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"STEAM POWER"

BY

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The generation and utilization of Steam for Power purposes is a subject which is of vital importance to all engineers. Although not historically the first prime mover, steam power was the first to be developed on an extensive scale. It was the first prime mover, moreover, which was independent of natural phenomena, and was consequently more flexible than its predecessors. For over a hundred years it was supreme. Towards the end of the 19th century, however, other prime movers came into use and to-day the supremacy of steam as a means of liberating power is by no means unchallenged. The problem of all prime movers is to get the maximum of useful work from a given source of energy and it is the aim of this paper to outline to what extent steam power achieves this result.

All prime movers fall into two broad classes. First, prime-movers which harness natural phenomena, such as air-power and water-power. This class of prime mover is dependent upon a supply of energy which is not controllable, nor flexible and is therefore restricted in its application.

The second class of prime movers are those which liberate and utilize the energy of fuels. This energy is liberated in the form of heat by combustion of the fuel and the heat is transformed into mechanical work by the prime mover. The transformation is effected by causing a rise of temperature in a working substance, and hence obtaining a range of pressure. This pressure difference is a mechanical phenomenon which can be easily harnessed for practical purposes. The working substances most usually employed are air and steam, although other substances, notably ether and sulphur dioxide have been used in special cases. The pressure difference in the working fluid is used either to drive a piston in a cylinder, or to drive a turbine.

Air is the working fluid in the internal combustion engine. The heat-contents of the fuel are liberated on the explosion of a carburetted mixture of the fuel and air in the cylinder itself. This causes a rise of pressure in the resulting mixture of gases, of which air is the largest component. The internal combustion engine has thus only one main organ—the cylinder, and this fact is a great point in favour of this type of prime mover.

Where steam is the working fluid, the combustion of the fuel takes place in the furnace of a boiler and the steam produced is lead away, either to the cylinder of an engine or to a turbine, to perform its work. The steam engine, therefore, has two main organs. First the steam generator or boiler, and second, the steam consumer, cylinder or turbine. The problem is thus of a two-fold character, comprising steam-raising and steam-using. It is convenient to regard them separately as far as possible, but the two aspects of the problem react upon one another and it is impossible completely to separate them.

Efficient steam raising aims at the transference of the maximum of the heat-contents of the fuel into the water in the boiler. Boilers are divisible into two main classes, fire-tube and water-tube. Both classes can be subdivided into many types which are all more or less familiar to members of this Society. The extent to which each type is successful in transferring the heat of the fuel to the water is shown by the following table :—

Boiler.	Efficiency %	Authority.
Tank (Lanc. & Cornish)	45—75 (Av. 60) ...	Kempe.
Loco. on Rail	42—80 (Av. 65) ...	G.W.R., etc.
Loco. Stationary...	40—50 (Av. 45) ...	G.W.R.
Water Tube	50—75 (Av. 65) ...	Kempe.
Marine (Scotch) ...	60—70	Kempe.
Bonecourt	90	Low.

The efficiency is defined as the heat transferred to the water evaporated by the combustion of one lb. of dry fuel, divided by the calorific value of the fuel.

Ignoring for the moment the Bonecourt Boiler which is a recent development, it is seen that the range of efficiencies is very large. An average has been estimated at 72% (Kempe). From 40% to 80% is a wide variation. What factors affect this figure and to what extent?

In the first place it is essential that the heat-contents of the fuel be wholly liberated—hence the first aim is perfect combustion. This depends entirely upon the adequate supply of air to the fire. A pound of good steam coal requires about 12lbs. of air as a minimum for complete combustion, and fuel oil about 14lbs. per lb. of oil. If this figure is not reached valuable gaseous fuels produced by the partial combustion are carried up the chimney and their heat content is lost. Analysis of the flue gases will show whether the air supply is adequate or not and adjustments can be made to correct any deficiency. If the figure is exceeded, heat is lost in raising the temperature of the extra air with consequent lowering of the furnace temperature. The furnace temperature is also affected by the rate at which the fuel is burned, being lower, the lower the rate of combustion. The rate of combustion is, as may be supposed, entirely dependent upon the rate of air supply, that is upon the draught. In general, furnace draught is of two kinds—natural and artificial. The use of natural draught involves the erection of tall chimney stacks, which are expensive, and moreover, the draught depends upon the high temperature of the exhaust gases. These hot gases carry away valuable heat, hence natural draught is very unsatisfactory. Artificial draught is of three kinds—induced, forced, and draught produced by the effects of a jet of steam or air. Both induced and forced draughts are dependent upon a fan which draws air over the fire, in the case of induced draught, and forces air over the fire in the case of forced draught. In general, forced draught is preferable to induced, since a smaller fan is required. The following figures of the rates of combustion achieved by natural and forced draughts give an idea of the relative merits of the two systems :—

Type of draught.	Vacm. prod. Inches of water.	Rate of Combustion. lbs. per sq. ft. G.A. per hour.	Remarks.
Natural	$\frac{1}{4}$ to $\frac{3}{4}$	15 to 25 or 30	
Forced (Moderate)	$\frac{3}{4}$ to $1\frac{1}{4}$	25 to 35	
Forced (Naval) ...	2 to 3	50 to 60	Water Tube Boilers

These figures refer to the combustion of good quality coal. The rate of combustion has an effect on the efficiency of the boiler. As the rate increases, the efficiency increases up to a point, beyond which it falls off. The maximum appears to be reached when the rate is about 25 to 30 lbs. per sq. ft. G.A. per hour. Above this rate the high velocity of the draught increases the loss due to unburned fuel and the smaller air supply per lb. of fuel increases the loss due to incomplete combustion. Below this figure the combustion is more perfect but the loss due to the heating up of a larger quantity of air per lb. of fuel reduces the final efficiency.

Where the grate area of the boiler is large the quantity of coal fired per hour at high rates of combustion becomes very large and resort is made to mechanical stoking.

The preceding remarks concerning draught refer to land boilers and marine boilers. The draught problem on the locomotive is somewhat different. Here the draught is caused by the exhaust jet of steam entraining air and thus causing a partial vacuum in the smokebox. The draught thus produced depends upon the velocity of the jet, which in turn depends upon the rate at which the engine is working. Hence the draught on a locomotive boiler is not constant. When stationary the draught is almost zero, and thus special provision has to be made for the creation of a draught. When running the draught may reach as high a figure as 8 inches of water, with a correspondingly high rate of combustion. It is thus apparent that the locomotive boiler accommodates itself practically automatically to the demands made upon it. The rates of combustion reached on locomotives are very high, varying normally from 60 to 90 lbs. per square foot G.A. per hour. Much higher figures have been quoted, some as high as 200. The falling off of the efficiency of the boiler at these high rates of combustion is very noticeable, however, and is due in a very large degree to the loss of unburned fuel thrown from the stack, as seen in Fig. 1. In America the high rates of combustion have warranted the introduction of mechanical stoking for the larger locomotive boilers.

