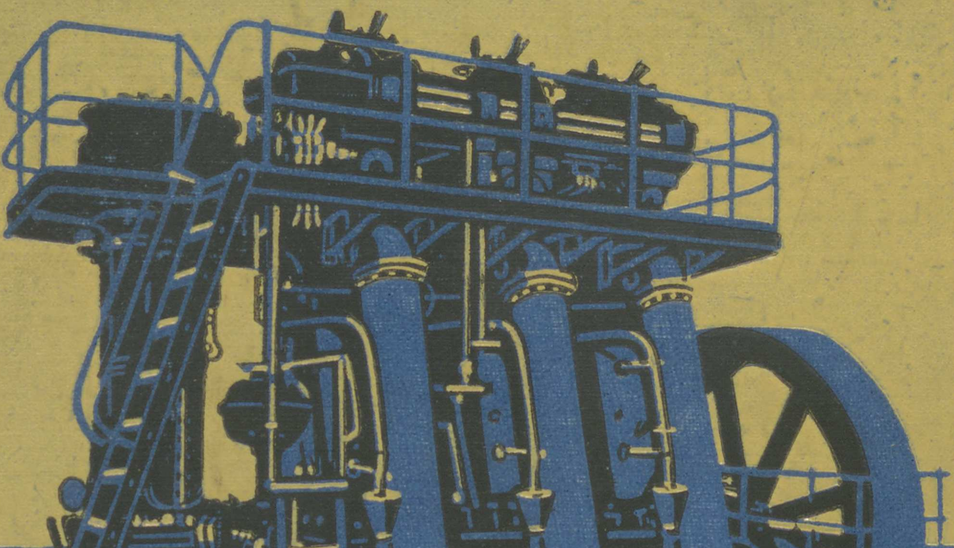
ALL ABOUT ENGINES

Edward Cressy



ALL ABOUT ENGINES

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By

EDWARD CRESSEY

Author of "Discoveries and Inventions of the Twentieth Century," "An Outline of Industrial History," etc. etc.

WITH A COLOURED FRONTISPIECE, AND 182 HALF-TONE ILLUSTRATIONS AND DIAGRAMS

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Preface

The boy of to-day lives in a world of engines—engines in front of him, engines behind him, engines all round him—and most boys are devoured with curiosity to know how they are made and how they work. They will go out of their way to see engines, pluck up courage to ask questions of those in charge, spend hours reading about them when a suitable book falls into their hands, and at night dream that they are spinning along at sixty miles an hour with their hand on the starting lever of a locomotive, or, more probably in these days, soaring 10,000 feet high in an aeroplane.

It is to satisfy such an admirable thirst for information that this book has been written. Beginning with an account of a simple engine, and an explanation of how it works by steam, the reader is next introduced to the pioneers and their difficulties in order to bring out more clearly the principles involved in the production of mechanical power. After a survey of the various types of steam engines and boilers, gas, petrol, and oil engines are described. These chapters are followed by brief accounts of the application of steam to the propulsion of railway trains and ships. Finally, power and its measurements are explained in an elementary way, and the book closes with a chapter on the problems of fuel, upon which the future of mechanical power largely depends.

The author has written throughout as for his own boys, and two of them, aged seventeen and thirteen, have read the whole of the proofs without apparently being bored. It is not pretended that they understood everything in it; a book of over 300 pages on engines which is wholly intelligible to a boy of thirteen should be burnt rather than printed. At the same time an effort has been made to exclude any discussion of matters which are of greater difficulty than importance. In the selection of material there must always be room for difference of opinion, and in this respect the author craves the indulgence of his readers. In a book of this kind there is ample opportunity for the exercise of judgment, but the essentials are a properly balanced view, numerous illustrations and the avoidance of statements which have to be unlearned by those who at a later stage will acquire their knowledge professionally.

Of the 182 illustrations about 150 have been specially drawn for the book, while the rest are reproduced by permission of leading engineers and manufacturers. For help in this and other ways the author desires to render grateful acknowledgments to Messrs. Marshall, Sons and Co., Limited, The Brush Electrical Engineering Co., Limited, Messrs. Galloway, Limited, Messrs. Babcock and Wilcox, Limited, Messrs. H. F. Yarrow and Co., Limited, The Crosby Gauge and Valve Co., Limited, Messrs. Holden and Brooke, Messrs. Hopkinson and Co., Limited, Messrs. Lockwood and Carlisle, Messrs. Belliss and Morcom, The British Westinghouse Co., Limited, Messrs. Greenwood and Batley, Limited, Messrs. C. H. Parsons and Co., Limited, Messrs. Crossley Bros., Messrs. Wolseley Motors, Limited, Messrs. Richard Hornsby and Sons, Limited, Messrs. Mirrlees, Bickerton and Day, The Electric Boat Co., Messrs. G. and J. Weir, Limited, The Bonecourt Waste Heat Boiler Co., Limited, and the Editor of "The Shipbuilder."

E. C.

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CHAPTER I

How a Modern Engine Works by Steam

NOBODY, from the oldest to the youngest among us, unless he possess not a grain of intellect or a spark of imagination, can look at a steam engine working without thinking of more than is apparent to the eye. To those whose life is lived away from workshops the number of pipes, levers, wheels, and quickly moving rods only bewilders, and simple facts are obscured by complexity of detail. And yet there is nothing very intricate about the engine. The man who has lived among engines could almost manage one blindfold. True, he would not get the most out of it, but he would make it work. The principles are the same in all engines, and as they can be learnt as easily from a simple one as from the most elaborate one ever built, we shall devote this chapter to an examination of the parts and of the duties they perform.

THE BOILER

The first necessity for a steam engine is a boiler which will supply as much steam as the engine requires. What sort of boiler shall we choose—vertical, Cornish, Lancashire, marine, locomotive, or water-tube? There they are, all of them interesting, and most of them the best for one purpose or another. Let us select one of the vertical type, which is easy to understand and efficient in use. Fig. 1 shows this boiler in section, so that the interior arrangements can be studied. The fire-grate is wholly surrounded by water, except in one place, where the furnace door is situated. The hot gases pass up into the flue on the right, thence through the tubes until they reach the up-take, leading to the chimney on the left. A door in the face of the up-take just above the furnace door enables the tubes to be cleaned out occasionally.

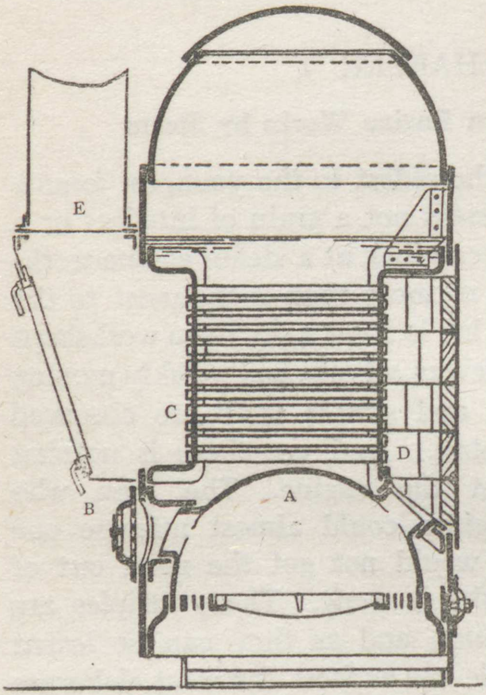

Fig. 1.—Vertical boiler, Cochran type
A, Fire-grate; B, Furnace door; C, Up-take; D, Flue; E, Chimney

Now, if water is heated in an open vessel the temperature, as measured by a thermometer, gradually increases until it reaches 212° Fahrenheit, or 100° Centigrade, when the water boils. At this temperature the pressure of the steam is just equal to that of the atmosphere. If the operation took place at the bottom of a mine the temperature of boiling water would be higher, because there is a greater thickness of air overhead; and if it were carried out on the top of a mountain the temperature would be lower because the thickness of the atmosphere overhead would be less. The temperature just given for the boiling point is true for the neighbourhood of sea level and with the barometer at 30 inches.

On heating water in a closed vessel the temperature and pressure both increase, and for every temperature there is a corresponding pressure of steam. Thus at a temperature of 212° Fahr. the pressure is 14·7 lb. per square inch, or equal to that of the atmosphere; at 293° Fahr. the pressure is 60·4 lb. per square inch; at 320° Fahr. it is 101·9 lb. per square inch; at 374° Fahr. 182·4 lb. per square inch; and so on. As boilers are not constructed to stand more than certain definite pressures, and as a man cannot always be watching the pressure gauge, some device is needed to enable steam to escape when the pressure exceeds that which the boiler was intended to bear safely. Such a device is shown in Fig. 2.

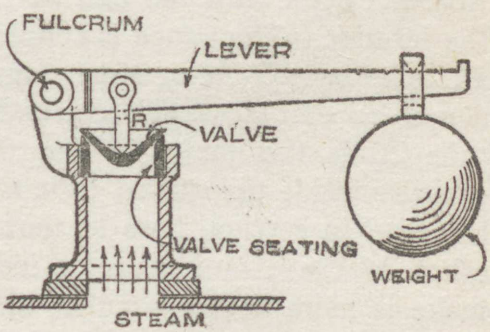

Fig. 2.—Lever safety-valve

The opening in the boiler is closed by a cup-shaped or "conical" piece of brass, which has been ground to fit the end of the seating upon which it rests, and this is held in place by the short rod pinned to the lever just above it. If the area of the opening covered by the valve is 6 square inches and the highest pressure in the boiler is to be 60 lb. on the square inch, the total force, when steam blows off, is $6 \times 60 = 360$ lb. By hanging a weight at the end of a long lever a much smaller one is required to balance the force on the valve. Thus if it is at eight times the distance of the valve from the fulcrum, the weight need only be $\frac{360}{8} = 45$ lb.

While the safety valve prevents accidents from too high a pressure, the man in charge has to see that enough steam is supplied to enable the engine to do its work; and in order to know how to manage the fire without continually blowing off steam at the safety-valve, he must know what the pressure in the boiler really is. For this purpose a pressure gauge is provided, and Fig. 3, Plate I, shows one of the Bourdon type, with the dial partly removed to show the interior. The gauge is connected to the boiler by a U tube or syphon, in which some of the steam condenses, so that steam never actually enters the curved tube inside the gauge. When the tap A is turned, pressure inside the curved tube B, which is not round but oval in section, rises to that of the boiler. The effect of the steam pressure inside this tube is to make it more nearly circular, and at the same time to straighten it. The end of the tube then pulls

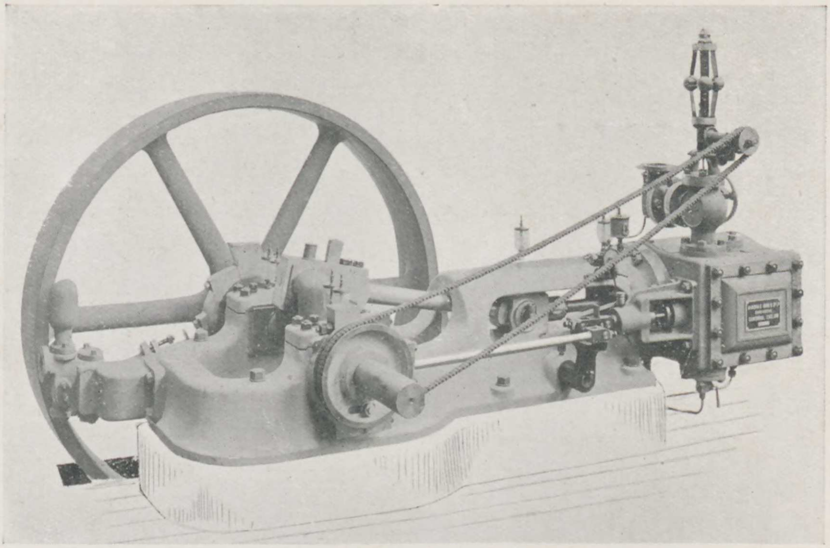

Photo by permission of Messrs. Marshall, Sons & Co., Ltd.

Fig. 5.—Good simple type of Horizontal Engine

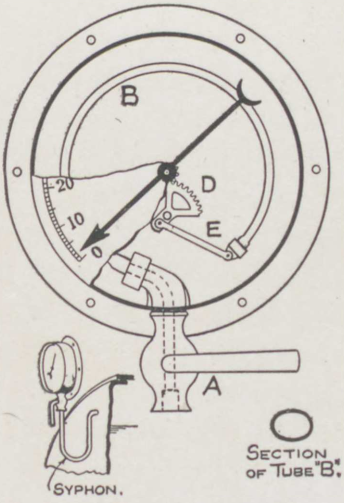

Fig. 3.—Bourdon Pressure Gauge

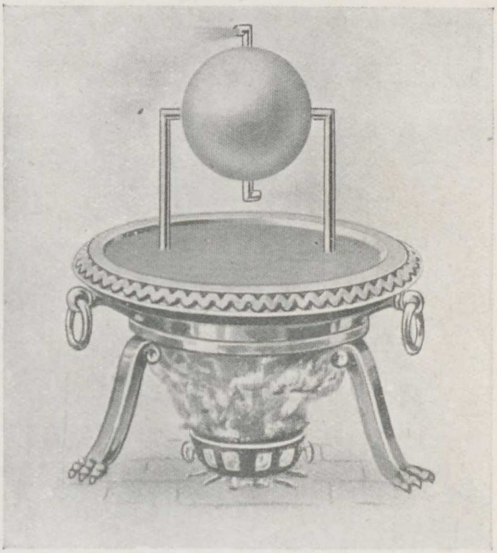

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Fig. 12.—Hero's Engine

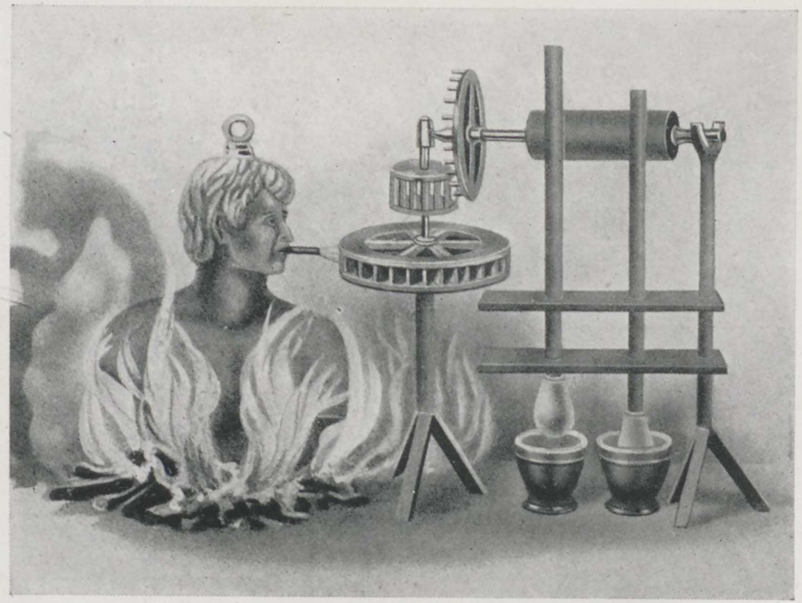

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Fig. 13.—Branca's Engine

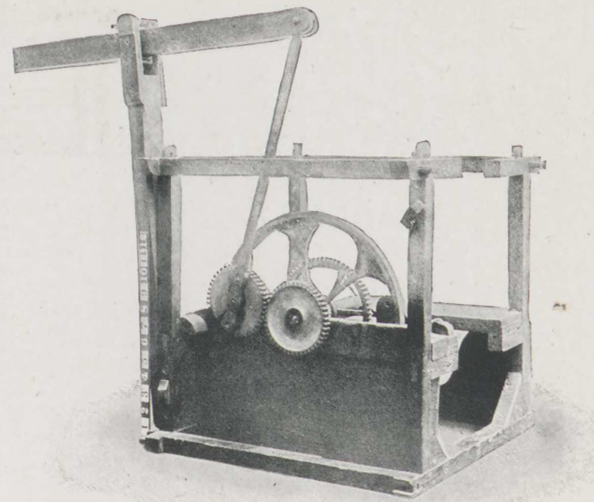

Fig. 19.—Model of Watt's Sun and Planet Motion

round the toothed sector D by means of the rod E, and the sector causes a toothed wheel on the axle of the pointer to rotate. The pointer then indicates on the dial the pressure of steam in the boiler.

There is one other safety contrivance fitted to all boilers which must be noticed now, and that is the water-gauge. If any part of the interior of the boiler upon which the hot gases play is not in contact with water it may become overheated. The metal is then injured, or at any rate buckling occurs, and stresses are produced which the boiler was not constructed to bear. Consequently, the water must be maintained above a certain level. On the other hand, it must not be too high, or some passes over with the steam, and as water is not elastic, in the sense that steam is, it is of no use in driving the engine. The water-gauge shown in Fig. 4 is a glass tube, communicating with the interior of the boiler above and below the proper water level, and the level of the water in the tube shows the level of the water in the boiler. When this gets too low more water is pumped in.

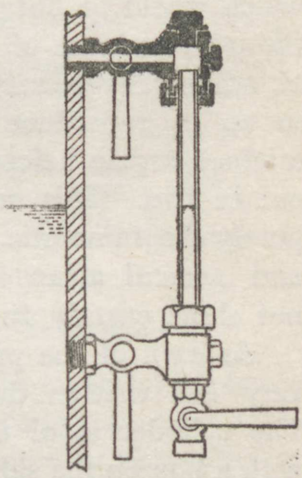

Fig. 4.—Water-gauge in part section

THE ENGINE

We can now consider a simple engine, learn its parts, and examine its mode of operation.

What an engine of this kind looks like in reality will be gathered from Fig. 5, Plate I, which shows the front view of one made by Marshall and Sons, of Gainsborough.

