to grapple with a question that has long exercised the minds of Engineers. Why should there be so much discrepancy between the calculated quantity of steam per indicated horse power per hour, and the measured quantity? Some fanciful writing has no doubt been indulged in by youthful scientists in explanation of the Molecular theory of heat, but he who seeks to demolish the work of Rankine, Clausius, and Clerk Maxwell, should be unusually well provided with intellectual " Energy." No engineer has yet met with a non-conducting cylinder or with a perfect gas. But the practical engineer who doubts the usefulness of these conceptions will probably alter his opinions if he attempts to study thermodynamics without their aid. These conceptions have unquestionably misled engineers into overestimating the advantages of using high rates of expansion under usual conditions, but the misleading has been at least as much the fault of the misled as of the misleaders.

I venture to believe that the discrepancy between theory and practice referred to by Mr. WEIR, can be explained without discrediting the teachings of the great thermodynamists, and the results calculated by physical formulæ as simple almost as the empirical formula so properly admired by Mr. WEIR.

A good part of the paper appears to be scarcely relevant to the subject, and the use of old terms with new meanings tends to confuse rather than to elucidate. On page 11 Mr. WEIR specially emphasises his view—"that bodies are endowed with heat energy when they are capable of giving out heat to other bodies," but he surely does not mean to maintain that a hot coal surrounded by other coals equally hot, is *not* endowed with heat energy? Unless he does, the ghost of Rankine will not trouble him; nor will the thermodynamists quarrel with the remainder of his specially emphasised views.

The definitions on pages 11 and 12 are as easy to understand as Bradshaw, but luckily it is not necessary to understand them. Mr. WEIR's formulæ confuse "temperature" with "heat," but apart from this they mainly serve to obscure the subject. If I understand Mr. WEIR correctly, his views may be expressed in very few words.

1.—No steam engine in practice can be made to develop more power per pound of steam generated than the P V equivalent.

2.—The heat used per pound of steam is less when the feedwater is raised to the temperature of the exhaust than when the feed is sent to the boiler at a lower temperature.

3.—The economy of stage expansion engines is increased by using a WEIR's feedwater heater in connection with each cylinder

No thermodynamist will gainsay the second enunciation. The efficiency of Mr. WEIR's feedheaters is too well established to be open to question, and I have no doubt stage heating will conduce to economy. Mr. WEIR's first proposition, however, requires a deal of proof, and I hope he will give us in full the experimental data that have led him to such a conclusion.