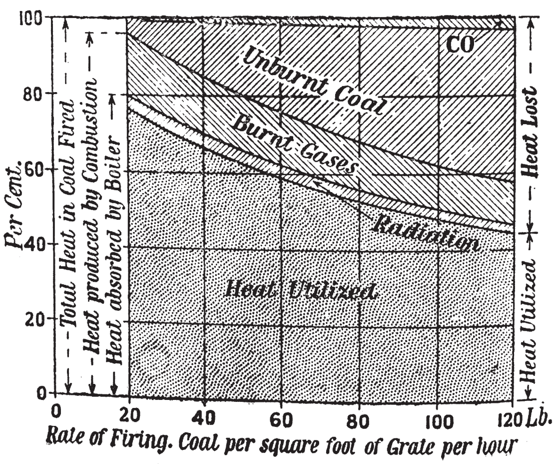


Fig. 1.

Having achieved complete combustion as nearly as practicable and thus liberated the maximum of heat from the fuel, the next step is to transfer the largest possible amount of this heat to the water.

The rate at which heat is transmitted through a large plate, the sides of which are maintained at two different constant temperatures, depends in the main upon the temperature difference. Fig. 2 represents the theoretical temperature difference and also

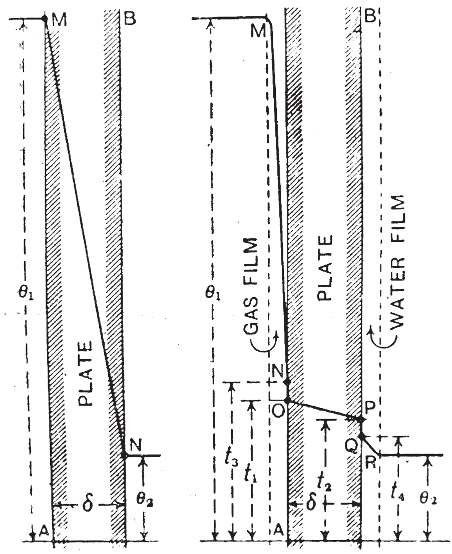


Fig. 2.

that which actually obtains. The enormous reduction in the temperature drop across the plate, compared with the actual difference between the temperature of the flue gas and the water, is due to the existence of films of comparatively stagnant gas and water which adhere to the plate. These films are very bad conductors and require large temperature heads to cause the heat to flow across them. The thickness of the gas film is ordinarily about .025″ and that of the water about .01″. A reduction of these thicknesses and a consequently greater useful temperature head across the plate may be effected by increasing the velocity of flow of the gas and water across the surface of the plate. This demonstrates very clearly the necessity of ensuring satisfactory circulation in the boiler and high gas speeds through the flues. Fig 3 shows the apparent circulation in a locomotive boiler as suggested by experiments conducted with a special boiler. The inherent tendency for the water to follow such a path has caused the arrangement of feed pipes as shown. Where top feed is adopted the trays are frequently inclined to produce a similar result. The influence of circulation on the efficiency of a boiler is demonstrated when a locomotive type boiler is used as a stationary boiler. It is found that such a boiler will not steam nearly so well as when used on the road. This is largely due to the fact that the riding of the locomotive produces a shaking up of the water in the boiler which considerably aids circulation. This effect is lost when the boiler is used stationary, with a consequent reduction of the boiler efficiency.

The gas speeds are of course, dependent upon the draught and the area of the flues. Obviously a reduction in the size of the flues is limited by considerations of heating surface. Pettigrew

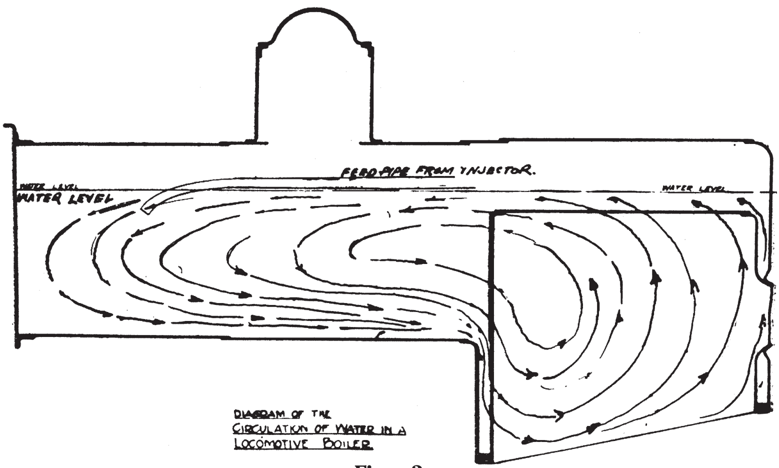


Fig. 3.

suggested, for locomotive boilers, that the flues should have their internal diameters about 1-90th of their length and this figure has been very widely followed. In the case of water tube boilers the gas speed is affected by the arrangement of the baffles in the furnace. The differences between the various types of water tube boilers are mostly in the arrangements of the baffles and tubes.

An average figure for the heat transmitted through the plates and tubes of a boiler is 71.7% of the heat-content of the fuel. This figure leaves 28.3% of the heat untouched. Attempts are made along three lines to utilize some of this heat. In one case the feed water is heated by some such device as a Green's Economiser, or other flue gas feed heater. This, of course, reduces the heat to be supplied by the boiler, with evident economy. A second method is to heat the air prior to passing it through the furnace. This results in a high furnace temperature, but it can only be done when forced or induced draught is used. The third way in which waste flue gas heat is utilized is to superheat the steam by means of smokebox superheaters. Where superheaters are fitted at the expense of evaporative heating surface it is problematical whether a gain in boiler efficiency results, but where the superheater utilizes the heat otherwise going to waste, the economy is obvious. Further aspects of superheating will be considered when dealing with steam using.