In order to understand how it works we shall have to look inside it, and for that purpose we shall rely mainly on diagrams in which what is unnecessary to the explanation is left out. Thus Fig. 6 shows a section through such an engine. For the sake of the reader who is not quite sure what "a section" means, it may be said that it is the view which would be obtained if the whole thing were cut through, and one of the cut faces were being looked at. Generally a section would be drawn to scale, so as to reproduce the exact proportions of the original engine before it was, in an imaginary sense, cut in two. This one is not drawn to scale. It is purely diagrammatic. It represents roughly the shape and general arrangement of the parts, but it does not show exactly their shapes or relative sizes.

As each of the parts on the drawing is named, a very full written description will not be required. The cylinder is of cast iron, shaped like a barrel, with a box on the side called a steam chest, and it has covers bolted over each end and over the steam chest. The interior of the cylinder and steam chest are connected by narrow steam passages or "ports," and there is another opening between them by which steam can escape from the cylinder when it has done its work. This may lead to the open air or into a condenser; but in this case it leads into the open air, and as there is no condenser the engine is said to be a non-condensing engine. What this means we shall learn later.

The cylinder is fitted with a plug or "piston," rendered steam tight by springy cast-iron rings lying

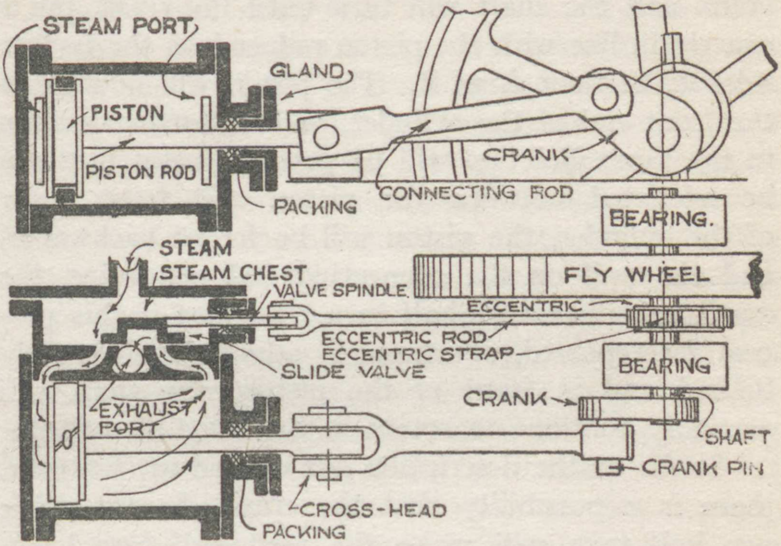

Fig. 6.—Diagram showing parts of a horizontal engine

in grooves in its curved face. It is attached firmly to a steel rod which passes through a steam-tight "stuffing box" on the front cover of the cylinder. This stuffing box contains oiled packing which fits closely round the rod and can be forced still closer by screwing in the gland. The gland is usually of brass and the hole in the cylinder cover is usually lined with the same metal. On the outer end of the piston rod is a block or "cross-head" which slides between guides to prevent the rod being bent. A steel connecting rod serves to communicate any motion of the piston to the crank shaft of the engine.

Now, if steam is admitted to the cylinder behind the piston, the latter will be forced forwards, the push will be communicated to the crank, and the crank and the shaft will turn until the crank pin is exactly in line with the piston rod and on the farther side of the shaft from it. The piston will now be at the front end of the cylinder, and no further motion in the same direction will be possible. But if steam be admitted between the piston and front cover of the cylinder, the piston will be forced backwards, and the pull on the connecting rod will bring the crank round another half turn. So that if this process be repeated, if steam is admitted alternately behind and in front of the piston, the shaft will probably continue to rotate in the same direction.

So far as the description has carried us, however, there is a possibility that the crank, having made one half turn, will make the next half turn backwards. Moreover, with a single cylinder engine there would be a tendency to stop on the "dead points," when the piston rod, connecting rod, and crank were in a straight line. For in that position the connecting rod merely pushes or pulls the crank-pin, and exerts no turning effect on the shaft. This difficulty is overcome by the flywheel. A heavy wheel requires a good deal of force to start it from rest, or to increase its speed, and when once it is moving much force is required to decrease its speed or to stop it. The first stroke of the piston sets the flywheel moving, and the flywheel carries the crank over the dead centre, so that at two points in its revolution the flywheel alone keeps the engine working. For ninety-nine per cent. of the time the engine drives the flywheel, and for one per cent. the flywheel drives the engine.

But it does more than this. Not only are there variations of pressure inside the cylinder, but the turning effort of the connecting rod alters with its position. Everyone who has turned the handle of a grindstone knows that the greatest effect is obtained when the push or pull is exerted at right angles to the crank. When this greatest effort occurs in the steam engine the flywheel is forced to turn more rapidly, and when the effort falls off the speed decreases very slowly, because of the flywheel. The flywheel, therefore, smooths out the inequalities of motion and gives steadiness. It is like a policeman keeping a crowd always on the move. But the policeman does not work for nothing. His services have to be paid for. Some of the force exerted by the steam is employed in turning the heavy wheel. There is no increase, but a decrease, in the work done by the engine. The only thing that can be said in its favour is that the engine would not work without it.

Let us now inquire how the steam is admitted to each end of the cylinder at the right moment to operate the piston. By referring to Fig. 6 it will be observed that the ports are partly covered by a sort of shallow box with the face downwards. This is the slide valve, and from its shape it is often called a " D " slide valve. The hollow in the under side of the valve is large enough to cover the middle or "exhaust" port, and *one* of the steam ports, but not both. As the valve moves backwards and forwards it not only uncovers each steam port in turn, so that steam can enter the cylinder, but it also places the covered port in communication with the exhaust port, through which the steam escapes into the open air or into a condenser. If this valve, then, moves backwards and forwards, always in the opposite direction to the piston, steam is admitted to each end of the cylinder alternately, at the right moment for continuous working.

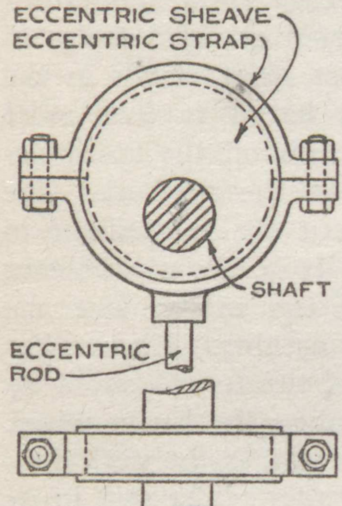

Fig. 7.—Eccentric

The usual device for securing this motion of the slide valve is called an eccentric (Fig. 7). An eccentric consists of a cast-iron disc or "sheave," keyed on to the shaft, with a strap fitting closely round it and connected by a jointed rod to the slide valve. Now if the hole in the sheave through which the shaft passes were in the centre the sheave would merely turn with the shaft like a wheel. But this hole is out of the centre—hence the term eccentric—and as the sheave rotates with the shaft the valve is moved backwards and forwards over the cylinder ports. The distance from the centre of the sheave to the centre of the shaft is called the "throw," and corresponds to the "throw" of a crank. The eccentric, in fact, acts like a small crank. If the "throw" is 2 inches the travel of the valve is 4 inches, but the sheave is fixed on the shaft so that the motion of the valve is opposite to that of the piston, so that when the piston is moving forwards the valve is moving backwards and vice versa.[1]

An engine supplied with these parts will run quite well so long as the work it is required to do, or the "load," is constant. But if the load varies the speed of the engine will vary, and if it is taken off altogether the engine will "race." Now racing is undesirable, not only on account of possible damage to the engine, but also because of the unnecessary waste of steam. Steam requires coal to produce it, and coal costs money. So that if money is not to be wasted, steam must not be wasted, and some means has to be employed whereby the engine takes only as much steam as it requires to keep up the speed.

Suppose a heavy weight is tied to a string. Let the string be held in the hand with the weight hanging down. Then let a gentle but gradually increasing circular motion be given to the suspended weight. As the speed increases the weight tends to fly farther outwards, but in doing so it also rises. This is the principle upon which the governor acts. Two iron balls are attached to rods which are held by pin joints to the top of the main rod in Fig. 8, in such

[1] This is not quite true. As will be explained later, the valve begins its stroke in a given direction just before the piston.

a way that while the balls can rise or fall, they are forced to swing round when the main rod is turned. Two other rods are pinned to the balls and to a collar round the main rod. This collar is connected to a valve in the steam pipe, by which the steam can be "throttled," so that a smaller quantity passes to the engine. The main rod is driven from the engine through pulleys and a belt, and toothed wheels. If the speed of the engine increases, the balls fly outwards, lift the collar, and shut off some of the steam. When the speed of the engine decreases the balls fall, the throttle valve is opened wider, and more steam passes to the engine.

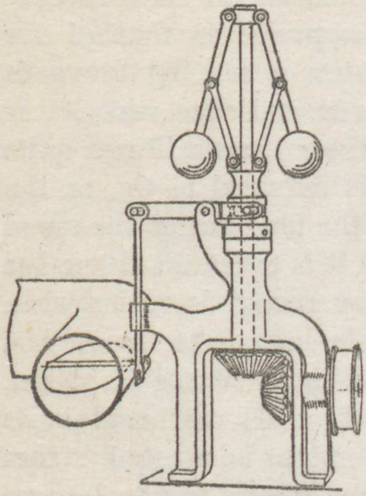

Fig. 8.—Simple form of governor

Every engine is constructed to run at a certain speed, and the governor is designed and adjusted to cut off steam when that speed is exceeded. Like the flywheel it acts as a policeman, not, however, in keeping the parts moving, but in preventing rushes. And, like the flywheel in another respect, it needs power to drive it.

The governor on the engine in Plate I is of a different type, though the principle upon which it acts is the same. It is called a Pickering governor, and there are three balls mounted on flat steel springs attached at their lower ends to the spindle, and at their upper ends to a loose cap. The governor is mounted directly over a valve in the steam pipe, and this valve is operated by a thin steel rod which passes through the main spindle of the governor.

We are now in a position to inquire more carefully what goes on inside the cylinder. When steam is admitted behind the piston it drives the latter forward, filling up the space behind the moving piston as rapidly as it can squeeze through the port. As we shall see later, the port is only open for part of the stroke, but even when the supply is cut off the expansive force tends to propel the piston forward. Moreover, the piston, piston rod, cross-head, and other working parts tend to continue their motion, just as a boy running at full speed cannot pull up immediately. When the crank reaches the farther dead centre this motion must, of course, come to an end, and the stoppage of this motion tends to set up very heavy stresses in the engine. This is prevented by causing the slide valve to close the exhaust port and to open the steam port a little before the piston has reached the end of its stroke, so that the steam forms a "cushion" which brings the piston gradually to rest. The clearance space in which this cushioning takes place, together with the volume of the steam port, is about one-eighth of the volume of the cylinder.

The control, in this way, of the admission and release of steam depends partly on the position of the eccentric with reference to the crank, and partly on the overlapping feet of the valve. In Fig. 9 the eccentric is shown with the throw at right angles to the throw of the crank, and a plain valve, with no overlapping feet, in mid-position. The piston, travelling to the left, has just reached the end of the stroke, and is ready to move to the right. But the steam port is not open. In order, then, that the port may open a little before the end of the stroke the eccentric must be set a little forward of the position shown, and the amount by which the port would then be open is called the " lead." It is usually fixed at one-eighth of the breadth of the port.

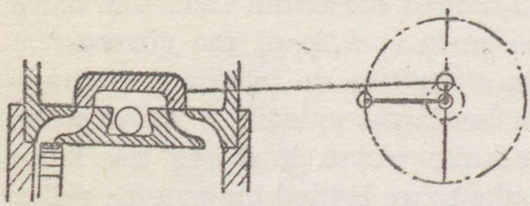

Fig. 9.—Simple slide valve, with no lap and no lead

Now consider Fig. 10, in which the feet extend beyond the steam ports when the valve is in mid-position. Owing to the outside lap,[1] the eccentric will have to be set still more forward from the right-angle position in order that the port may be open at the end of the stroke. The sum of this angle and

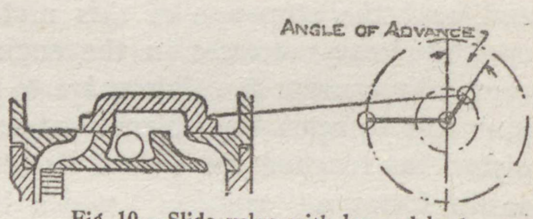

Fig. 10.—Slide valve with lap and lead

[1] Outside lap is the amount by which the feet of the valve extend beyond the port when the valve is in mid-position.

the last one is called the "angle of advance," so we get the rule: angle required to allow for lap + angle required to produce lead = angle of advance.

Since the lap on the outside of the valve had to be allowed for in the angle of advance, why, it may be asked, is it put on the valve at all? The reason will be clear if the reader considers what happens when the valve is moving backwards—that is, from right to left. The piston is now moving to the right, and the effect of the outside lap is to shut off steam before the piston has completed its stroke, and this saves steam. When water is converted into vapour, this vapour becomes more and more elastic as the temperature rises, and it is not the full force of the boiler pressure but the expansive force of the steam which is used in the engine. If only a small portion is admitted and then the admission port is closed, it will exert a force on the piston right up to the end of the stroke in its effort to expand. It is, in fact, usual to cut off at three-quarters, one-half, one-third, one-quarter, or even one-fifth stroke in order to utilise this expansive property to the full. Of course, the pressure and temperature both fall during expansion, so that the average force acting on the piston is less than that which would be produced by the boiler pressure acting throughout the whole stroke.

For example, if steam is admitted at 150 lb. on the square inch and cut off at one-fifth stroke, it expands to five times its original volume, and the pressure falls to 30 lb. on the square inch. As we shall see better later, even this is wasteful, because steam at 30 lb. on the square inch is still capable of doing work. Besides, it would never do to play with steam at 150 lb. on the square inch in the first chapter! And, for reasons which cannot be given here, the slide valve will not allow of steam being cut off so early as one-fifth of the stroke.

The outside lap, therefore, delays the admission of steam *to* the cylinder, and cuts it off earlier. In other words, the outside lap controls the admission of the steam, and the larger the overlapping feet the longer time are the ports closed during each stroke of the piston.

The reader will probably be wondering by now why the author has been so stupid as to bore him with this minute analysis of valve motion so early in the book; and if he can keep a secret he shall be told. There are a good many boys, and even young men, who set out to make an engine and who succeed admirably up to a certain point. The workmanship is good, the joints are tight, and every part is polished in a way that reflects the patience and loving care which has been bestowed upon the work. But when steam is admitted the engine refuses to work, and—whisper this low—they have to get an engineer to set the valve for them!

Now this is perfectly unnecessary. A boy who has the skill and perseverance to make an engine has the intelligence to adjust it, and if he really wishes to know how it works he should construct the model shown in Fig. 11 and spend a few hours in making experiments with it. The black parts are cut out of thin wood or stiff card and fastened to a board in the positions shown by tacks or drawing pins. A is a piece of card or thin wood upon which a piston and rod have been drawn, and a strip of wood or card B, representing the connecting rod, connects it with the circular disc C representing the crank or crank disc. For these joints a drawing pin with its point upwards is convenient, and the point

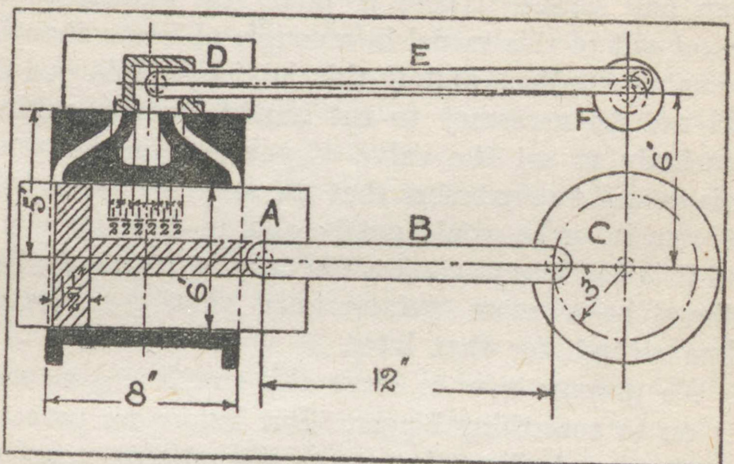

Fig. 11.—Model for study of valve motion

can be rendered less dangerous by a piece of cork. D, again, is a piece upon which the valve is drawn, and it is similarly connected with a smaller disc F through a connecting rod E. The parts A and D are free to slide backwards and forwards on the board. It is a good plan to mount the discs C and F on small wood pulleys connected by a rubber ring so that they both rotate at the same speeds, and piston and valve move together.

Having made a piece of apparatus like this, it is no use playing with it. Make several copies of the card D with varying amounts of lap, study the effect of lead varying from nothing up to a quarter of the width of the port, and measure roughly the magnitude of the angle of advance. Note also the cut-off for varying lengths of lap, and find out why it is that with a valve like this steam is never cut off earlier than half stroke. There is more real knowledge to be got out of this model in a couple of hours than in weeks of reading, and if this advice is followed it will not be necessary to eat humble pie by asking somebody to set the valve of your engine for you. It is as well to remember that the man you asked had to learn it, or he would not be able to do it for you; and it is not wise to confess too early in life that other fellows have more perseverance than you have. Time enough for that later.

We propose now to leave this simple engine and get on to something bigger. But before we proceed to examine boilers that evaporate fifteen tons of water every hour, and engines that yield a thousand or ten thousand horse-power, it will be a good plan to look backwards and see how the early pioneers succeeded in the face of difficulty and disappointment in clearing the way for those who came after. What is that you say? You want to know what horse-power is, and how to find the horse-power of an engine? Well, here you are.