The final average result of the burning of coal in the furnace of a boiler is indicated in Fig. 4. Eighty-five per cent of the

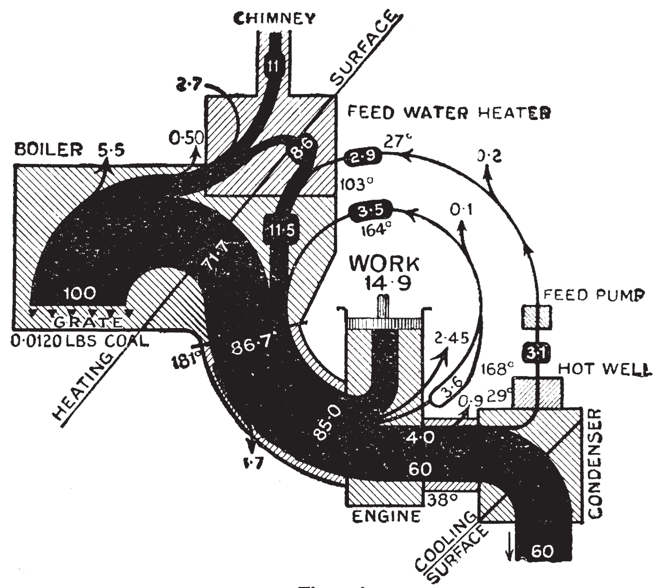
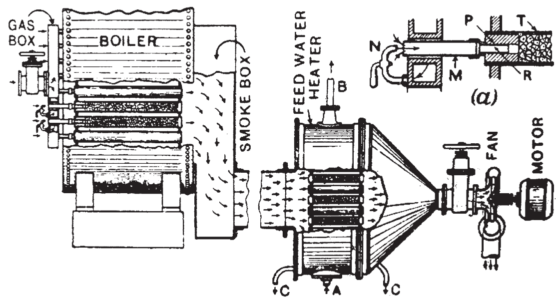


Fig. 4.

heat content is definitely in the steam and is available for use in the engine. Of the remaining 15%—2.7% goes in radiation, 11% goes in loss due to heat carried away by flue gases and in unburned fuel, and 1.3% goes in losses in feed heaters, etc. To improve on these figures will mean modifications and additions to the boiler plant. While all such efforts are desirable it is to be noticed that a sound economy is only effected when the upkeep of the apparatus installed does not nullify the saving effected.

Attempts are continually being made to improve the efficiency of steam-raising and one—the Bonecourt Boiler (Fig. 5) calls for comment. This boiler utilizes the phenomenon of surface combustion to effect a most economical process of steam-raising.

When a mixture of fuel gas and sufficient air for its combustion is directed against an incandescent mass of porous material such as firebrick, the gas burns without flame at the surface of the firebrick and a very high temperature is produced. In the surface combustion boiler which has been developed by Prof. W. A. Bone, and Mr. C. D. McCourt, crushed firebrick is packed into the tubes of a boiler and a feed heater. The firebrick is raised to incandescent heat by means of a flaming jet of the gas passing through the tubes. This jet is then shut off, extinguishing the flames, and then it is



1.—Bonecourt surface combustion boiler.

Fig. 5.

immediately turned on again. The gas then burns without flame and the temperature of combustion is very high. The combustion is so complete and the plant is so effective that an efficiency of 90% has been claimed. One of these boilers has been erected for trial at the National Fuel Research Laboratories and the results of extended tests and observations will be awaited with interest.

A further novel method of steam-raising, upon which comment has recently been passed in the daily Press is the Brunler boiler. This apparatus injects a carburetted mixture of fuel and air under water in a steel container. The mixture is ignited under the water and the combustion proceeds in the ordinary way, the whole of the heat being given up to the water. It is claimed that the efficiency of the apparatus is 100%, if not more! Such a claim is, of course, markedly fantastic; further details and figures may, however, foreshadow some important developments in the theory and practice of steam-raising.

Considering now the question of using the steam, it is obviously true that if an engine performs a cycle of operations in which it takes up heat, does work, and rejects heat then

Heat taken up = Work done + heat rejected.

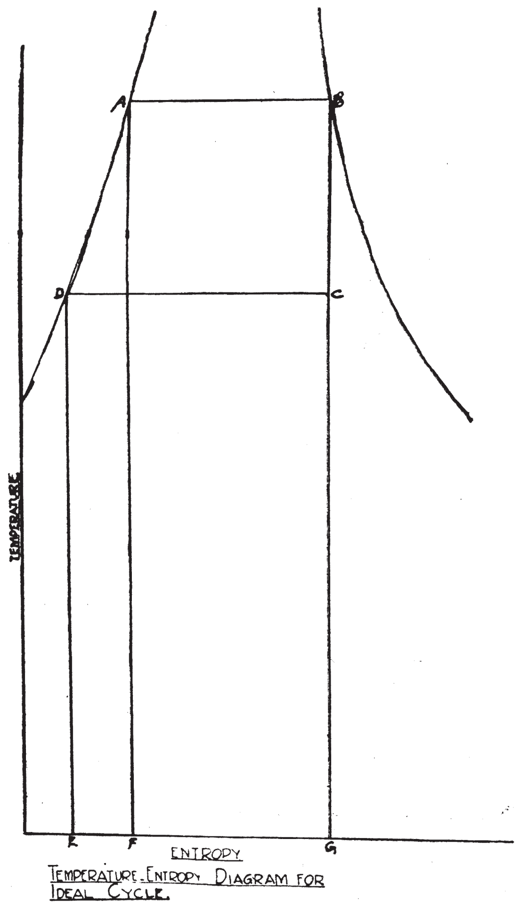


Fig. 6.

The efficiency of the cycle is of course work done ÷ heat taken up. This cycle may be most conveniently represented graphically. In Fig. 6, area represents heat and ordinates are temperature. One pound of water is considered. The process of raising the temperature of the water from feed temperature to that corresponding to boiler pressure is represented by the line D.A. and the heat necessary by the area D.A.F.E. The further process of evaporation is represented by the line A.B. and the heat involved by the area A.B.G.F. This is, of course, the latent heat of evaporation. The heat entering the cycle is thus the area D.A.B.G.E. If the steam thus produced is expanded adiabatically, doing work, to the pressure corresponding to the initial temperature, and is then condensed the area A.B.C.D. represents the work done and the area D.C.G.E. represents the heat rejected. The efficiency of the cycle is obviously A.B.C.D. over A.B.G.E.D. The cycle thus illustrated is the theoretically most efficient cycle possible for steam working over such a temperature range. It is apparent that the wider the range of temperature involved, the higher will be the efficiency. A range between 101° F. (corresponding to a condenser pressure of 1 lb. per square inch abs.) and 397° F (Corresponding to a boiler pressure of 225 lbs. per square inch gauge) gives an efficiency on this ideal cycle of 30.68. Lower condenser pressures are not satisfactory for reciprocating engines, because in order fully to benefit from the low pressure, the engine would have to expand the steam down nearly to that pressure. This would entail enormous cylinders and the gain would be nullified by extra mechanical friction consequent thereon. Higher boiler pressures are possible, but the resulting temperature increase and hence the increase in efficiency are small compared with the increase of pressure. Moreover a boiler constructed to work at such high pressures will cost more to maintain and will present design problems which may be difficult of solution. In this connection water tube boilers are definitely advantageous. The absence of large cylindrical shells makes high pressures possible without unduly high working stresses in the material. Boilers are sometimes constructed to work at pressures up to and even above 350 lbs. per sq. in., but such pressures are by no means common and 250 lbs. per square inch may be regarded as high compared with the average. The diagrams in Fig. 7 show the effect on the ideal efficiency of an engine when (a) the condenser pressure is kept constant and the boiler pressure is varied and (b) the boiler pressure is kept constant and the condenser pressure is varied, the steam being assumed dry saturated at commencement. When an engine is non-condensing the lower temperature limit is fixed by the prevailing barometric pressure and is in general about 212° F. The ideal efficiency of an engine working over a range of from 225 lbs. per square inch gauge to atmosphere (14.7 lbs, per square inch abs.) is 19.89%. This engine working with a condenser pressure of 1 lb. per square inch absolute has an efficiency, as seen, of 30.68%. The economy effected by condensing is thus obvious. If the steam be superheated a further increase of the ideal efficiency is effected. This increase is small, however, being in general about 4 to 5% of the efficiency when using saturated steam. This, in itself, is a small economy, but a greater economy is effected by superheating in reducing the condensation losses in the cylinders and it is in this latter direction that the chief economy is effected.