If a weight of 1 lb. is lifted a height of 1 foot, 1 ft.-lb. of work has been done, and that is a unit of work. The next step is more easily put into a table:

2 lb.	lifted	through	1 ft.	=	2 ft.-lb.
1 lb.	,,	,,	2 ft.	=	2 ft.-lb.
3 lb.	,,	,,	1 ft.	=	3 ft.-lb.
1 lb.	,,	,,	3 ft.	=	3 ft.-lb.

and so on, so that 10 lb. lifted through 25 feet represents 250 ft.-lb. of work, and generally the work done in lifting x lb. through a vertical height of y feet is $x \times y$ ft.-lb. This statement is not only true in reference to lifting weights, but in all cases where a force applied to a body succeeds in moving it or deforming it—that is, altering its shape. Thus if a force of 10 lb. applied to a heavy table is sufficient to move it steadily across the room without leaving the floor, then 15 ft.-lb. of work will have been done when it has moved $1\frac{1}{2}$ feet, 30 ft.-lb. when it has moved 3 feet, 70 ft.-lb. when it has moved 7 ft., and so on. Again, if a quantity of gas is enclosed in a long, uniform tube by a piston, and if the piston is forced slowly inwards so that the length occupied by the gas is half the original length, then the average force employed multiplied by the distance through which the piston has moved will give the work done in compressing the gas.

Suppose, as another example, a force is applied to the handle of a grindstone, or the mangle used in the laundry. If the arm to which the handle is attached is 1 foot long and the force necessary to keep the grindstone or mangle moving steadily is

7 lb., we can calculate the work done in the following way :

Distance moved by force in one revolution[1]	$= 2 \times \frac{22}{7} \times 1$
	$= \frac{44}{7}$ ft.
Work done in one revolution	$= \frac{44}{7} \times 7$
	$= 44$ ft.-lb.

And for 20 revolutions, $44 \times 20 = 880$ ft.-lb. would be required.

It will be evident that work can be stored up in a body which is lifted or deformed, or set in motion. A weight of 14 lb. raised to a height of 5 ft. will have had 70 ft.-lb. of work done upon it, and there will be 70 ft.-lb. of energy, or ability to do work, stored up in it. For in falling back to its former position it can be made to draw a rope or a pulley, or raise by means of a lever another weight. But it would not do 70 ft.-lb. of work because the lever or pulley would produce friction, and work would have to be done to overcome that. Similarly the gas would not push the piston back quite to its original position because of the friction against the walls of the tube. And finally the grindstone or mangle would turn for a time after the force was removed, and would in this way raise a weight. Compare also the action of the flywheel described on p. 8. But even these will not give back all the work that has been put into them.

[1] The circumference of a circle is $3\frac{1}{7}$ or $\frac{22}{7}$ times the diameter. Hence the circumference of the circle formed by the handle of the grindstone is $2 \times \frac{22}{7} = \frac{44}{7}$.

A body or a machine which, as in these examples, is capable of doing work, is said to possess energy. Energy due to position, as in the case of the weight, is called *potential energy*, and energy due to motion, as in the case of the grindstone, the mangle, or the flywheel, is called *kinetic energy*. The energy stored up in the gas may, for the present, remain unclassified. We shall need these ideas later.

Now work may be done quickly, or it may be done slowly. A thousand ft.-lb. may be done in an hour, or it may be done in a minute, and the rate of doing this amount of work is sixty times greater in the second case than it is in the first. To measure the rate at which work is done we need a unit, and that chosen is 33,000 ft.-lb. per minute. It is called a horse-power, though it would require a pretty strong horse to raise nearly 15 tons one foot high in one minute or 1 lb. 33,000 feet high in the same interval of time. If, therefore, the number of ft.-lb. of work done in a minute is divided by 33,000 it gives the rate in horse-power. How, then, is the horse-power of an engine calculated?

Consider the piston in the cylinder with the steam pressing on it, and let the average pressure per square inch throughout the stroke be represented by P. If the piston is A square inches in area the total force acting on it will be $P \times A$. In one stroke of length L feet, the work done will be $P \times A \times L$ ft.-lb., and in N strokes $P \times A \times L \times N$ ft.-lb., or arranging the letters so that they are easily remembered, P.L.A.N. Lastly, since 1 horse-power is

33,000 ft.-lb. per minute, the horse-power of the engine is :—

$$\frac{P.L.A.N.}{33000}$$

This represents the work done in the engine by the steam, and not the work which the engine will do, because some of it is used to drive the engine itself. How the mean effective pressure P is ascertained for the purpose of this calculation, and how the work given out by the engine is measured must, however, be left to a later chapter. Meantime, let us consider the pioneers.

CHAPTER II

The Pioneers before Watt

FOR a hundred and fifty years the steam engine has been the most powerful agent in altering the habits of mankind and in moulding the customs of the civilised world. A century and a half ago there were hardly any factories, no railways or telegraphs, and only slow-sailing ships which depended upon wind and weather for the power which speeded them upon their way. Few metals were known, and even iron and steel were produced in quantities less than a thousandth of those turned out from the world's furnaces to-day. Kings, and princes, and parliaments we should still have had, but without the steam engine none of those other great things would have come about. Even the British Empire could not have developed as we know it, and the whole world would, relatively speaking, have stood still. And since great effects often come from little causes these causes are not unimportant; so that now we know how a steam engine works we will go back to the beginning of things and see how the early pioneers faced their difficulties and came near to achieving their ends.

The real story of the steam engine begins with the invention by James Watt in 1765; but, like most other great inventions, it was preceded by a long chain of fruitless endeavour. From the first discovery of fire and the effect of heat upon water, the latent power in the steam which escaped in bubbles from its surface must have been dimly recognised. That this invisible giant revealed its strength in many ways—sometimes to the hurt of the curious—can hardly be doubted. In all probability some of its secrets were discovered, but were lost again by the simultaneous death of those who had dared to pierce the veil. The mists of antiquity hide many a triumph, and not a few grim tragedies.

Two thousand years ago, in the great city of Alexandria, at the mouth of the Nile, lived one Hero, who seems to have made many ingenious experiments with fire and liquids and gases. And among other things he invented a steam engine. From an inspection of Fig. 12, Plate 1, it will be seen that it consisted of a boiler with two upright tubes, bent at right angles at the upper ends. A ball of metal, with short, straight tubes fixed on opposite sides, was placed between the upright tubes, so that it could spin round on a horizontal axis. Two other tubes, bent at right angles, were fixed to the ball in the position shown in the figure. When a fire was lighted beneath the boiler the water boiled, steam entered the ball and escaped from the bent tubes, and owing to changing its direction in the bent tubes it urged the ball round. Models of Hero's engine, made in glass, can be purchased from any scientific instrument makers for a small sum. But a more satisfactory contrivance can be made out of a half-pound coffee tin, a couple of pieces of copper tubing, some stiff wire, solder, and a soldering iron. In this and the glass-form boiler and rotating portion are in the same piece.

For sixteen hundred years after Hero's invention there was no further progress. Books were scarce and, until the invention of printing in 1445, had to be copied laboriously by hand, so that few could possess them. Moreover, the Great Schism separated the Eastern and Western sections of the Roman Empire, and the stores of ancient learning remained jealously guarded in the East, while Western Europe was sunk in barbarism. But with the sack of Constantinople by the Ottoman Turks in 1451, scholars and manuscripts flowed westwards, and in Italy especially there was a new enthusiasm for learning.

The Italian scholars, however, were not content to accept the mere statements of the old writers without question. Where these dealt with mechanics or natural science they were put to the test of experiment. Old explanations were found to be wrong and new facts were added to knowledge. Galileo, watching a hanging lamp swinging slowly to and fro in the cathedral, and timing it by the beat of his pulse, discovered the law of the pendulum—that if the swings are small they are completed in equal times. Dissatisfied with the statement that heavier bodies fell to the ground more rapidly than light ones, he allowed bodies of different weights to drop from the top of the leaning tower of Pisa, and found that they touched the ground at the same instant. And by these and other experiments he laid the foundation of the modern science of mechanics.

Again, Torricelli, a pupil of Galileo, invented the barometer, explained atmospheric pressure and the action of the common pump, and made clear the meaning of the ancient saying that "Nature abhors a vacuum." It followed from Torricelli's experiments that the atmosphere which surrounds the earth presses upon its surface with a force of 14·7 lb. per square inch at the sea level. This pressure is greater at the bottom of a well or a mine, and less as we ascend a mountain. Since the body of a man has an area of about 15 square feet, the pressure he supports under ordinary conditions is nearly 15 tons!

In these times of intense curiosity and feverish inquiry lived one Branca, who pursued his studies in the University of Padua. He constructed an engine in 1619 which is illustrated in Fig. 13, Plate 2. In this case the boiler did not rotate itself, but was used merely to supply steam. The revolving portion consisted of a wheel formed of two discs, with divisions between which acted as vanes. The steam formed in the boiler issued from a tube and, impinging upon the vanes, caused the wheel to spin round. In the illustration it is shown working a mortar for grinding materials to powder. Nearly three hundred years later, when tools and materials had endowed inventors with new and more wondrous powers, Dr.

Gustaf de Laval, applied this method of using the force in a jet of steam in the turbine which bears his name.

But these inventions were still far short of an engine of practical value. A number of clever men devoted the greater part of their lives to the problem before it was even partially solved. Denis Papin, a French Huguenot, spent many years at it. He studied medicine at the University of Paris, and afterwards assisted the still more famous Frenchman Huygens in some of his experiments. Forced, with many other Protestants, to flee from France in 1681, he lived for some years in London, where he was Curator of the Royal Society. Then he migrated to Germany and became Professor at the University of Marburg. Early in his career he constructed an improved pump for raising water out of mines, made a diving bell, and showed how water could be raised to a temperature higher than its ordinary boiling point by heating it in a vessel in which the lid was held down by a weight. On this last account he may be regarded as the inventor of the safety valve.

In 1674 Papin tried to raise water by the explosion of gunpowder. A tall cylinder was fitted with a piston. The bottom of the cylinder was capable of being removed. A charge of gunpowder and a slow match were placed on this, which was immediately fixed in position. When the explosion occurred the piston was driven to the top of the cylinder, and as it fell by its own weight it pulled down a rope passing over a pulley. Water was raised in buckets attached to the other end of the rope.

This method, however, was far too slow and cumbrous to be successful. Sixteen years later, in 1690, Papin tried the effect of boiling water under the piston. The steam forced the piston up, the fire was removed from beneath the cylinder, and the piston fell again. But though the apparatus worked, the slowness and the labour of moving the fire were against its success.

Papin's final attempt was made in 1704, when he undertook to construct a pump to clear the water from the mines in Westphalia. This time he used a boiler under which a fire could be kept burning continuously, see Fig. 14. The steam passed into a cylinder partly filled with water. Under ordinary circumstances it would have rapidly condensed by contact with the water, but this was prevented by a wooden float, nearly as large in diameter as the cylinder, forming practically a piston. Cooling was also prevented by an iron box attached to the float and containing a red-hot iron ball.

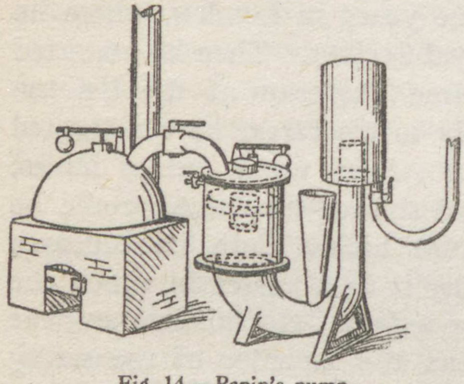

Fig. 14.—Papin's pump

The steam forced the float down, driving the water into another cylinder, where it compressed air, and the compressed air was used to force water to a higher level. Each stage of the process was regulated by taps or "cocks." By the time the compressed air had done its work water flowed into the cylinder again from the reservoir, steam was admitted from the boiler, and a further quantity of air was compressed. With this apparatus water is said to have been forced to a height of 70 feet; but the workmanship was faulty, the pipes leaked, and the ultimate result was a failure. Nevertheless, Papin had made two advances of considerable importance: he had invented the safety valve, and he had shown that steam could be made to act on a piston contained in a cylinder.

While Papin was endeavouring to solve the problem in Germany, Captain Savery was busy in England. He had advantages in that he had been trained as a military engineer, was a skilful mechanic, had amused himself with clock making, and invented a machine for grinding glass. His attention seemed to have been turned to the steam engine by the condition of the Cornish mines. Worked, as many of them had been, before the invasion of Britain by Julius Cæsar, the ore was only to be found at great depths, and here the miner came into conflict with his great enemy, water, which poured in at a far greater rate than he could raise it with the clumsy means at his disposal.

Savery's engine consisted essentially of a boiler and two egg-shaped vessels. The egg-shaped vessels were connected with the boiler at their upper ends, and with the well or pit at their lower ends. Before starting all taps were closed. Steam was allowed to flow into one of the vessels, and then the supply shut off. The cock leading to the well was now opened, and cold water poured over the outside of the vessel. The steam inside was condensed to water. Since a cubic inch of water at 212° Fahr. forms 1,600 cubic inches of steam at the same temperature and pressure, a vacuum was produced in the cylinder, and the water pressure of the atmosphere on the surface of the water in the well or mine forced it up the pipe until it filled the vessel. Connection with the well was then shut off, steam was again forced into the vessel, and the water driven up the pipe to the overflow. This pump lifted the water, and then forced it to a higher level. Both vessels were used, so that while one was filling with water the other was discharging.

Several of Savery's engines were set to work in Cornwall, and at least one in Staffordshire, at a coal mine near Wednesbury. But they were very liable to get out of order, and when attempts were made to force them the boiler blew up or the steam "tore the engine to pieces." Before they had been in use very long a better engine was invented by Thomas Newcomen, and of Savery's engine there is little record beyond his own description.

Thomas Newcomen was a blacksmith and iron worker who lived in the quaint old town of Dartmouth, in Devonshire. He was not a man of education, but there is some reason to believe that he was familiar with the work of Papin and Savery. In 1705 he made a model engine which was an improvement on the others. It consisted (see Fig. 15) of a boiler with a furnace beneath it and a cylinder above. The cylinder was provided with a piston which was forced upwards when steam was admitted below. The cylinder being then cooled by immersion in water, the steam was condensed, and the piston descended, partly by its own weight and partly by the pressure of the atmosphere on its upper surface. On this account the engine was called an "atmospheric" engine.

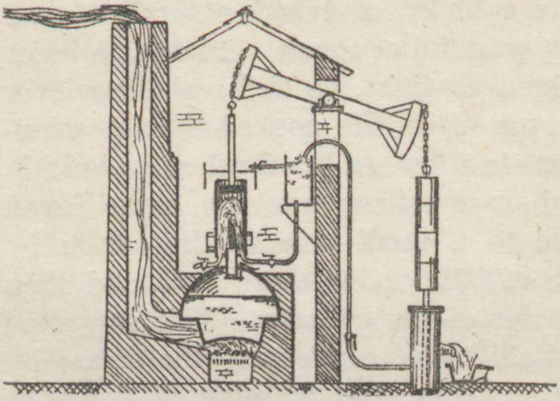
Fig. 15.—Newcomen's engine

The piston was connected with one end of a beam, to the other end of which was attached the rod of a pump. When the steam piston was forced upwards the pump piston, or "bucket," as it is often called, fell, forcing up the water in the pump barrel by its own weight, as the steam piston fell under the pressure of the atmosphere, the pump piston rose, and water from the well flowed into the pump barrel.

This model worked satisfactorily, but it was six years before Newcomen could get an order for a full-sized one. But in 1711 he undertook to construct one for a colliery near Wolverhampton. In trying to make this engine work to his satisfaction, he was led to an important improvement. Both in the small and the large engine he had tried a tank of water round the cylinder, and had naturally found the method very wasteful of steam. Further, in order to make the piston air-tight, he had a shallow layer of water on the top of it. He noticed that occasionally the engine made a few strokes much more quickly than usual, and on inquiring into the cause found that it was due to a small hole in the piston by means of which a little water every now and then reached the interior of the cylinder. This suggested to him the desirability of condensing the steam by a jet inside the cylinder, and he adopted this plan with great advantage.

You can imagine the eagerness with which he watched every movement, and how he bent his thoughts to discover any little alteration which would improve the machine upon which he had laboured for many years. But the next step came from a boy named Humphrey Potter, who was less interested in the engine than in obtaining more time for play. He was engaged to turn the taps admitting steam and water alternately to the cylinder, and, tiring of the monotony of this task, he conceived the idea of fastening the taps to the moving beam in such a way that the engine opened and closed them itself. The result was surprising, for the speed of the engine was increased from six or eight to fifteen or sixteen strokes a minute. The boy could not time the operation half so well as the engine could. At a later date the cords used by Potter were replaced by rods by Henry Beighton, of Newcastle, an arrangement which was more durable and certain in its action.

Newcomen's engine arrived at a fortunate time for the mining industry. Coal had not been much used as a fuel, and had been obtained mostly from near the surface. But when the miner sought it at greater depths, water disputed with him for its possession. He raised it in buckets by a winch, or pumped it up by the aid of horses or by hand labour, and still it gained on him. So when the engine erected near Wolverhampton proved a success, it was soon followed by a second and third at pits near Newcastle. The fourth engine was put up at Austhorpe, near Leeds, in 1714. It had a cylinder about 2 feet in diameter and there were two pumps, each 9 inches in diameter; while the water is said to have been raised through a height of nearly 100 feet. The inventors—for Newcomen had a partner named Calley, of whom little is known but his name—received £250 a year for working it and keeping it in order. And the task was worth it. Great difficulty was experienced with the boiler, which in the early years had to be renewed annually.

When the fame of Newcomen's engine became noised abroad, a demand for his assistance came from the tin and copper mines of Cornwall and the lead mines of Cumberland. The first Cornish engine was set up at the Wheal Fortune mine in 1720. It was a huge contrivance, considering the tools and workmanship of the day. The cylinder was 47 inches in diameter, and the speed of working was fifteen strokes a minute. The mine was 30 fathoms, or 180 feet, deep, and the barrels of the pumps were 15 inches in diameter. About 800 gallons were raised per minute. The engines were soon in use all over England, though only a few appear to have been made by Newcomen himself. Some were built by Smeaton, the famous engineer who built the Eddystone Lighthouse, and who had seen the Austhorpe engine at work when a boy.

In the districts where coal was cheap the engines were successful, but in Cornwall they were terribly expensive to work. The cylinders of some of the engines were 5 and even 6 feet in diameter; while one at the Walker Colliery, near Newcastle, was 7½ feet in diameter and had a 10-foot stroke. At every stroke this cylinder had to be filled with steam —aye, more than filled, for on entering the cold chamber much of it was condensed. Some of the Cornish engines consumed 13 tons of coal a day! Again, the workmanship was very imperfect. Some of the engines constructed or repaired by Brindley had wooden cylinders, built up like a barrel, and held together with iron hoops! The lower portions of the boilers were made of copper, and the upper portion of lead! But for a time it kept water from the mines, enabled the miner to pursue his calling, and enabled coal especially, which was now, in the first half of the eighteenth century, coming into use for the manufacture of iron, to be raised to the surface.

As the engine became better known the inventor vanished. You would have thought that a man who had conferred such benefits upon his generation would have been at least famous, and probably wealthy. Fame perhaps he had, but it was known to but a few people of his own day ; and wealth he had not, or his later life and end would not have remained unrecorded. No one knows how, when, or where he died ; and this fact renders it probable that he ended life poor and friendless, leaving others to grow richer as a result of his labours.

CHAPTER III

James Watt: The Man and his Work

IT has been said of James Watt that his merit lay in the fact that he was not merely an engineer. He had read widely, was interested in many things, and possessed a vivid imagination. He was familiar with books written in French, German, and Italian, and could talk freely upon poetry, sculpture, and philosophy. He was as much at home in the fields and hedgerows as he was in the workshop; and yet, until he was nearly forty, he had to struggle hard both for life and for a living.

Born at Greenock in 1736, he was the son of a carpenter who made furniture and ships' fittings, and repaired nautical instruments as opportunity occurred. Fragile and delicate in body, shy and reserved in manner, young Watt mixed but little with other boys, and spent most of his spare time reading at home, taking long walks into the country—often with a book in his pocket—and watching the men in his father's workshop. At school he made very little progress, but at home he acquired a great reputation as a teller of stories.

At eighteen it was decided that he should become a scientific instrument maker—and in those days the only scientific instruments were those used by draughtsmen, surveyors, and navigators. In Glasgow, the nearest town, there was only one man who could, by any stretch of language, be termed an instrument maker, and he called himself an optician. He lived by "repairing all sorts of things, from fishing rods to spectacles," and to him young James Watt went for a year.

That period was quite long enough for a smart lad to plumb the depths of his employer's trade, so in 1755 he decided to go to London for further experience. Carrying a letter of introduction from Professor Dick, of the University, and travelling on horseback with a relative of his father's, a sea captain, he took twelve days on the journey, his chest of clothes meanwhile being sent to Edinburgh by road and conveyed the rest of the distance by sea. But London instrument makers would have none of him. He had not served, and was not willing to serve, a seven years' apprenticeship, and upon this matter the rules of the trade were unyielding.

For a time he worked for a watchmaker, and then managed to find an instrument maker who gave him a year's instruction for a fee of 20 guineas. He lived in one room on 8s. a week, and made a little money by private work in his spare time. But his health was not good, and he returned to Greenock in 1756. Then after a rest at home he made an effort to set up in business for himself in Glasgow; but in those days the tradesmen of many towns were banded together to prevent unqualified persons from practising their crafts, and no man could ply his trade without their permission. So when the Corporation of Hammermen objected to him on the grounds that he was not the son of a burgess and had not served a proper apprenticeship, he had to seek other quarters.

When in this predicament he met with a slice of good fortune. He secured a room within the University, over which the townspeople had no jurisdiction. It was a small room, not more than 20 feet square, but it was large enough for his purpose, and its position enabled him to make friends among the professors. He made quadrants for mariners, and when orders for these failed, he made musical instruments and repaired scientific apparatus belonging to the University. But it was a hard struggle, and he devoted many hours to study and experiment which, if he had been able to choose, he would have preferred to spend in making a living.

It was in 1759 that his friend Robison called his attention to the steam engine. There were none in Glasgow, but Watt had read about it and promptly made a model of one, which refused to work. Then learning that there was a model of Newcomen's engine belonging to the University, which was then in London for repairs, he asked for it to be returned. At the same time he read everything he could find in the University Library upon the subject, and made many experiments, employing for his apparatus glass phials such as were used by apothecaries, or chemists as we call them to-day, and tubes of hollow cane. In 1761, in order to ascertain what force steam could exert, he fixed a small syringe to the top of a closed vessel filled with water and heater (a Papin's digester) and placed a weight on the top of the piston. The piston was only $\frac{1}{3}$ inch in diameter, yet the steam lifted a weight of 15 lb., representing a pressure of more than 150 lb. per square inch! Here was force enough, if only it could be utilised. But when he had proceeded so far he had to put his experiments on one side in order to undertake work that was more profitable.

The Newcomen model (see Fig. 15) arrived in 1763, and gave Watt plenty of food for reflection. It had a cylinder 2 inches in diameter, with a stroke of 6 inches, and the boiler was about as large as a kettle. The engine would only make a few strokes, and then stopped, as though there was no more steam. Yet according to the dimensions of larger engines the boiler was of ample proportions for such a small cylinder. By experiment and calculation he ascertained the weight of steam necessary to fill the cylinder and the weight of steam produced by the boiler in a given time; and he found that the boiler was capable of supplying more than enough steam for the engine.

There was evidently some source of loss here, and it gradually dawned upon him that the cold walls of the cylinder condensed most of the steam that entered. This would be more serious in a small engine than in a large one, because the surface of cylinders of different size decreases far less rapidly than the volume. The cooling effect of a small cylinder is, therefore, greater than that of a large one. But this did not help him much, and he sought, by reading and experiment, for some means of preventing this. He found that steam required six times its weight of cold water to condense it without altering its temperature, thus rediscovering what his friend Professor Black had previously discovered. He made the cylinder of wood to reduce the cooling effect, he enlarged the area of the grate, and placed flues through the boiler to increase the rate of production of steam, but all to no purpose. Finally he concluded that the cylinder must, by some means or other, be kept as hot as possible, in order to avoid condensation. How to do this and at the same time to condense the steam was what puzzled him.

One Sunday in the spring of 1765, when he was out for a walk, the solution of the difficulty flashed across him. Why not have a separate condenser, a separate chamber into which the steam could pass for condensation, while the cylinder walls were kept as hot as they could be? Rising early the next morning, he borrowed a syringe, about $1\frac{1}{3}$ inches in bore and 10 inches long, made a cistern

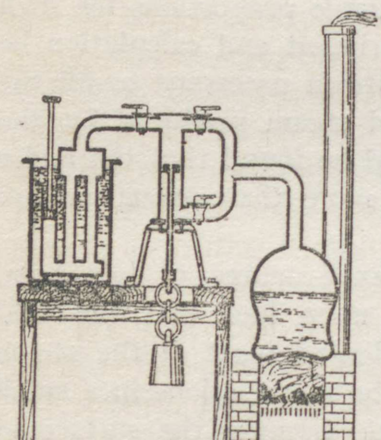

Fig. 16.—Watt's model

of tin plate with a pump in it, and immersed this in cold water as shown in Fig. 16. He hung a weight on to the piston rod, got up steam in the boiler, and passed it through the cylinder until the latter was hot and free from air, and then made a few strokes with the pump to draw a little of the steam into the condenser. At once the piston rose sharply, lifting as it did so the weight of 18 lb.

The problem was solved! The pump required very little power, and could easily be worked by the engine itself. Instead of spraying water into the cylinder, the water could be sprayed into a separate vessel, a condenser, into which the steam could be drawn from the cylinder by a pump. Moreover, why should not the cylinder be kept hot by making it with double walls and providing it with a jacket of steam? These and many other improvements soon occurred to Watt, but the first problem was to make a full-sized engine in order to convince people of the value of his invention.

The construction of a full-sized engine, however, was a more difficult task than he had yet essayed. His own experience had been in light metal work; there were very few skilled mechanics in Scotland and, above all, there was need for secrecy, lest someone should rob him of the benefits of his invention. Watt started to make an engine with a cylinder 6 inches in diameter and 24 inches stroke, working first in a cellar and, later, in a disused pottery works. He could not get the cylinder cast, and would have had no means of boring it had he been able to do so ; and it had to be hammered out of sheet metal ! Moreover, not only tools, but money was needed. His business, which had prospered for a time, had now fallen away, and in 1766 he had to relinquish his experiments for a time and take to surveying for a living.

Meantime, Watt looked about for someone to help him, and thought himself fortunate in securing the interest of Dr. Roebuck, who had established the Carron iron works a few years before. The Doctor paid his debts, amounting to about £1,000, in return for a two-thirds share in the invention. It was patented in 1769 ; but the engine, with a cylinder 18 inches in diameter, constructed for Dr. Roebuck in that year, did not answer expectations, and shortly afterwards Dr. Roebuck failed.

Watt's fortunes were now at their lowest ebb. His wife had died, he had a young family, he was hard worked and ill paid, his health was bad—all his life he had suffered from severe headaches—and it seemed as though his invention would come to nothing. His letters at that period revealed the deep despondency into which he had fallen. But he was encouraged by his friends, and his own indomitable spirit brought him through.

Through his friends he got into communication with Matthew Boulton, a Birmingham manufacturer and a man of wealth, enterprise, and personality. He was interested in the steam engine, but had many things on his hands. Finally, however, he was persuaded to take Roebuck's place, and in 1773 Watt entered into partnership with Boulton and made arrangements to have his engines made by his skilled workmen in the works at Soho, Birmingham.

Let us now examine a little more closely the nature of Watt's invention. In the specification of his patent of 1769 he said:

"My method of lessening the consumption of steam, and consequently fuel, in fire engines consists of the following principles:

"First, that vessel, in which the powers of steam are to be employed to work the engine, which is called the cylinder in common fire engines, and which I call the steam vessel, must, during the whole time the vessel is at work, be kept as hot as the steam that enters it; first, by enclosing it in a case of wood, or any other materials that transmit heat slowly; secondly, by surrounding it with steam or other heated bodies; and thirdly, by suffering neither water nor any other substance colder than steam to enter or touch it during that time.

"Secondly, in engines that are to be worked wholly or partially by condensation of steam, the steam is to be condensed in vessels distinct from the steam vessels or cylinders, though occasionally communicating with them; these vessels I call condensers; and, whilst the engines are working, these condensers ought at least to be kept as cold as the air in the neighbourhood of the engines, by application of water or other cold bodies.

"Thirdly, whatever air or other elastic vapour is not condensed by the cold of the condenser, and may impede the working of the engine, it is to be drawn out of the steam vessels or condensers by means of pumps, wrought by the engines themselves, or otherwise.

"Fourthly, I intend in many cases to employ the expansive force of steam to press on the pistons, or whatever may be used instead of them, in the same manner as the pressure of the atmosphere is now employed in common fire engines. In cases where cold water cannot be had in plenty, the engines may be wrought by this force of steam only, by discharging the steam into the open air after it has done its office.

"Lastly, instead of using water to render the piston or other parts of the engines air and steam tight, I employ oils, wax, resinous bodies, fat of animals, quicksilver, and other metals in their fluid state.

"And the said James Watt, by a memorandum added to the said specification, declared that he did not intend that anything in the fourth article should be understood to extend to any engine where the water to be raised enters the steam vessel itself, or any vessel having an open communication with it."

From the point of view of construction the really important feature of the invention was the separate condenser and air pump—and the air pump was essential. The water which formed in the condenser could have been got rid of by connecting it with a pipe leading to a well rather more than 34 feet deep—34 feet being the greatest height to which the pressure of the atmosphere will force a column of water into a vacuum. But all water contains a little dissolved air which is driven off with the steam; and this air, together with air which entered through imperfect joints, accumulated in the condenser. The only way to remove it was by means of an air pump, and every "condensing" engine, therefore, must be furnished with this contrivance.

The statements that the cylinder must be kept as hot as possible and the condenser as cold as possible, show that Watt recognised that the steam engine was a heat engine, that the power to work the engine came from the heat resident in the steam, and that steam was only a means of conveying heat from the fire to the cylinder. Any substance which expanded as it cooled could be made to serve the purpose; but water was the most convenient and in many respects the most suitable.

This fact is more particularly emphasised by his reference to using steam expansively. If steam is allowed to enter the cylinder during the whole length of the stroke, a whole cylinder full of steam at, roughly, the pressure in the boiler is used every time, and the temperature and pressure at the end of the stroke are the same as at the beginning. But if steam be cut off at, say, one quarter of the stroke, only one-fourth of the quantity of steam is used, and the piston is pushed forward for the remaining three-quarters, not by the pressure in the boiler, but by the expansive force of the steam itself. The temperature and pressure are now lower; the steam has lost some heat, and that heat has been turned into useful work in pushing the piston. All engines, from the time of Watt, are worked expansively, whether they are condensing or non-condensing. The disadvantage of the latter is that the steam which is discharged into the air is still capable of doing work, and therefore some of the heat which it has taken up from the fire is being wasted.

As we shall return again to questions of the power and efficiency of steam engines, we can now follow the career of James Watt a little farther. When he entered into partnership with Boulton his troubles were by no means over. His patent had been in existence for some years, there were unscrupulous rivals in the field, preliminary expenses would be heavy, and they felt that unless they could obtain an extension of time their efforts might bring them no benefit. Two courses were open to them: to secure an extension of the patent by applying to the Patent Office, or to get an Act of Parliament passed protecting them for a term of years. They chose the latter, and after a great deal of trouble and delay, Parliament, in 1775, granted them an extension of twenty-five years.

The first engine was constructed to blow the bellows of John Wilkinson's iron works at Broseley, in 1776, and in the same year another was supplied to a distillery at Stratford. Then the Cornish mines claimed attention. They were so far from the coal-fields, and the consumption of coal by Newcomen's atmospheric engine was so great, that the Adventurers, as the proprietors of the mines were called, were on the brink of ruin. Moreover, the influx of water was becoming greater with increasing depth, and the engines erected by Newcomen, and later, on the same principle, by Jonathan Hornblower, were unequal to the task. Some of the mines had closed down and others were on the point of doing so when Watt's engine appeared in the field. The fact that for a given power it consumed 60 per cent. less coal than the atmospheric engine was its special recommendation, and orders soon began to flow in to the Soho factory.

Watt himself lived almost entirely in Cornwall for some years, superintending the erection of his engines. But he was a better man in the laboratory and workshop than he was in the committee room, and the terms upon which the engine was sold necessitated frequent dealings with the purchasers. Boulton's and Watt's remuneration for putting down the engines and keeping them in order was fixed at one-third of the saving in the cost of fuel. This sum was so large that, though the Adventurers gained greatly by the change, they soon began to resent handing over even this proportion, and to bargain for better terms. Watt was no hand at bargaining. His health was still poor, he was peevish and irritable, and his upright mind rebelled against people who, having made an agreement, and not lost by it, were anxious to break it. Time after time did Matthew Boulton have to journey to Cornwall to smooth matters over. He was a man of business habits, of charming manners, and ready address. He could do what was quite impossible to Watt, and had Watt searched the country from end to end it is doubtful whether he could have found a man better fitted in all respects to co-operate with him.

The trouble with the Cornishmen was not the only one which had to be faced. The Soho works had extended very rapidly, and Boulton had many irons in the fire. Financial difficulties arose, money had to be borrowed, and there were times when bankruptcy seemed to be the inevitable end. But they weathered the storm and gradually emerged from their difficulties to enjoy the fruits of their labours. In Boulton's words, they set out "to make steam engines for the world," and they made them. Said he on one occasion, "The country is steam engine mad"; and from that day to this the madness has never ceased.

The earlier Watt cylinders—those constructed up to 1778—were of the type shown in Fig. 17. The cylinder, it will be observed, was open at the top end, and totally enclosed in an outer vessel filled with steam. Starting with the piston at the top of its stroke, the steam pressed it down until it reached the lowest point. The steam valve then closed, the equilibrium valve opened and, by admitting steam to the lower half of the cylinder, made the pressures above and below the piston equal. The piston was then drawn up by the weight on the pump rod at the other end of the beam. Immediately it reached the top the valve leading to the condenser opened and the piston was pressed down by the force of the steam into the vacuum created by the condenser. The valves were opened and closed by rods from the beam as in the Newcomen engine. The arrangement in this and all Watt engines is very difficult to explain, even with a

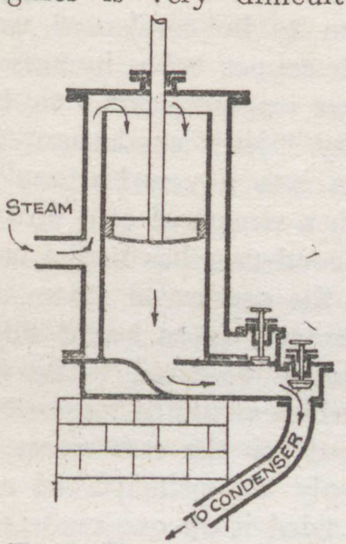

Fig. 17.—Watt's early cylinder

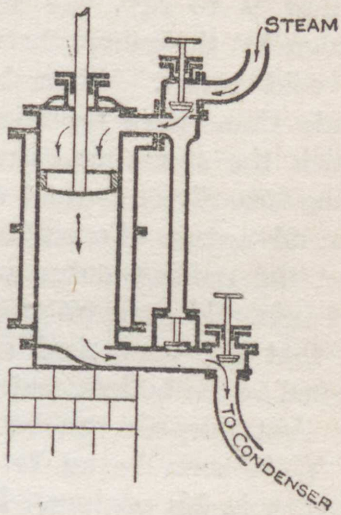

Fig. 18.—Watt's later cylinder

drawing, and as it is now no longer used its consideration may be omitted.