The ideal efficiency of any prime mover using steam is thus limited by practical considerations and in general will not be greater than 35.5%. This corresponds to saturated steam at a boiler pressure of 400 lbs. per square inch abs., and a condenser pressure of 0.5 lbs. square inch abs.

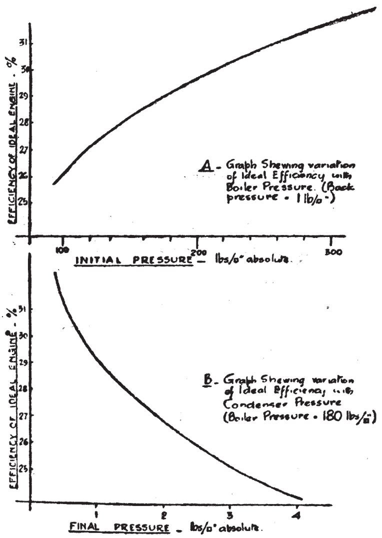


Fig. 7.

The ideal cycle shown on the temperature-entropy diagram may also be represented on a pressure volume diagram. In this ideal diagram the shape of the expansion curve for saturated steam is, however, very uncertain. For superheated steam the expansion is of the form $pv^{1.35}=K$. Zeuner suggested that for saturated steam it had the form

$$pv^{m}=K.$$

He gave m the value

$$m=1.035+0.1q.$$

where q is the initial dryness fraction. This, however, is not the case. Consider the expansion of steam from 225 lbs. per square inch abs. dry saturated to atmospheric pressure. The correct ideal adiabatic curve plotted from information obtained from the temperature-entropy diagram, is A.B. (Fig. 8). The Zeuner curve, having m = 1.135 is C.D. For practical purposes the shape of the curve is taken to be hyperbolic, *i.e.*,

$$p.v. = K \quad \text{(line E.F.)}$$

and for calculations concerning hypothetical indicator cards this curve is used.

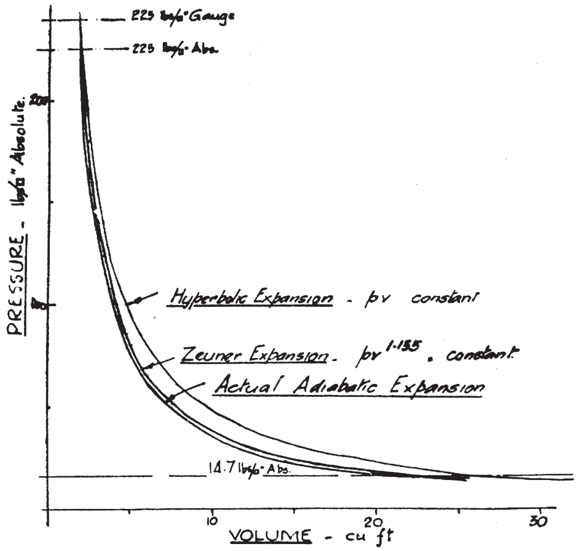


Fig. 8.

A further modification in arriving at the theoretical indicator diagram is to stop the expansion short and not to continue it right down to the condenser pressure. This eliminates the long "toe" of the diagram. This theoretical indicator diagram is compared with the ideal pressure-volume diagram corresponding to the ideal cycle, in Fig. 9.

The ratio of the area of the actual indicator card obtained from the engine to the theoretical indicator card is known as the "diagram factor." This figure ranges from 70 to 95% and varies with the size of the engine.

In practice the actual indicator card falls short of the ideal for various reasons. Fig. 10 shows a typical engine indicator card for a non-condensing engine compared with the ideal pressure-volume diagram. The area included between the two lines represents the various losses which occur. Shaded area

A. represents the loss due to drop of pressure in the steam pipe. In order to reduce this loss it is advisable to have the steam pipe as short as possible, of large diameter and well lagged. The area B. represents loss due to condensation as the steam

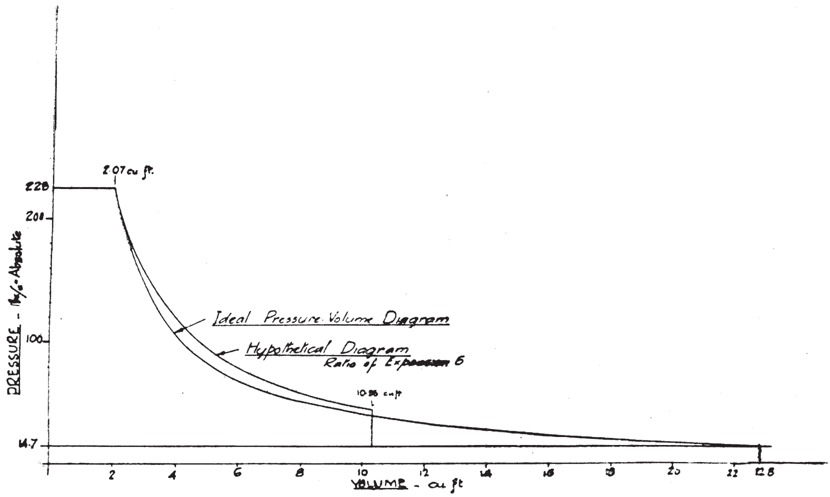


Fig. 9.

expands, and the loss due to leakage. These losses may be reduced by jacketing and by the use of superheated steam. It is in this connection that superheated steam effects the most economy. The Uniflow Engine which formed the subject of a

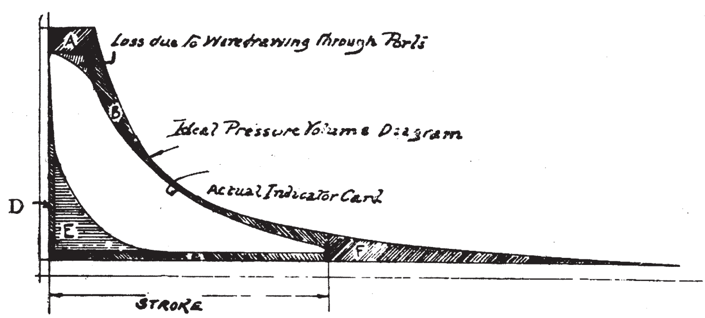


Fig. 10.

recent paper read before the Society shows a marked decrease in the loss due to condensation. The area C. represents the loss due to the difference between the exhaust and condenser pressures, the work thus lost being used in causing the steam to flow from the cylinder to the condenser.

The area F. represents the loss entailed by not expanding down to the back pressure. The area E. represents the loss in compression, which although it reduces the useful work in the cylinder is a practical necessity, since it is expended in bringing the reciprocating parts of the engine to rest gradually. The loss in the clearance passages is represented by area D. This loss is somewhat reduced if the compression is carried to a figure approaching admission pressure, since less steam is used per stroke. Very high compression, however, seriously reduces the effective work and is only adopted in high speed engines. The rounded corners of the diagram are, of course, due to the throttling of the steam through the ports and past the valves as they close. The wiredrawing losses through the ports may be reduced by increasing port areas and reducing friction in the steam passages. The wiredrawing past the valves can be reduced by increasing the velocity of the valve at opening and closing and by maintaining the maximum port opening for as long a period as possible. Slide valves, in general, are not so satisfactory in this respect as tappet valves.

The ratio of the actual thermal efficiency of the engine to the ideal thermal efficiency is called the "Efficiency Ratio." This figure is quoted below for various types of engines :—

Engines.	Effic. Ratio %.
Single Condensing	50-65.
Two Cylinder Compound	65-75.
Triple Expansion	68-75.
Uniflow	60-75.
G.W.R. "Castle" Class Loco.	56.

The mechanical efficiency of the steam engine at full load varies from 70 to 90%. When the engine is not working at full load the mechanical efficiency, of course, is less, with consequent effect upon the steam consumption. The engine tends, however, to become uniformly efficient at all loads when using superheated steam, principally due to the reduced condensation losses.

The solution which the reciprocating condensing engine offers to the fundamental problem of the prime mover is demonstrated by the diagram shown in Fig. 4, which shows the heat flow through the whole of an average plant. Starting with a stream 100 units wide, representing the heat of combustion of the fuel, 71.1 units pass direct to the water. There is a loss of 5.5 units due to radiation and a further loss of .5 units on the way to the feed heater. Here 2.7 units are lost in radiation and 8.6 units are absorbed by the feed water. The waste gases carry

11 units up the chimney and the final result of the boiler plant is 8.6 units absorbed by the feed heater and 71.7 units absorbed by the boiler itself. The feed water itself has brought with it 2.9% of the original heat which it has salvaged from the hot well and the total feed heat stream of 11.5 units, together with a stream of 3.5 units wide from the jackets joins the main stream of 71.7 units through the boiler to give 85% of the original heat in the steam. In the steam pipe 1.7 units are lost. In the cylinder 14.9 units are transformed into work. In passing it may be said that this 14.9 is further reduced by the mechanical friction of the engine to a figure of about 12.4 units of work, actually available at the crank shaft. Continuing with the heat stream in the engine, 2.45 units are lost in engine radiation and 3.6 units go to the jacket, of which .1 is lost in radiation from the jacket. In the condenser 60 units are lost in the cooling water and the remaining 4 units lose .9 in the way to the hot well and a further .2 from the hot well to the feed pump.

A heat energy stream diagram (Fig. 11) through an average locomotive shows a final result of 4% of heat of combustion utilized for traction purposes. Here losses due to

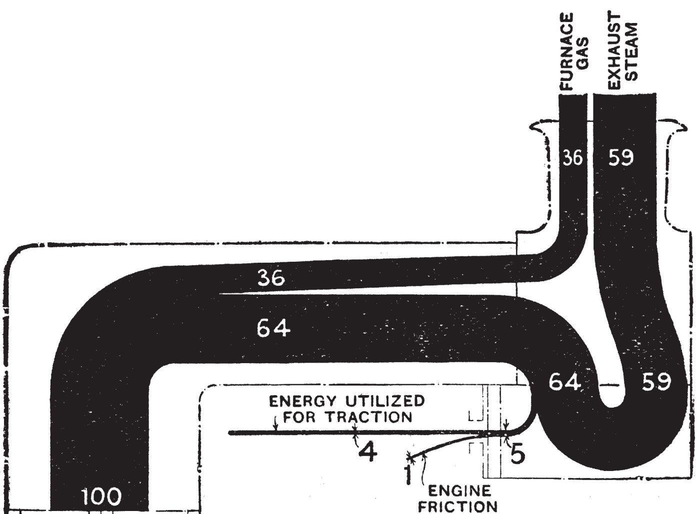


Fig. 11.

radiation and unburned fuel have been neglected. Fig. 12 shows a typical heat energy stream through a "Castle" Class Locomotive as revealed in the published results of the recent trials of "Caldicot Castle." It should be noticed that this diagram does not represent the results of any one test, but the general inferences from the whole series of tests.

In view of the low figures for the ratio of useful work to heat of combustion it may well be suggested that the day of the reciprocating steam engine is done. The one great point in its favour, however, is that it is a very simple machine, compared with other prime movers and it requires considerably less attention. In addition it is very flexible, starts easily and is very reliable. In view of these practical advantages the opinion of the author is that the day of the reciprocating steam engine is by no means ended.

The other prime mover which uses steam as a working substance is the turbine. A turbine is, of course, a wheel upon which are mounted blades forming passages through which the steam flows, causing the wheel to revolve and thus doing work.

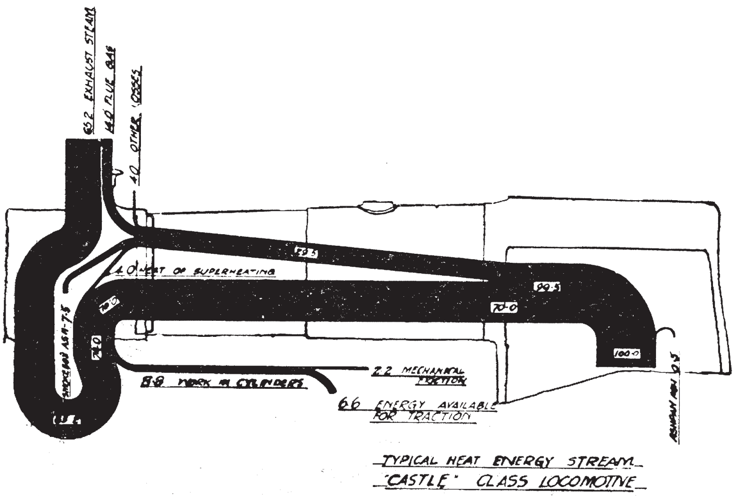


Fig. 12.