The cylinder described had certain disadvantages, and was replaced by the form shown in Fig. 18. In this the steam jacket was fed independently of the cylinder, as it is in engines to-day, and a port was constructed leading from the steam supply pipe into the space above the piston. The mode of operation was similar to that in the earlier one. Steam first acted on the upper side of the piston; then the equilibrium valve opened to render the pressure above and below equal; next the weight on the pump rod pulled up the piston; and finally the condenser valve opened and permitted the steam to press the piston down again.

The condensers used were of the "surface" type —that is to say, the steam to be condensed was drawn by the pump through copper tubes immersed in cold water. When larger engines came to be made these were replaced by "jet" condensers, in which the steam was drawn into a vessel where it came into direct contact with a stream of cold water. The advantage of a surface condenser lies in the fact that the cooling water and the condensed steam do not mix. If pure water is scarce, as on board ship, so that the condensed steam is required to be returned to the boilers, water which would be impossible for that purpose can be used for the condensers.

Watt soon began to apply the principle of expansion in his engines. He tried it on one made for the Soho works in 1776, and definitely adopted it on an engine made to pump water at Shadwell in 1778. It is possible that he was led to adopt it less on theoretical grounds than in order to reduce the force acting on the piston towards the end of its stroke. At the same time he was aware that by cutting off at half stroke he obtained nearly twice the power from a pound of steam—a fact with which he had been familiar since 1769. As the pressure used in his engines was only about 10 lb. on the square inch above that of the atmosphere, he secured all the expansion he needed in a single cylinder. But as Jonathan Hornblower took out a patent in 1781 for a double-cylinder engine in which the steam passed first through one and then worked against a vacuum in a second, he laid greater stress on the principle of working expansively in the patent which he took out in 1782.

So far the engines constructed had only been suitable for pumping—they gave a to and fro motion and not a rotary one, suitable for driving machinery. Watt, always on the look out for new applications of, as well as improvements in, his engine, saw what was required, and puzzled long and earnestly how to secure it. It is curious to us, who see the crank so frequently, that this device was not thought of sooner, but to the engine builders of those days it was not so clear. A model of the crank was, among other contrivances, made in the Soho works, and a workman gave the secret away, so that when Watt was ready to put a rotary engine on the market he found that a Mr. Pickard, of Birmingham, had patented the crank; and as he never adopted other men's inventions on his engines, he was driven to seek for some other device.

Finally he settled on the "sun and planet" motion shown in Fig. 19, Plate 2. In this arrangement one toothed wheel was fixed rigidly, so that it could not rotate, to the arm hanging from the "pump" end of the beam. The other toothed wheel was fixed to the shaft carrying the flywheel. As the arm rose and fell the first wheel ran round the second, with the teeth locked together, so that the second was bound to rotate. The most curious thing about the contrivance, at any rate to those who have not studied mechanism, is that the flywheel makes two complete revolutions for each "up and down" movement of the suspended rod—that is, two revolutions for every two strokes of the engine. The rotation of the flywheel is, therefore, twice as fast, and, in the case of a slow movement of the piston, much more regular than if a crank had been used.

Now, though a slow, irregular motion is no disadvantage in pumping, it is a serious defect in an engine for driving machinery. Watt saw that in obtaining rotary motion from his single-acting engines, in which the steam was only effective during alternate strokes, he would have to depend on a heavy flywheel, and a heavy flywheel required power to drive it. Consequently he began to think of means whereby the steam could be made to act upon the piston at every stroke. The idea of a double-acting engine was in his mind—he even had a drawing of it—in 1774, but it was not until he began to develop the rotary engine after 1780 that he commenced to work out his ideas in practice. And his patent of 1782, in addition to laying extra stress on expansive working, covered also the double-acting engine and the "sun and planet" motion.

The double-acting cylinder involved alterations to the other parts of the engine. The old single-acting cylinder had only pulled the end of the beam, not pushed it; and the piston rod exerted that pull through a rope or chain lying over a circular arc in order that the force might always act at right angles to a line joining it with the centre of the beam. If only a pin joint had been used between the piston rod and the beam the former would have been bent backwards and forwards at every stroke; but the flexible connection was no use when the piston rod had to make both a pull and a push, and Watt had to devise a more rigid method of communicating the motion.

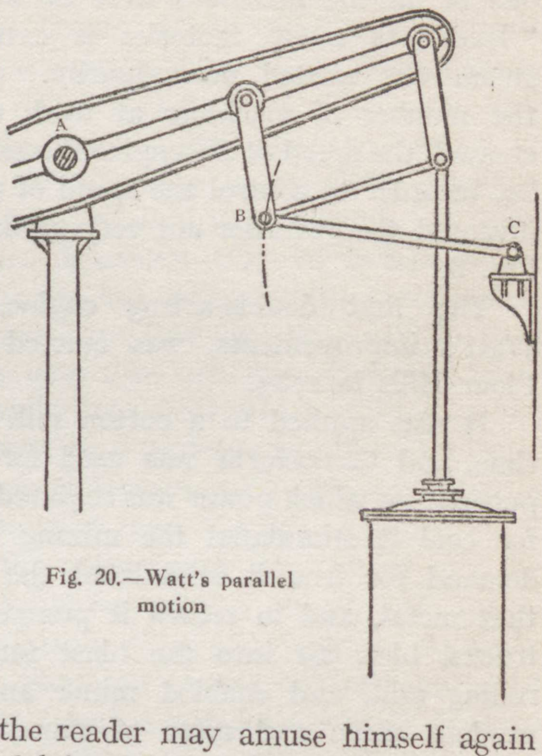

Fig. 20.—Watt's parallel motion

The form adopted is shown in Fig. 20, and the reader may amuse himself again by making a model in card or thin wood. All that needs to be said is that A and C are fixed points, A representing the centre of the beam and C being on the wall of the engine house; and that the end of the piston rod is pinned to the frame at B. All the other joints are free.

While the double-acting cylinder, aided by the flywheel, gave a regular motion throughout each revolution, the engine was still imperfect for driving machinery. It continued to take the same amount of steam and to exert the same power. Whether one or all the machines were at work, and as the "load" in many factories is extremely variable, steam was wasted unnecessarily. Moreover, when the number of machines at work decreased or increased, the speed of the engine increased or decreased. So, in order to control the speed of the engine, Watt invented the governor not very unlike that shown in Fig. 8.

The first double-acting engine, containing all Watt's improvements, was erected for the Albion Flour Mills in 1785.

It was applied to a cotton mill about the same time, and thenceforth was used for any and every purpose for which power was required. By its demand for coal it stimulated the mining industry, by its demand for iron it stimulated the manufacture of that metal, and in return it pumped water, hauled trucks, blew air into the blast furnace, drove the rolling mill, and enabled miner and ironworker to produce more and more of those materials which were essential to industrial progress. Without the steam engines the inventions of textile machinery would have been far less effective than they were, and the extraordinary development of cotton spinning and weaving which took place towards the close of the eighteenth century could never have occurred. Before Watt's time there were no steam engines—

only steam pumps, useful but limited in their application. England was, in every material respect, an agricultural country; but, impelled by the driving force of the steam engine, she became, during the Napoleonic wars, the workshop of the world.

And what has history to say on the importance of British manufactures in those days, when a series of wars drained the country of its wealth in men and money? In 1750 the National Debt was only £78,000,000—not a large sum as we count national indebtedness to-day, but still large enough for those times. When the American War of Independence closed in 1784 the amount owing by the Government of this country was over £200,000,000. And in 1815 it had swollen to over £800,000,000. Before a country can run heavily into debt two conditions must obtain. There must be confidence in her rulers—confidence that her statesmen will not repudiate a written obligation as a mere "scrap of paper," and confidence that the resources of the country and the industry and intelligence of the people will enable them to produce more than they require for subsistence, so that they can pay an accumulated debt out of the surplus. And it was the existence of these conditions which enabled the Government to multiply the National Debt by four in thirty years, and by ten in a little over half a century.

When Napoleon called us a nation of shopkeepers he thought only of our mercantile marine and of the commercial towns on the coast. His vision never extended to the Midlands and the North, where

Watt's steam engine was pumping water, raising coal and iron, and driving mills and factories. And when Wellington said that the Battle of Waterloo was won on the playing fields of Eton he forgot that the national credit, which enabled us to continue the war unbeaten when every other country in Europe had been humbled to the dust, was established and maintained by clever inventors, beginning as, and often to the end of their days remaining, poor men; by men who, amid grime and dust and sweat, won coal and wrought iron into wonderful machines; and by women and children who toiled amid the heat and moisture of the cotton mills.

And of all those who created this new epoch in the world's history, the greatest was James Watt. Each played his part, but compared with him they were as the raw apprentice to the most accomplished mechanic, as the merest tyro at the law to the subtlest Lord Chancellor. For it might almost be said that he was born out of his time. He was not a mere inventor, proceeding to solve a narrow problem by trial and error. His methods were the scientific methods employed even by few men long after he was dead. He saw, it may be vaguely, and he employed in his engines, principles which were only stated in precise language or in a mathematical equation when his engines had been in use for over sixty years. And he swept the field of inquiry so completely that until 1884 there was no improvement of any importance in steam engines that had not been expressly foreshadowed in his specifications.

CHAPTER IV

Raising Steam

A BOILER is a vessel for converting water into steam, and steam is wanted because, pound for pound, it contains more heat than water, from which it was formed. Whether the steam is to be used for warming buildings, or for certain factory processes, or for producing power in engines, it is the heat it contains that is valued. And as the heat is produced by burning coal the boiler is a device in which the energy of burning coal is absorbed by water and conveyed by means of steam to wherever it is required. Every pound of fairly good coal yields 14,000 units of heat on burning. Some of this is lost by warming bodies in the neighbourhood of the boiler, and some goes up the chimney in the waste gases, and the best boiler is that in which these losses are reduced to the least possible quantity.

Some boilers are constructed to give steam regularly over long periods; others have to be capable of producing it at short notice. From some boilers the heat is conveyed by steam at low temperature, and from others at high temperature; and since the pressure exerted by steam is entirely dependent upon its temperature, except where a special appliance, called a superheater, is employed, there is for every temperature a corresponding pressure. The power of a boiler is measured by the amount of water it will convert into steam at a particular temperature or pressure every hour, and it may vary from a thousand or two to thirty or forty thousand pounds per hour!

Now the first essential of all boilers is that they shall be capable of withstanding the pressure of the steam they produce, and the second is that the heat shall be conveyed rapidly and without loss to the water. With every pound of coal yielding 14,000 units of heat during combustion, and every unit of heat transformed into work capable of doing 778 ft.-lb. of work or lifting over a third of a ton 1 foot from the ground, there is need of strength if accidents are to be avoided. Professor Thurstan calculated that, at a pressure of 100 lb. on the square inch, there is sufficient energy inside an ordinary cylindrical boiler to hurl it 3½ miles in the air. Yet modern boilers are working every day at 200 lb. and 225 lb. on the square inch, and men are moving freely about among them, secure in their confidence that the design and workmanship are equal to any test which could be applied. To a person with any imagination it is a queer sensation to walk over the top of one of these reservoirs of energy and to realise that within a few seconds you might find yourself 15,000 feet or thereabouts above the ground.

The best shape for resisting internal pressure is a sphere, because a sphere has a smaller area of surface for a given volume, or, conversely, a larger volume for a given area of surface, than any other form. If a liquid or a gas is forced into a vessel of any other shape it tends to become a sphere. Thus, an oval boiler would tend to become cylindrical, and in a cylindrical boiler the flat ends tend to bulge—in fact, all flat sides have a tendency to curve outwards under internal pressure; and during these deformations some of the joints would probably give way. But as it would be very difficult to bend the plates for a spherical boiler—they would have to be pressed—the usual form adopted is that of a cylinder. The flat ends are prevented from bulging in two ways: long rods passing right through from end to end, called "longitudinal stays" (Fig. 21), and brackets or "gusset stays" (Fig. 22) fastening the flat ends to the curved sides.

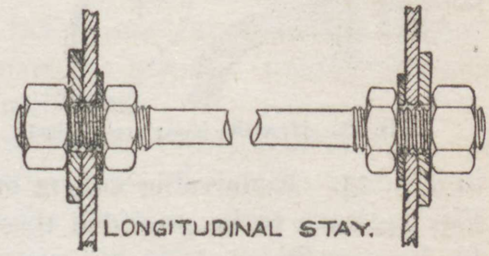

Fig. 21.—How a boiler is strengthened lengthways

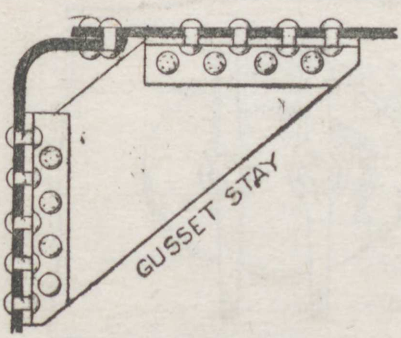

Fig. 22.—How the ends of a boiler are strengthened

After Newcomen's copper boilers with lead tops, wrought-iron was used, but this has now given way to steel, the plates varying from $\frac{3}{8}$ inch to $1\frac{1}{2}$ inches in thickness. Holes for the rivets can be punched, but should always be drilled, as the plate is less likely to be weakened. The joints are finally made steam-tight by "caulking" or hammering with a blunt-ended chisel, as in Fig. 23. Removable covers or "manholes," as in Fig. 24, have to be provided to enable the last rivets to be put in, the boiler to be inspected, and the scale removed from time to time. Though these openings are about 16 inches long by 10 inches wide there is not much room for a man to squeeze through. A friend of the writer's, of substantial build, was once working inside a boiler, and on endeavouring to get out found that he was

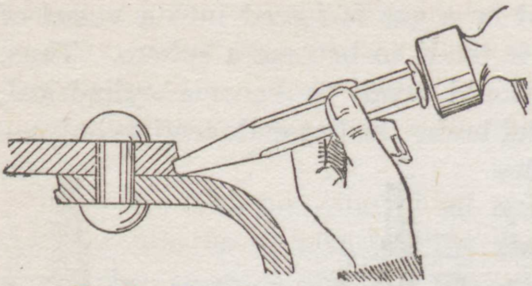

Fig. 23.—How the joints are caulked

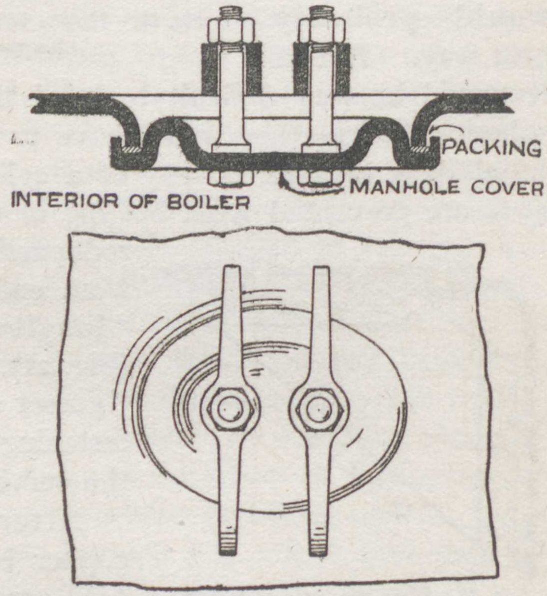

Fig. 24.—Manhole and cover

fast! The only thing that could be done was to turn the hosepipe on him. Under the douche of cold water he shrank sufficiently to be pulled through. Men who are built for "comfort rather than speed" are not very well suited for boiler inspection and scaling.

In order that a boiler may produce the largest quantity of steam from the smallest weight of fuel, it must be so designed that:

(*a*) The fire burns regularly and fiercely.

(*b*) There is a large area of surface in contact with the fire or hot gases on one side and water on the other; and

(*c*) The water should circulate rapidly from the hotter parts of the boiler, near the fire, to the cooler parts, remote from it.

Let us now see how these results are attained.

Common Types of Boiler

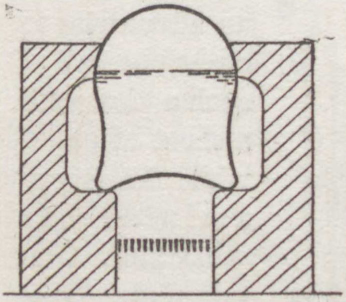

Fig. 25.—Watt's wagon boiler

In the days of James Watt the favourite type of boiler was the "Wagon," shown in Fig. 25. The boiler rested on brick walls with the grate between, and it was only expected to stand a pressure of, say, 10 lb. on the square inch. The strength of this type of boiler was increased by making it cylindrical, and the heating surface by fitting tubes from end to end, which conveyed the hot gases from the

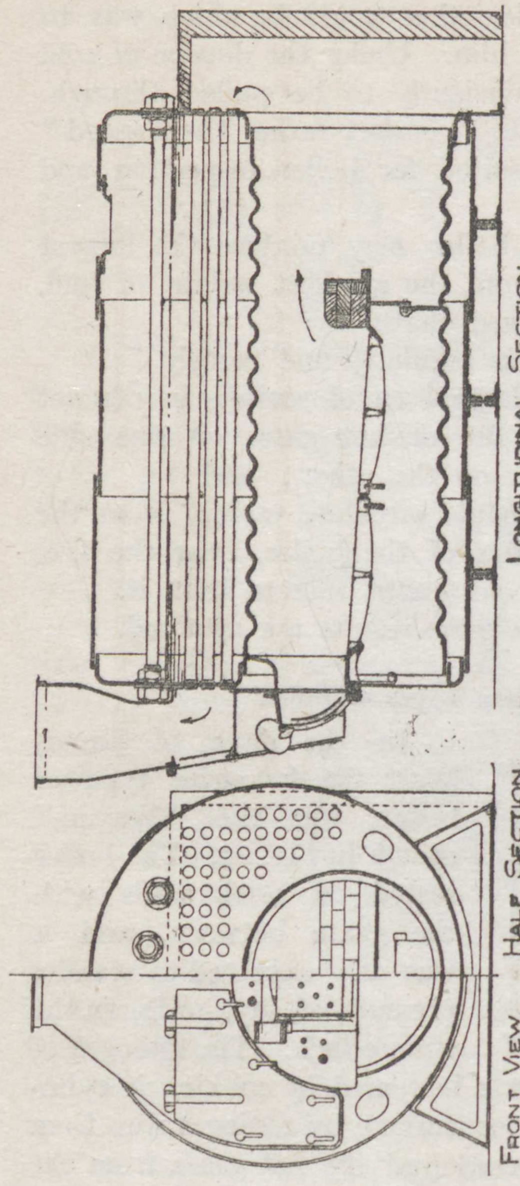

Fig. 26.—" Dry-back " boiler

far end to the front. This type is represented to-day by the "dry-back" or colonial boiler shown in Fig. 26. The end view is shown in half section, one side of the figure representing the outside and the other a section of the boiler. The student who is not used to reading drawings will find it an advantage to cover one half of such a view with a sheet of paper while he is examining the other half. The tubes are "expanded" into the tube plates by a special tool, to make steam-tight joints, and the boiler may either be built in brick-work or be furnished with an iron casing for the grate.

These boilers are very seldom seen in England, but they are common enough on sugar plantations and in other industries on the outskirts of civilisation. They are cheap, but neither economical nor very safe. A great deal of heat is lost from the sides and dry back, and scale tends to settle on the bottom of the shell over the fire. The metal at this point tends to become overheated, it expands, and subjects the boiler to strain. It does excellent work, and is safe enough in intelligent hands, but it is a boiler to avoid if you can afford a better one.

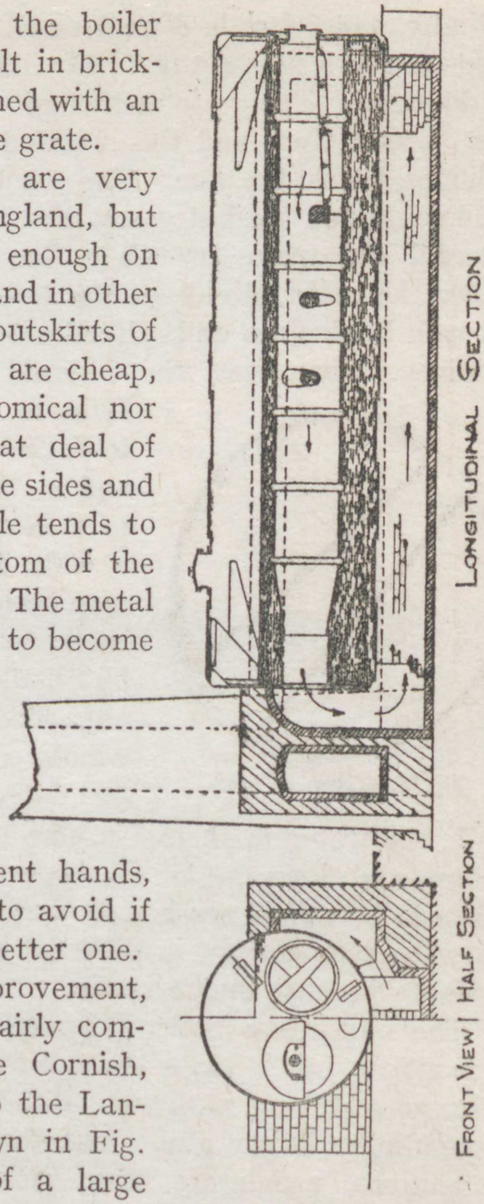

Fig. 27.—Lancashire boiler

A very early improvement, and one which is fairly common to-day, is the Cornish, which is similar to the Lancashire boiler shown in Fig. 27. It consists of a large cylinder, 5 or 6 feet in diameter and 20 to 25 feet long, through which passes a narrow cylinder, 15 to 24 inches in diameter. The grate and ashpit are formed in the first 5 or 6 feet, and the remainder of the smaller cylinder forms the flue. The whole boiler is set in brickwork, and the hot gases, after emerging from the internal flue, pass through a flue in the brickwork under the boiler, divide at the front end, and return through brick flues on both sides of the boiler to the chimney. Sometimes the internal flue is placed a little to one side in order to improve the circulation, and as the hot gases flow, to a large extent, through a wide flue without communicating their heat to the water, the flue is crossed by "Galloway tubes" (Fig. 28). These are water tubes which, crossing the wide flue, intercept the hot gases, while the water in them becomes heated, is rendered lighter, and flows out of the upper end. This causes steam to be raised much more quickly, and by equalising the temperature in different parts of the boiler tends to prevent undue strain.

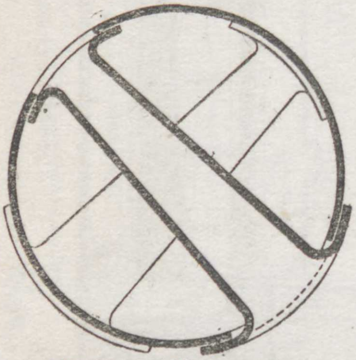

Fig. 28.—Galloway tubes

The Lancashire boiler (Fig. 27) is exactly similar in principle, but is larger—6 to 8 feet in diameter and 25 to 30 feet long, with two or three furnaces of correspondingly larger size. The flues are often made in sections, which are often joined by Adamson's

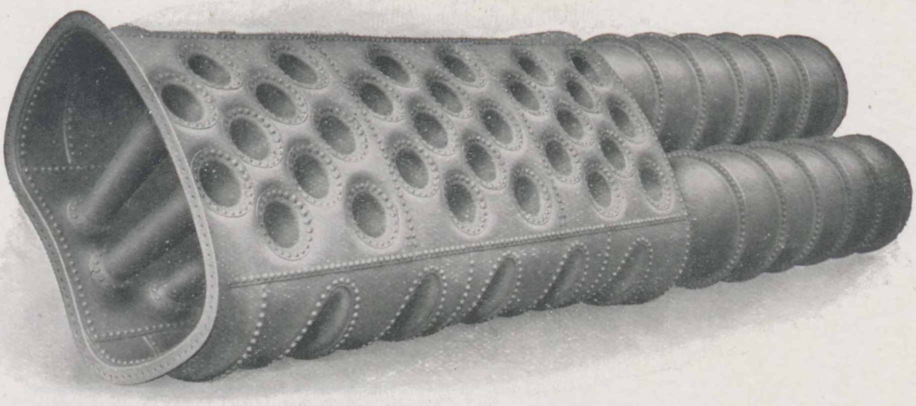

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Fig. 32.—Galloway's Flue

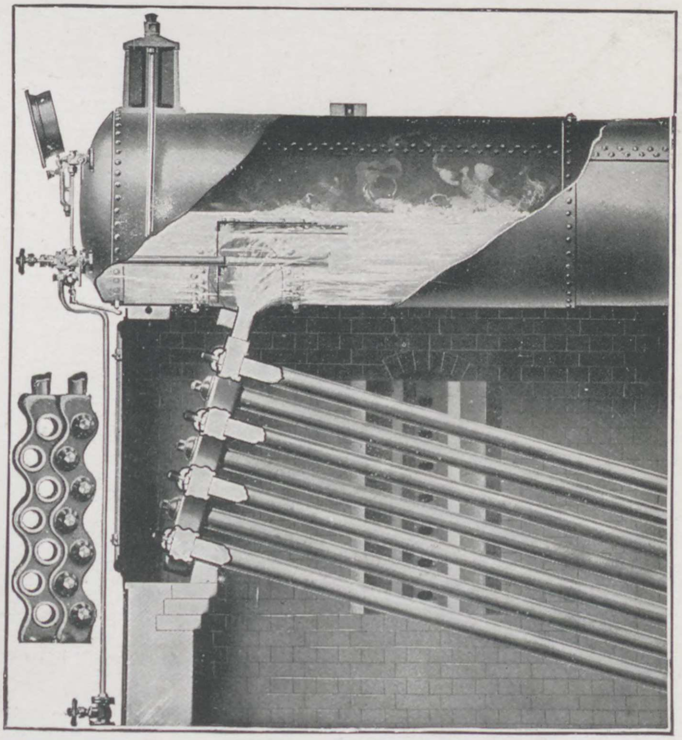

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Fig. 40.—Partial Vertical Section of Land Boiler; and view of a Header with and without Handhole Fittings

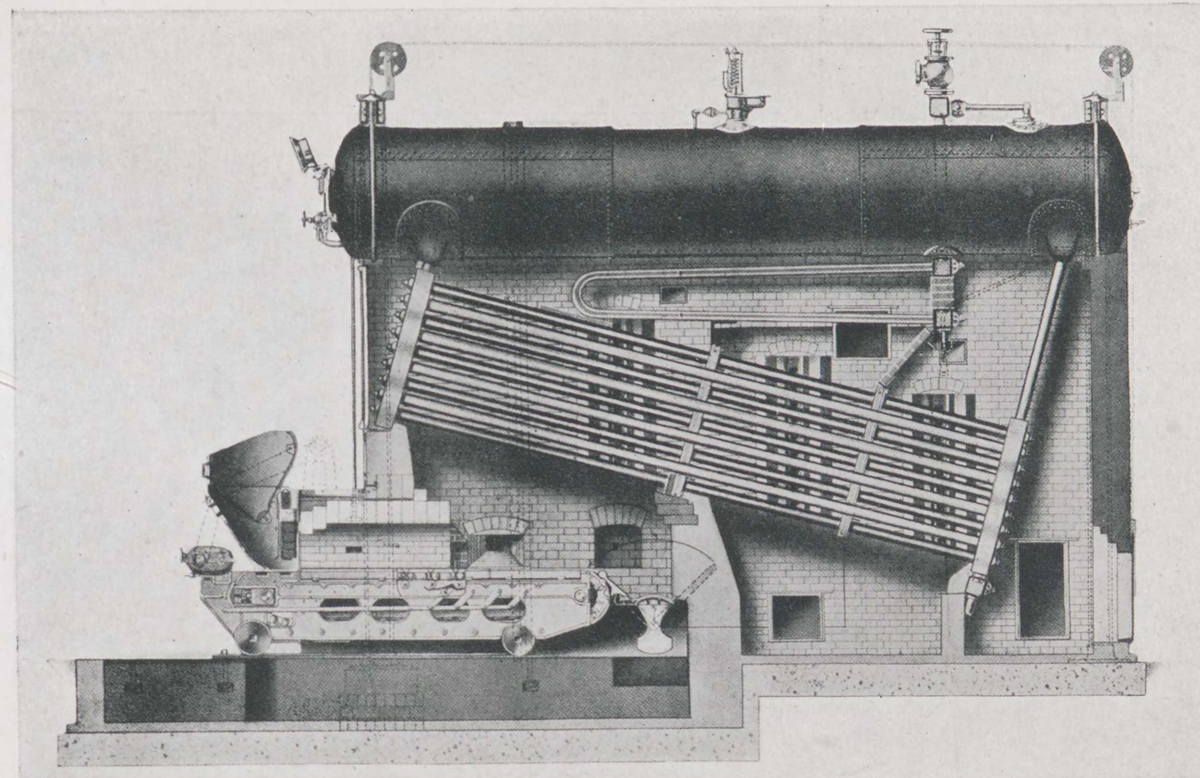

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Fig. 41.—Water Tube Boiler

rings shown in Fig. 29. The end of the flue section is flanged, or has a sort of lip formed upon it, and a flat ring of steel is placed between the ends of the sections. It confers stiffness on the tube, and the rivets are not exposed directly to the hot gases.

While the flues must have a certain amount of stiffness to prevent them sagging, the chief disadvantage arises from the fact that they are necessarily hotter than the boiler shell; and owing to their length they press strongly against the ends of the boiler. Thus if a flue of a 30-ft. boiler is exactly the same length as the shell at the freezing point, there will be about ¾ inch difference between them when the average temperature of the flue is 500° Fahr. and of the shell 350° Fahr. One method of allowing for this difference is to join up the sections of the flue by expansion rings, as shown in Fig. 30. A still more flexible flue is obtained by using corrugated tubes illustrated by Fig. 31. The slight bending which occurs—like the opening and closing of the pleating of an accordion—is then distributed over the whole length of the flue. If it is concentrated at one point the metal is liable to become "fatigued" and to lose its elastic qualities.


Fig. 29.—Adamson's ring


Fig. 30.—Expansion ring


Fig. 31.—Corrugated flue

In some forms of Lancashire boiler—notably those made by Galloway, Limited—the flues are only separate tubes at the furnace end. Beyond that they are united to form a single flue as shown in Fig. 32 on Plate 3. The oval form is not so strong as the circular, and the flue needs to be stiffened by a number of Galloway tubes; but these increase the heating surface, improve the circulation, and raise the rate at which water is converted into steam. All sorts of devices have been tried to cause the hot water to move more rapidly over the heated surface, and more particularly to prevent the formation of quiet "pockets" of cooler water in any part of the boiler. Some of these consist essentially of guides to direct the stream of hot water as it rises in the immediate neighbourhood of the grate.

Taken on the whole, the Lancashire boiler is a very good one for large factories and power stations. It may take five or six hours to raise steam from the cold; but once the brickwork is hot it is economical of fuel, and the large quantity of water it contains enables it to deal with a sudden demand for power. Moreover, the fires may be "banked" for a long time without the boiler and its setting becoming cold. It is safe for low pressures, and is used often for producing steam at 200 lb. on the sq. inch.

The "Loco" type of boiler shown in Fig. 33 is by no means restricted to use on railways, but is also employed for engines driving agricultural machinery, for traction engines, for road rollers, and for other purposes. The principal feature is the large number of tubes. In railway engines there may be 250 of them, from 1½ to 2 inches in diameter, but in stationary locomotive boilers they are 3 or 4 inches, and there are fewer of them. In a locomotive, moreover, the tubes are of brass or, more generally, steel, and the firebox and stays of copper. Copper is more expensive than iron or steel, but stands the action of the fire better. While we shall deal with the locomotive in a separate chapter, it is worth while noting here that the chief difficulty

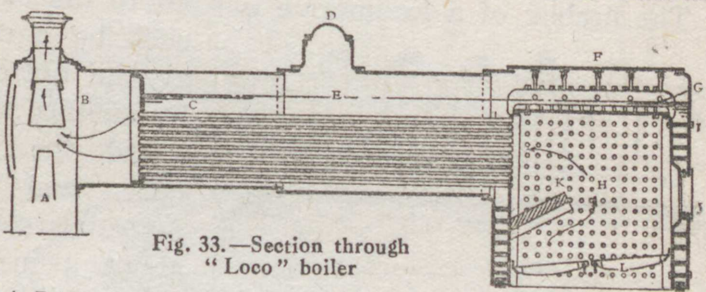


Fig. 33.—Section through "Loco" boiler

A, Exhaust Steam; B, Smoke Box; C, Fire Tubes; D, Steam Dome; E, Water Level; F, Stays; G, Girder Stays; H, Furnace; I, Stays; J, Door; K, Firebrick Arch; L, Firebox

is to raise steam fast enough to draw a heavy train. The size is limited by the height of the bridges and tunnels, by the distance apart of the driving wheels, and by the length of wheel base possible with curves on the existing lines. It is not an uncommon thing for the pressure to drop very seriously when a heavy load is being hauled up a steep incline.

About ten years ago the Great Western Railway endeavoured to overcome to some extent the restrictions on the size of the boiler by making the barrel slightly conical, with the greatest diameter at the firebox end. This, apart from their size, is the most striking feature of locomotives of the "Great Bear" type. The larger diameter lies behind the driving wheels. It enables a bigger firebox to be used, and increases the proportion of water at the hottest end of the boiler. Another advantage is that the surging backwards and forwards of the water when the engine varies its speed—which is liable to leave the crown of the firebox uncovered—is to some extent prevented by the conical shape.

The firebox of a locomotive is fixed to the outer shell by a ring at the bottom, by another ring round the fire door, and by numerous stays, about 4 inches apart, to the sides. Owing to the great difference in temperature between the firebox and the outside shell, great stresses are thrown on these stays, and failure is common. Some fireboxes have curved crowns, and others have flat crowns like the Belpaire firebox—a type growing in popularity. The curved crowns are merely suspended by stays from the boiler shell; the flat crowns are stiffened by small girders as shown in Fig. 34. The number and dimensions of these stays or girders are largely a matter of experience; the tendency of the firebox to change its shape renders it almost impossible to make exact calculations of the stresses which have to be borne.