The ideal cycle of operations for a turbine, however, is exactly the same as that for a reciprocating engine working between the same temperature limits. The reciprocating engine, of course, utilises the pressure difference corresponding to the temperature range to operate a piston and crank mechanism, whereas a turbine utilizes the pressure difference to produce on the steam flowing through it, a change of momentum in a direction tangential to the circumference of the wheel. The change of momentum is effected in various ways, and turbines are classified, according to which method is adopted, into two main groups—Impulse and Reaction. An impulse turbine is one in which the rotor is driven entirely by the impulse of jets of steam impinging upon blades attached to it. De Laval, Curtis, Zoelly, and Rateau turbines are of the impulse type. The de Laval turbine expands the steam in one stage and extracts the resulting kinetic energy in one step. The Curtis, Zoelly and Rateau turbines have several stages for expansion. A turbine of the Zoelly and Rateau type may be described as a series of de Laval wheels. Curtis turbines consist of stages in each of which expansion takes place in one set of fixed nozzles and the kinetic energy is extracted in a series of steps.

A Reaction turbine is one in which the reaction of steam expanding in the nozzle causes the nozzle to move. Turbines operating by pure reaction alone are not practicable. A type of turbine which combines the reaction and impulse of expanding steam is the Parsons turbine. In this turbine the steam expands continuously through fixed passages and moving passages, the general direction of flow being axial. In the Ljungstrom turbine the general direction of flow is radial and both sets of blades are moving. This gives a high relative velocity, and a consequently greater stage efficiency, with a normal rate of revolution of the wheels. The kinetic energy resulting from the expansion in the one series of passages is extracted in the other series of passages, where, however, a further drop in pressure takes place, with consequent reaction on the wheel. Thus the wheels are caused to revolve both by the impulse of the impinging jets and also by the reaction of the leaving jets.

It is obvious that which ever type of turbine is considered a complete knowledge of the nature of the flow of steam through nozzles is very essential. The history of this theory is very interesting and a fascinating sequence of events led up to our present advanced state of knowledge of the problem.

The discharge per unit area of cross section of a nozzle will be a maximum at the throat. If the steam be assumed to expand according to some such law as

$$p\,v^{m} = K.$$

then it can be shown that the maximum weight flow through the nozzle will occur when

$$\frac{P_t}{P_1} = \frac{2}{(m+1)}^{\frac{m}{m-1}}$$

where P_1 refers to the initial state and P_t to the state at the throat. It is thus apparent that the discharge is independent of the final state P_2. Professor Osborne Reynolds suggested that this is due to the fact that the velocity of flow at the throat is then equal to the velocity with which sound, or any other wave of extension and compression is propagated through the fluid. It is thus impossible for any lower pressure than P_t to make itself felt at the throat. The final velocity at the exit from the nozzle, of course, will be higher than the velocity at the throat and will depend upon the difference between P_t and P_2, but the weight of discharge from the nozzle depends only upon the initial pressure P_1 and the throat pressure P_t.

It has been previously shown that the adiabatic expansion of saturated steam was assumed by Zeuner to follow the law

$$p\,v^{1.035\ +\ .1q} = K$$

where q = dryness fraction.

If the steam is initially dry saturated this becomes

$$p\,v^{1\cdot135} = K$$

Putting this value for "m" into the relation for maximum weight flow through a nozzle

$$\frac{P_t}{P_1} = \left(\frac{2}{(m+1)}\right)^{\frac{m}{m-1}} = .577.$$

The theoretical discharge from the nozzle can easily be calculated from these figures. Experiments showed, however, that the flow from a nozzle was actually greater than that calculated. This was all the more strange since, in calculating the theoretical flow, no account was taken of friction which would certainly reduce the flow in practice. Various ingenious attempts were made to account for this discrepancy. Professor Rateau, in particular made some exhaustive experiments and allowed for any initial moisture which might have been in the steam. Professor Callendar commenting on these experiments, says : "In spite of this, his results were too high according to the theoretical formula, and he was unable to reduce them to the desired limit, although he considered and applied carefully all possible corrections tending to reduce the discharge, but omitted to mention at least one very important correction acting the other way." An explanation was offered by Professor Callendar, in a paper read before the Institution of Mechanical Engineers in 1915, from which the foregoing remarks were quoted. The explanation, which has satisfactorily withstood all tests applied to it is that the effect of the very short interval of time in which the expansion takes place, is sufficient to alter the conditions of expansion from those ordinarily obtaining to something very different. When steam initially dry saturated expands adiabatically slowly, condensation takes place as the expansion proceeds and the whole fluid is in a state of complete stability. When steam is expanded very rapidly, however, experiments have shown that condensation does not take place accordingly and the steam become supersaturated ; that is, although its pressure is lower than that corresponding to saturation it remains dry and is said to be in a "metastable" state. The law for the expansion of steam in this metastable state is

$$p\ v^{1\cdot 3} = K.$$

which is the same as that for superheated steam. Using this value for "in" the condition for maximum weight flow through the nozzle

$$\frac{P_t}{P_1} = \frac{2}{(m+1)}^{\frac{m}{m-1}} = .5457.$$

This gives a calculated discharge which is slightly higher than the experimental figure, the difference being consistent with the effects of friction. The whole process can be effectively demonstrated on a Mollier chart of Total Heat and Entropy (Fig. 13). The steam, which need not necessarily be superheated at commencement, when expanded adiabatically under normal equilibrium conditions, would reach the point "C," and the corresponding adiabatic heat drop is measured by the line "A C." When expansion is metastable, however, the heat drop is "A B," the point "B" lying on the line of constant pressure for superheated steam which is carried into the wet region because the steam is supersaturated. The heat drop for metastable expansion is thus less than that for equilibrium expansion. When the steam regains equilibrium conditions it does so at constant total heat and constant pressure. This process is represented by the line "B D." The steam at the finish is thus drier, and has more entropy and more total heat than if it had expanded under equilibrium conditions.

The experiments which aided Professor Callendar to these conclusions, were conducted in 1897 by, C. T. R. Wilson. They consisted of experiments on the nature of the condensation of mixtures of air and water vapour, when expanded very rapidly. They afford a striking example of the value to engineering of abstruse experiments in pure physics, which apparently could have no bearing on any practical problems.

The effect of these conclusions upon the theory of turbine design is at once apparent. In all types of turbines the change of momentum of the steam in the direction of rotation is the measure of the work done by the turbine. The change of momentum is dependent upon the velocity of the steam and on the weight of steam flowing through the turbine. The velocity and weight are both affected by the supersaturation effect referred to. In Professor Callendar's Steam Tables figures are given which take this effect into consideration.

The efficiency ratios for various types of turbines are shown in table.

Type of Turbine.	Efficiency Ratio. Per cent.
Parsons	56-67.
Curtis	65-70.
Zoelly	67-70.
Rateau	60.

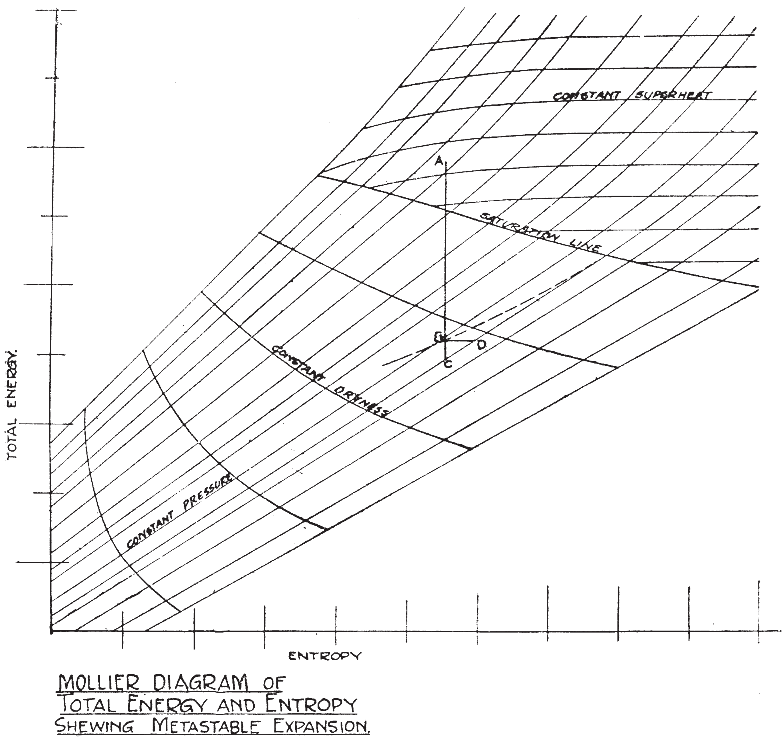


Fig. 13.

The shaft H.P. is usually about 98 per cent. of the work done on the rotor. If the Efficiency Ratio is taken at 70 per cent. and assuming a boiler efficiency of 85 per cent. and an ideal engine efficiency of 34.5 per cent., corresponding to a boiler pressure of 360 lbs. per sq. inch absolute, saturated steam and a condenser pressure of .5 lbs. per sq. in. abs., the final overall efficiency of useful work to heat of combustion is 19.75 per cent.

This is nearly 50 per cent. in advance of the efficiency of the average reciprocating engine quoted and demonstrates that the turbine is a much more economical prime mover than the reciprocating engine.

It is, however, a much more delicate machine and requires careful handling. If allowed to get out of condition, either in itself, or in any of its auxiliaries, its efficiency suffers very considerably, but when working under satisfactory conditions it is undoubtedly the finest prime mover in existence.

This brief summary of the problems of steam power has necessarily left many points untouched. Sufficient has been said, however, to indicate the complexities of the problem and to demonstrate that there is an immense field for further research. It is of especial importance to British engineers that research into steam problems be encouraged, for it is certain that in this country, at all events, steam power has no serious rival.

The Author desires to record his thanks to Professor Low and Professor Dalby and Messrs. Arnold and Co., for the permission to reproduce diagrams.

DISCUSSION.

In opening the discussion, the Chairman (Mr. Cook) said he felt sure that all present would feel that the time had been well spent, and he would like to congratulate the author for his interesting paper. Particularly, he would like to say how much he enjoyed the comparative tables of boilers, engines and turbines, and also the heat energy steam diagrams for the ordinary locomotive, and also for the "Castle" class, particularly the latter. He referred to the last paper read before the Society by Mr. J. G. H. Warren, in which he (Mr. Warren), emphasised the difficulty which confronted the earliest designers of locomotives; namely, to concentrate the whole of the then existing steam engine on to a carriage. This state of affairs was still apparent when it was realised that the "Castle" class boilers, although not so bulky, generate more steam than the Stirling boilers at the Central Boiler Station. In spite of this higher rate of output, the Stirling boilers left a higher proportion of unburnt fuel than the "Castle" class boilers.

He had received a communication from Mr. Dumas to the effect that he was unable to attend, but would like to contribute to the discussion :—

"In reading Mr. Dymonds' paper, I could not help thinking that he had made out a case for the electrification of railways.

If the overall efficiency of a turbine is nearly 20 per cent., while that of an average locomotive is only 4 per cent., this means that a given quantity of coal will produce nearly five times as much work in a power-house as at the drawbar of a locomotive. I am not an electrician, but it seems to me that when all conversion and transmission losses have been deducted this should still leave a substantial amount of money available for covering interest on cost of equipment. On the other hand, I was surprised to learn how nearly the efficiency ratio of a "Castle" class locomotive approaches that of a simple condensing engine. I should have imagined it to be very much less in proportion. In the "Daily Telegraph" for March 2nd last, there is an article on steam generation, which is well worth reading by anyone interested in steam production. In it the author refers to some experiments with steam at a pressure of 3,200 lbs. per square inch, with a corresponding temperature of 706°F. At this pressure water turns gradually into steam, which occupies the same volume and absorbs no latent heat. A special plant using steam at this pressure is projected, and it is estimated that it would have an efficiency of 30 to 35 per cent."

Mr. C. T. Cuss referred to Professor Bone's research, remarking that ten or eleven years had elapsed since the results of the research were published. In view of the very high efficiency quoted to-night, he would like to know why during that period of time, progress had been so slow. Could the author suggest any reason to prevent the Great Western from attaining such great efficiencies? He thought it very strange that coal is still being consumed in open grates in 1925. With regard to the combustion of fuel under water in the Brunler boiler, he would like to know what effect the products of combustion would have on the fabric of the boiler. He would like to congratulate the author on the very interesting diagram of the heat energy stream for "Castle" class, after the manner of Professor Dalby, even if it were not quite correct. He would like to draw the attention of the meeting to the Michell Crankless Engine which was a perfectly balanced prime mover. He would like to know whether the adoption of this crankless engine for locomotive, would enable some of the waste heat to be utilised. He observed that the theoretical efficiency was always much greater than that obtained in practice, and he would ask if any practical tests could be instituted to each locomotive as it came from the shops, so that conditions nearer to the ideal might be attained. He then proceeded to describe such a test, using as a basis for comparison diaphragms with various sized holes through which just sufficient steam could be passed to move the locomotive.