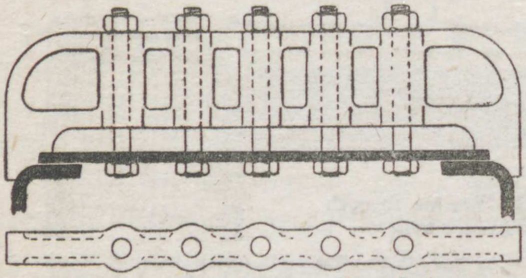
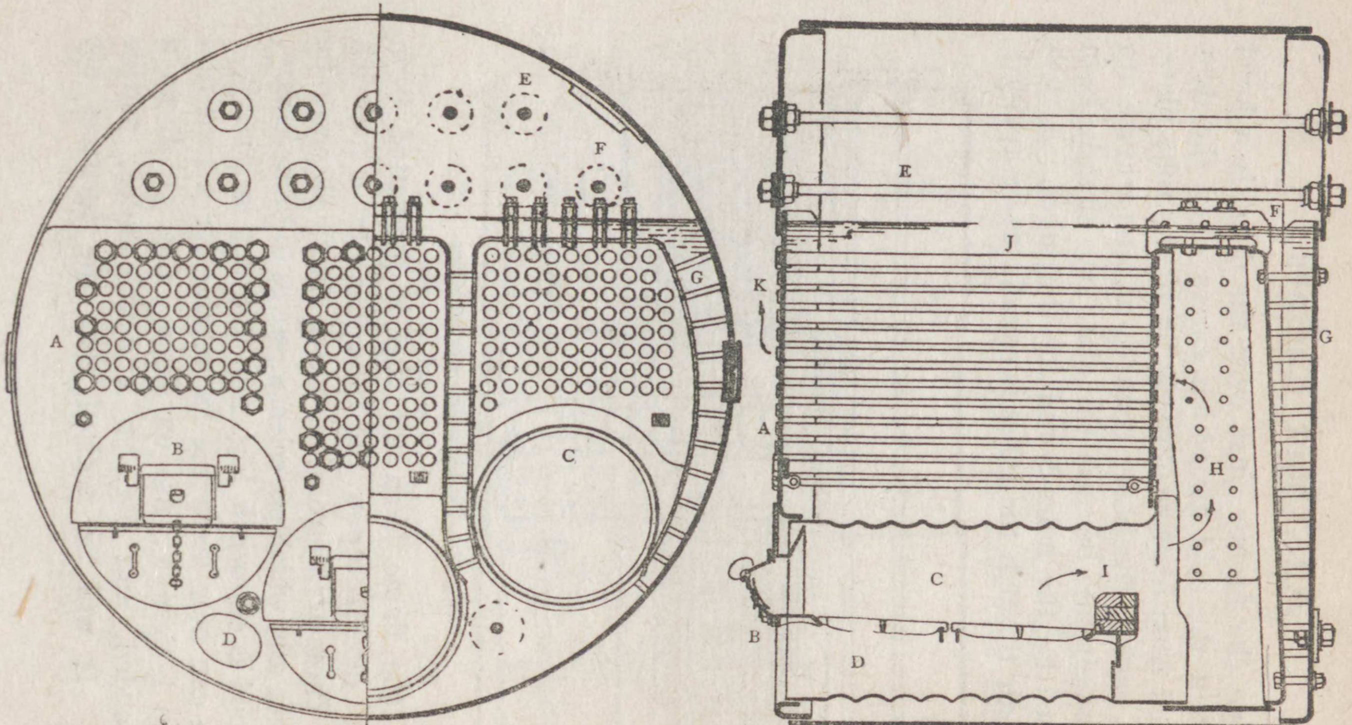


Fig. 34.—Girder stays on Loco firebox



FRONT VIEW. HALF SECTION. LONGITUDINAL SECTION

Fig. 35.—Single-ended marine boiler

A, Tubes; B, Furnace Door; C, Furnace; D, Mudhole; E, Stays; F, Girder Stay; G, Stays

A, Tubes; B, Furnace Door; C, Furnace; D, Ashpit; E, Stays; F, Girder Stay; G, Stay; H, Smokebox; I, Bridge; J, Water; K, To Funnel

Inside the firebox, just over the door, is a hood to prevent the cold air which enters when the door is opened from blowing directly on to the tube plate. At this part of the boiler changes of temperature are very undesirable, because the plate has already been weakened by the holes bored for the tubes. A rush of cold air through the tubes is equally to be avoided.

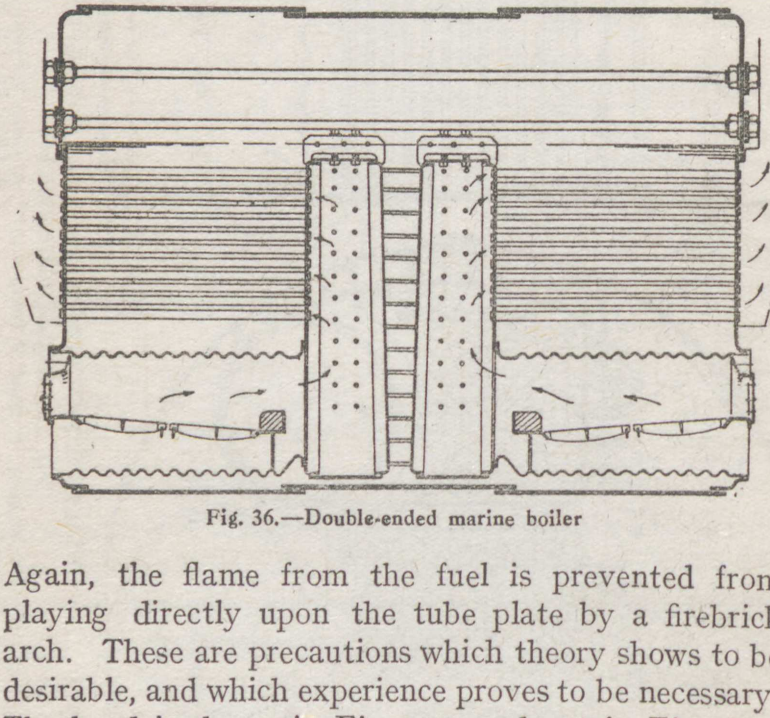


Fig. 36.—Double-ended marine boiler

Again, the flame from the fuel is prevented from playing directly upon the tube plate by a firebrick arch. These are precautions which theory shows to be desirable, and which experience proves to be necessary. The hood is shown in Fig. 149, and not in Fig. 33.

We can now leave the locomotive for a time and turn to boilers for use on ships. Fig. 35 shows a single-ended, and Fig. 36 a double-ended, marine boiler. It will be noticed that the furnaces are similar to those of a Lancashire boiler, but shorter, and that the gases return through tubes above the furnaces. A single-ended boiler may have one, two, or three furnaces, according to size, and a double-ended boiler four or six furnaces. Compared with a Lancashire boiler, however, they are short and fat, this form fitting most economically into the space available on board ship. A large specimen is no light weight—each of the twenty-four double-ended boilers on the *Olympic* weighs 105 tons.

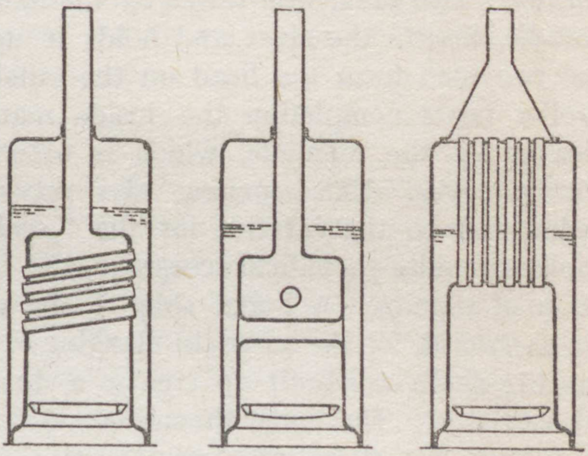


Fig. 37.—Some vertical boilers

Several types of vertical boiler are shown in Fig. 37, and another one was illustrated in Fig. 1. In all cases the firebox is totally enclosed in the boiler shell to which it is attached by a ring round the lower end, another round the fire door, and stays. In order to increase the heating surface, water cross tubes, or fire tubes, are fitted. These boilers are rarely made in large sizes or for high pressures, and are usually to be found in small factories and workshops, or supplying steam for winches and cranes.

They take up little floor space, and are easily rendered portable by mounting them on a wheeled truck.

It will be clear that the making of a boiler, even of an ordinary type, is an awkward job. The plates have first to be cut to shape, bent, and drilled. The rivets are heated in a small forge fire in charge of a boy, who hands them with a pair of tongs to a man inside. This man, who works by the light of a tallow candle, inserts the rivet and holds it up, while one or two men form the head on the outside. As the boiler nears completion the inside man enters and leaves by the manhole, which is afterwards closed by a cover. This opening also serves to obtain admission to the interior for the "scaler"—for all boilers require periodical scraping—and for the execution of repairs. A boiler shop is the noisiest place in the world, for the incessant clanging of the hammers as the shells are built up creates a din which is indescribable. The men themselves do not seem to mind it, but those who are accustomed to quieter surroundings wonder how they manage to retain their sanity amidst the uproar.

After being fixed in position, all exposed parts of the boiler are covered with a paste containing asbestos. This dries fairly hard and, being a bad conductor of heat, prevents loss by radiation to surrounding objects. In some cases—locomotives, for example—this covering, or "lagging," as it is called, is covered with sheet iron, which is then beautifully enamelled and lined. At one time, before asbestos was used, wood and felt were extensively employed for lagging, but these substances are of small durability and tend to char. They may even take fire, and Mr. Edgar Allen, in his book on "The Modern Locomotive," describes how lagging of this kind once took fire when he was riding on the footplate. They were just entering a tunnel, and as it was impossible to stop, he and the driver and fireman were almost suffocated by the cloud of acrid smoke before they emerged. It was not an experience which one would care to repeat.

Water-tube Boilers

All the boilers so far considered belong to the fire-tube class—that is to say, the hot gases pass through the flues or tubes surrounded by water. In this arrangement the fire gets very close to some of the water, but most of the water remains a long way from the fire. Moreover, the circulation of the water over the hot surfaces is irregular, except in the Lancashire and some vertical boilers in which water tubes are used. The great advantage for rapid steaming of having a small quantity of water very near to the fire was recognised by inventors for many years, and a number of different forms have been devised, but of these only a few have survived.

One of the earliest, and still a very useful form, is the Stirling, illustrated diagrammatically in Figs. 38 and 39. It consists of three upper and two lower drums connected by curved tubes. The grate was placed in front and the hot gases were caused to pass in the direction shown by the arrows by means of baffle plates behind each bank of tubes. The circulation of the water is a little difficult to follow; but the feed enters the back top drum, passes to the back lower drum, whence it passes to the front lower drum.

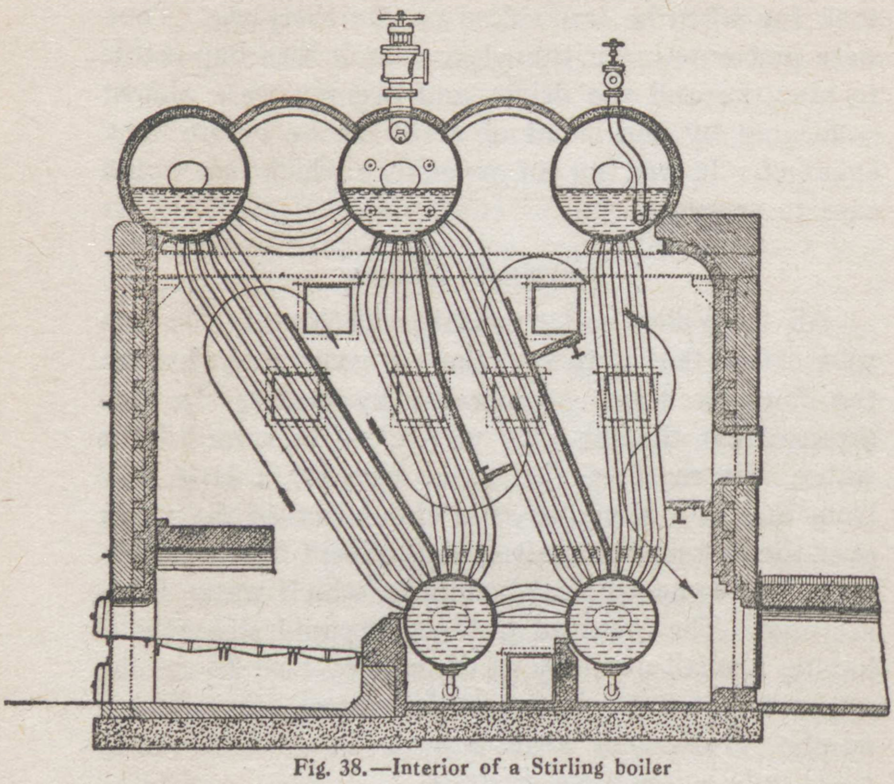


Fig. 38.—Interior of a Stirling boiler

Steam is generated in the first three banks of tubes, and collects in the middle top drum. Another variety differs mainly in having straight tubes. Both are efficient, but take up a good deal of space.

The next type is that made by Messrs. Babcock and Wilcox, Ltd., who have works in England, and associated Companies with works in France, Germany, and America. From Plate 4, Fig. 41, it will be seen to consist of inclined tubes, communicating by means of

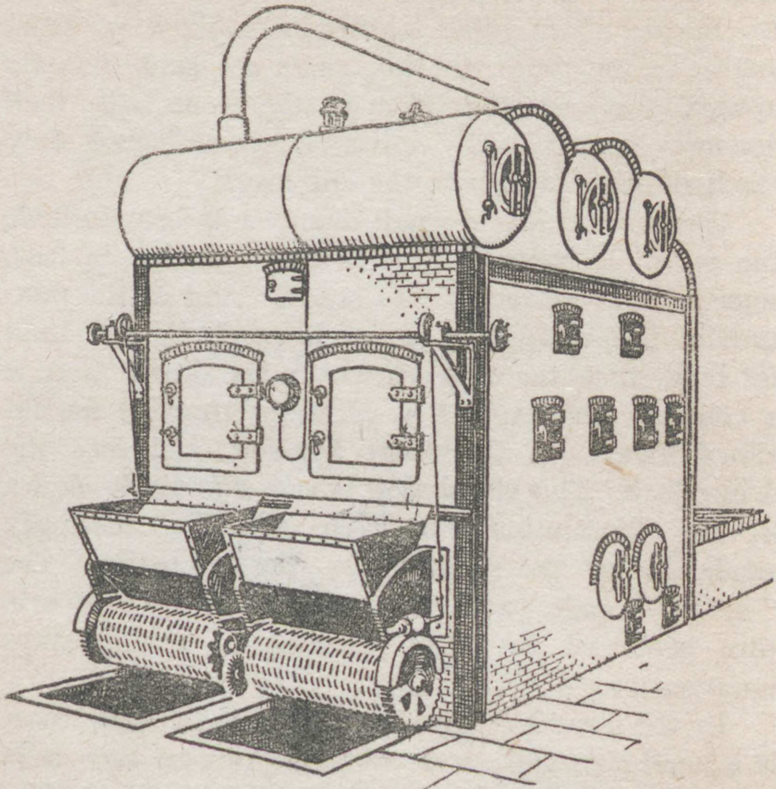


Fig. 39.—Exterior of a Stirling boiler

"headers" with a steam and water drum above. The tubes are arranged in vertical rows, not exactly over one another, but zigzag, as will be seen from the view of one of the headers on Plate 3, Fig, 40. If there are seven pairs of headers, each carrying eight tubes, there will be fifty-six tubes in all. As a matter of fact,

$92\frac{1}{2}$ per cent. of the heating surface is in the tubes. The lower end of each rear header communicates with a mud drum, in which sediment is deposited. By means of firebrick baffle-plates, fixed at right angles to the tubes, the hot gases are made to pass upwards between the tubes in the front half, then downwards, and finally upwards again, before they reach the flue leading to the chimney.

The tubes being of small diameter (3 or 4 inches), the water in them is heated very quickly—in fact, some of it is converted into steam. And as the mixture of hot water and steam is much lighter, bulk for bulk, than the cooler water in the drum, there is a constant and rapid flow of water through the inclined tubes, up the front headers, and into the drum itself. This circulation is very effectively shown by the illustration on Plate 3. The relatively small size of the steam drum, the strength of the "dished" ends, and the uniformity of temperature produced by rapid circulation render stays unnecessary.