Replying to the Chairman's remarks on the higher output of the "Castle" class boilers, the author said that this underlined his remarks concerning the shaking-up effect due to the road, which effect was always present with a locomotive no matter how good the road. Such shaking up must materially assist the circulation which tends to increase the steaming capacity. Referring to the higher proportion of unburned fuel in the Stirling Boiler Plant, the author said that this was news to him. He would have thought that the lower rate of combustion and the steadier firing would give much better result in Stirling boilers than in locomotive boilers.

Referring to Mr. Dumas's remarks on electrification, the author said that he could only reply that he (the author) certainly had made out a case for electrification, and this also was effected by Mr. Cuss's point regarding the ideal combustion of coal. One was constantly reading alarmist reports concerning the depleting coal resources of this country, and it was therefore vital that the coal should be utilised to the best advantage. If the coal were distilled in retorts and the valuable products such as coal tar and its derivatives extracted, the gaseous products could be used to fire Bonecourt boilers. Steam so generated would drive high efficiency turbines driving electric generators. With the present state of knowledge this would enable the highest amount of useful work to be obtained from the coal. He was not in a position to say whether the saving effected by electrification would be sufficient to cover the change-over costs and transmission costs, and still show an ultimate saving. He explained by means of a temperature-entropy diagram a probable reason for the "Castle" class locomotive having as good an efficiency ratio as an average simple condensing engine.

Replying to Mr. Cuss's remarks, *re* the Bonecourt boiler being very slow in development, the author said at the time the results of Professor Bone's research were published, the general tendency amongst steam producers towards higher efficiencies was to use higher boiler pressures, which, being a development along lines of existing practice would undoubtedly find greater favour at that time than the adoption of such a radical change as the Bonecourt principle. With regard to Brunler boilers, he had seen no reports as to the disposal of the products of combustion, amongst which would, undoubtedly, be some acids, but he imagined that if these were dissolved and remained in the boiler, there would no doubt be some deterioration of the fabric of the boiler. He thanked Mr. Cuss for his complimentary remarks concerning the "Castle" class heat energy stream. Mr. Cuss had remarked that some doubt was attached to the accuracy of the diagram. The author went on to say that he would hasten to assure him that, although it was not possible for very good reasons to construct such a diagram for any one of the tests run between Swindon and Plymouth in March, 1924, yet he would point out that it represented very fairly the general inferences to be deduced from those tests and, moreover, would probably represent very fairly the general state of affairs for the "Castle" class as a whole. In any case it certainly demonstrated that the "Castle" class compared extraordinarily favourable not only with contemporary simple British locomotives, but even with some recent compound locomotives. It was well known that the "Castle" class could operate heavy trains over main lines at cut-offs ranging from 25 to 18 per cent., or even 16 per cent., while some recent compound engines were not able to improve on that ratio of expansion to any very considerable extent. Regarding the arrangement for testing locomotives by means of an orifice in a diaphragm he thought it would be valuable for comparing engines of the same class, but he questioned whether it would be possible to use it as a basis of comparison for different classes. In any case, he thought that it could only be a measure of the mechanical efficiency of the engine.

Mr. Crane said it had been emphasized that the circulation of the water in the boiler had a considerable effect on the steaming capacity. He would like to know whether any mechanical means had been adopted to promote circulation in the Stirling boilers.

The Author replied that there was no question that the circulation of water in the boiler did very materially assist the steaming qualities. On the locomotive the circulation was largely achieved by careful proportioning of the water spaces around the firebox, while the conditions of service furthered this end. With the Stirling boilers the arrangement of the tubes was determined by two considerations :—

(1) It is necessary that ample allowance shall be made to accommodate the changes due to differences of temperature.

(2) By careful arrangement the maximum of circulation can be obtained from the "Thermo Syphon Effect."

Apart from these points in the design of water tube boilers generally, he was unable to say whether any special provision was made to promote circulation.

Mr. Millard said he would like to know whether the use of oil fuel would considerably reduce the loss clue to unburnt fuel.

Mr. Pearce said the author had referred to tappet valves. He would liked to have had more elaborate details. It seemed to him that the separate inlet and exhaust valves giving control over the expansion without affecting the compression, was a very valuable asset in reducing heat losses. The G.W. valve gear, he felt, was much in advance of other companies gears, because it permitted better expansion ratios. Regarding the published results of the "Castle" trials, he thought that in future tests regard would have to be paid to several points at which losses occur, which have not been measured in the past, particularly steam blowing off at safety valve and steam used by ejector and blower, and that closer attention to these points in future similar tests would probably be very helpful.

In reply to Mr. Millard, the author thought that there was no question that the loss due to unburnt fuel would be very considerably decreased when using liquid fuel, than when using coal. For one thing a fair proportion of the loss with a coal fired locomotive is due to the coal being lifted straight through the tubes when fired through the opened firehole door, especially if the fireman has not made much use of the coal-watering cock. Such a state of affairs did not obtain when using oil fuel, both because the oil is burnt almost immediately upon entering the firebox and also because the box remains closed during the whole period and no sudden inrush of air takes place.

The Author, in replying to Mr. Pearce, said he was obliged for his remarks, coming as they did from one having extensive experience of locomotives on the road. With regard to tappet valve gears, he had felt that much more ought to have been made of many points in the paper, and tappet valves were such a point. Tappet valves were unquestionably superior to slide valves in many respects—at least on paper—particularly were they superior in giving, as Mr. Pearce pointed out—an exhaust independent of the cut-off. He was inclined to agree with Mr. Pearce, that the G.W.R. valve gear was one of the finest in this country, and much of its superiority was due to the long stroke and large ports and steam laps. He went on to say that much improvement in the ratio of expansion was not very likely, but suggested that the attention to the compression side of the indicator card might result in further economy.

In closing the discussion the Chairman referred to diaphragm tests mentioned by Mr. Cuss and said that he would go further than the author in saying that he doubted whether such a test would be of value, even in comparing locomotives of the same class. It was necessary to remember that some older locomotives develop more power than newer locomotives of the same class, because the cylinders are bored out and tyres turned down with consequent increases of the tractive effort. It is often remarked by drivers that new locomotives out from Swindon factory are inferior to older ones of the same class, which is really to be expected when the increase in tractive effort consequent upon reboring cylinders and turning down of tyres is considered.