In the headers, opposite the ends of each tube, is a hand-hole and cover, which admits of each tube being cleaned or replaced with a minimum of trouble, so that the boiler can be kept in good condition, and repairs effected cheaply and expeditiously. The grate area is a large proportion of the floor space, so that, compared with other types which have been considered, more water can be evaporated per pound of fuel without forcing. It is easy and cheap to transport because none of the parts are of excessive

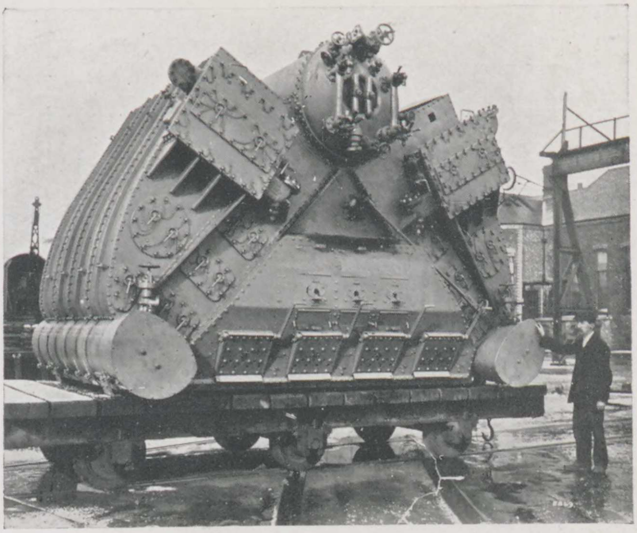
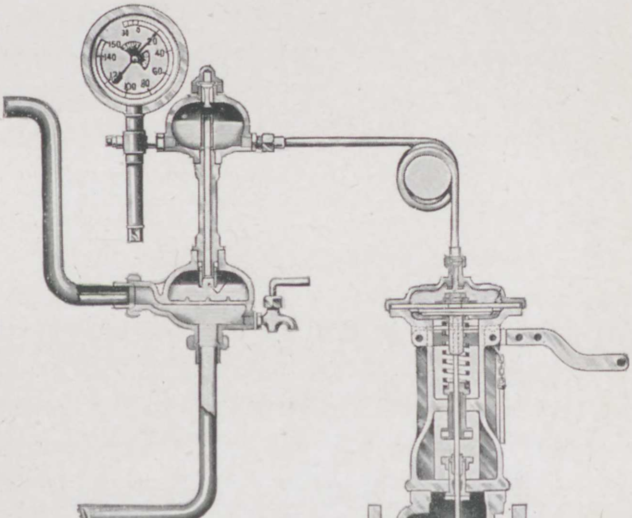


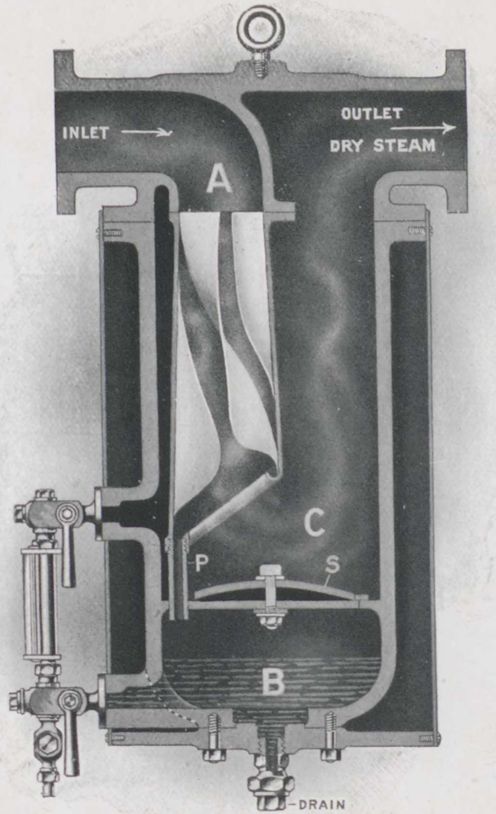
Photo by permission of Messrs. A. Yarrow & Co., L'd.

Fig. 43.—A Yarrow Boiler



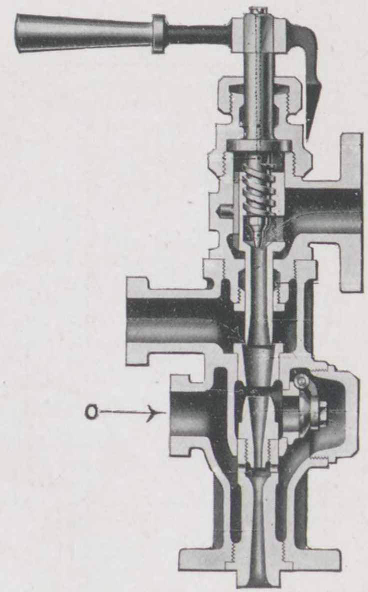
By permission of the Crosby Valve and Gauge Co., Ltd.

Fig. 47.—Crosby Feed Water Regulator



By permission of Messrs. Hopkinson & Co., Huddersfield.

Fig. 53.—Hopkinson's Steam Dryer



By permission of Messrs. Holden & Brooke, Ltd.

Fig. 58.—Section through Injector

size or weight, and steam can be got up within an hour of lighting the fire. Finally, by a modification of the furnace only, it can be used for any kind of fuel — coal, oil, timber, rice husks, sugar - cane refuse, and any other substance that is combustible.

For use on ships the drum is placed at right angles to the tubes and over the front headers as in Fig. 42, and the water is conveyed from the rear header to the drum by means of horizontal tubes. This gives a shorter boiler, whicn is rather more suitable for the restricted space available. The brickwork is also replaced by a sheet-iron

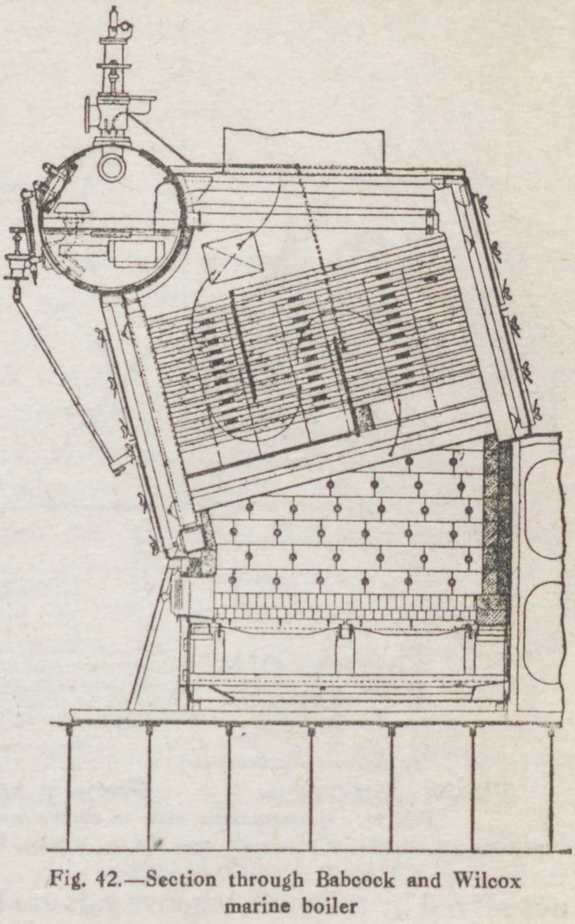


Fig. 42.—Section through Babcock and Wilcox marine boiler

casing with firebrick lining. The marine type is often used for land purposes. It can be made in smaller parts which are more easily transported to places which are

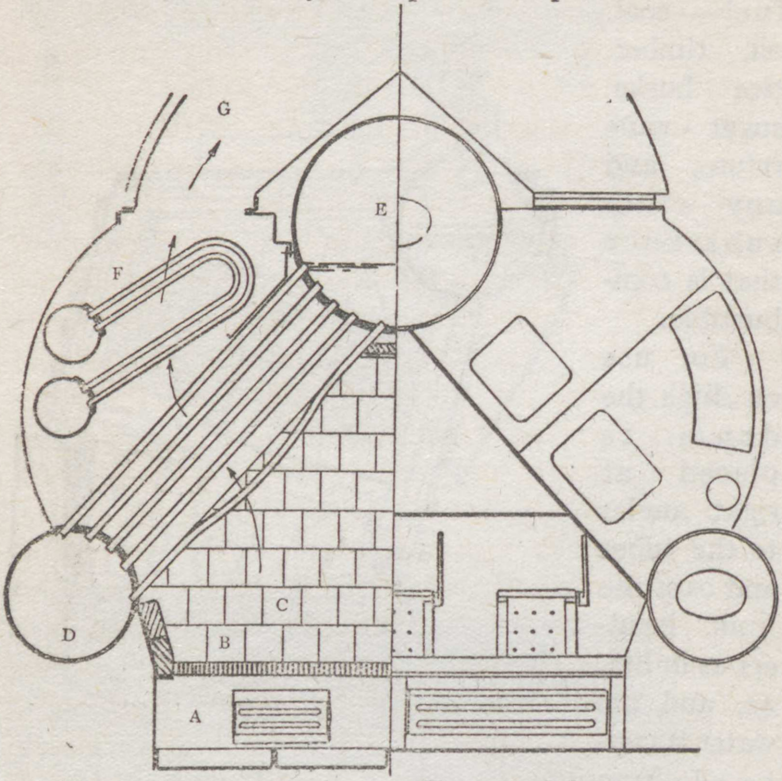


Fig. 44.—Diagrammatic view of three-drum boiler

A, Ashpit; B, Firebars; C, Furnace; D, Water Drum; E, Steam Drum; F Superheater; G, To Funnel

not served by railways, where roads are bad, and where appliances for lifting heavy weights are not available.

The next type of boiler to be described is the Yarrow, or three-drum boiler, and is used only on ships, for which it is specially designed. In its modern form it is the outcome of many years of practical experience and exact scientific experiment. From the illustration (Fig. 43) on Plate 5 and the section in Fig. 44 it will be seen to consist of a steam drum connected by a large number of tubes with two water drums, situated on a level with the grate.

In their passage from the grate to the up-take, the hot gases pass through the tubes on each side. Those which are nearer to the fire become the hotter, some of the water they contain is converted into steam, and the mixture of steam and hot water flows up into the steam drum. Meantime, cooler water flows down the outer tubes into the water drums, and then follows the hot water and steam up the inner tubes. A constant circulation is thus kept up, and the steam is raised very rapidly. The up-take, leading to the chimney, has a partition down the centre, and a damper on each side enables only one set of tubes to be used when less steam is required. An improvement of very considerable importance consists of angle-iron baffles laid between pairs of the outer row of tubes, thus securing a more equable distribution af temperature. The outer casing consists of a double thickness of sheet steel with a layer of asbestos between, and the whole boiler is extraordinarily light, considering the large amount of water which it is capable of evaporating per hour.

Provisions for Safety

The pressure inside a modern boiler may be anything up to 250 lb. on the square inch. If the fire is withdrawn the temperature will fall and the pressure will gradually decrease, but for an hour or more it may be sufficiently high to drive the engine, though not with maximum load nor with the same speed. Yet if the boiler bursts the whole of that energy will be expended within a second, the building in which it is situated will be wrecked, huge pieces of steel will be flung a mile away, and men in the immediate neighbourhood will be killed. In the year 1910 there were one hundred explosions in the United Kingdom, resulting in the death of thirteen persons and injury to sixty-one others. In the United States, in the same year, the number was more than five times as great, and both deaths and injuries much greater in proportion. But in both countries the number is gradually decreasing, and for this we have to thank better design and workmanship, more intelligent management, and more frequent inspection.

It has already been pointed out that in designing a boiler the first essential is to avoid strains, and in management the most necessary precaution is to keep the boiler clean. All natural waters contain dissolved salts which are deposited as the water is boiled away. From time to time men have to get inside boilers and scrape this off. Some may be got rid of by occasionally opening a "blow-off" cock situated near the bottom of the boiler, and the amount may be considerably reduced by softening the water before it is admitted. The addition of sodium carbonate to water containing calcium bicarbonate and sulphate causes the calcium salts to be thrown out, while the

PLATE 7

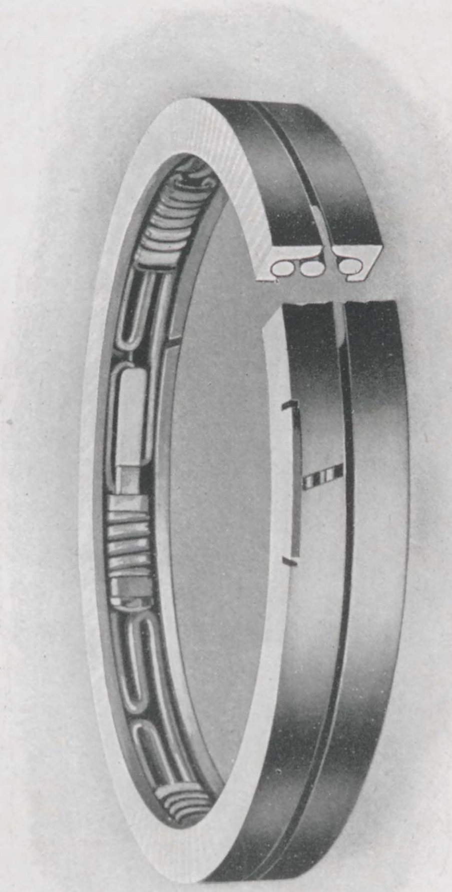


Photo by permission of Messrs. Lockwood & Carlisle

Fig. 61.—A Piston Ring

PLATE 8

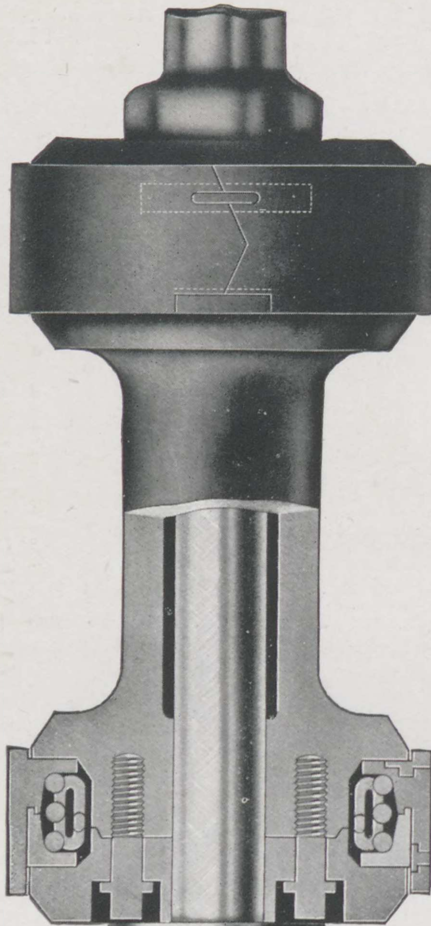


Photo by permission of Messrs. Lockwood & Carlisle.

Fig. 72.—Piston Valve

soluble sodium salts remain in solution. In districts where the water is very "hard" this process has to be employed.

The presence of oil in the boiler water is productive of greater trouble. It causes the water to froth so that the level cannot be ascertained from the water-gauge, and if it settles on the metal surface it is liable to char, and to lead to over-heating. It can often be partially got rid of by opening a blow-off cock fixed near the water level, but it should, if possible, be removed before it enters, and this is not easy. Granted, however, that the boiler is well designed, and well looked after, the two precautions necessary to avoid accidents are to prevent the pressure rising to beyond a certain limit, and the provision of an ample supply of pure water.

In the first chapter an illustration was given of a simple type of lever safety valve. Suppose the area of the valve is 4 square inches, and it is required to blow off at 60 lb. per square inch. Then the total pressure on the valve is $4 \times 60 = 240$ lb. If the distance of the weight from the fulcrum is ten times the distance of the rod which holds down the valve, the weight on the end of the lever will have to be $\frac{240}{10} = 24$ lb. This is an excellent safety valve for stationary boilers at low pressures. If the lever be dispensed with, and the weight placed over the valve, as in Fig. 45, we get what is called a dead-weight safety valve. It will be seen that the valve is held down on its seating by a sort of bell-shaped cover around the rim of which the weights are carried. Moreover, the steam is not discharged directly into the atmosphere of the boiler house, but into a pipe through which it can be led outside. As the weights are enclosed they cannot be tampered with, and the valve is, as far as possible, fool-proof.

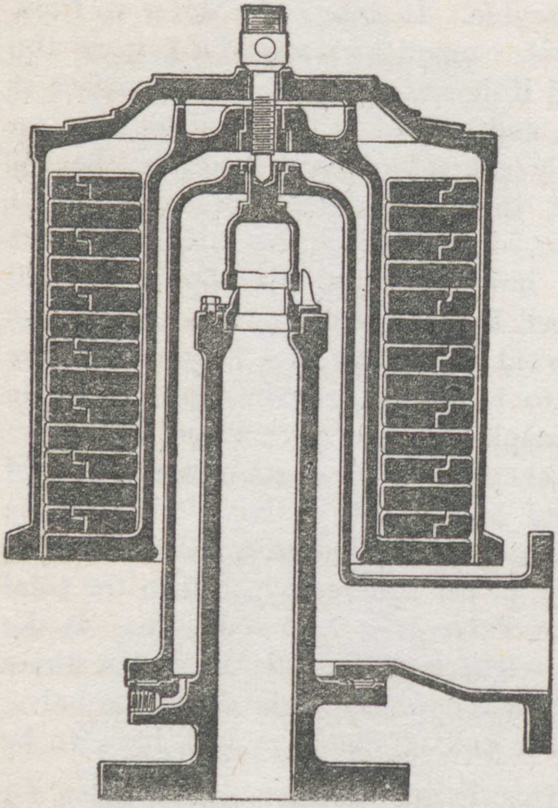


Fig. 45.—Dead-weight safety valve (Hopkinson's type)

Sometimes the safety valve is fitted with high and low-water floats, as in Fig. 46, so that it gives warning of the undesirably large or dangerously small quantity of water in the boiler. An inspection of the diagram will show how this acts. The valve may be raised by the pressure of the steam beneath it, by the rise of the high-water float, or by the fall of the low-water float; and the attention of the man in charge is at once drawn by the noise of the escaping steam to the steam and watergauges.

For locomotives and marine boilers the dead-weight and lever safety valves are unsuitable, and the valves are held down on their seatings by springs.

The tendency of the age is to make fool-proof as far as possible every mechanical device the use of which is attended with danger. So in spite of water gauges, water-level alarms, and water-level regulators, and men in charge, there is always one other fitting to a boiler which, while it may not prevent an accident, reduces the damage that results from it. On the top of the fire-box, which is liable to become overheated if the water level falls too low, is a safety plug. This consists merely of a stud with a hole through the centre, and the hole is filled with an alloy which remains solid so long as it is covered by water, but melts if it is uncovered. If it melts a jet of steam enters the firebox or furnace, the pressure in the boiler is relieved, and the fire is put out. No insurance company will accept risks unless this precaution is adopted.

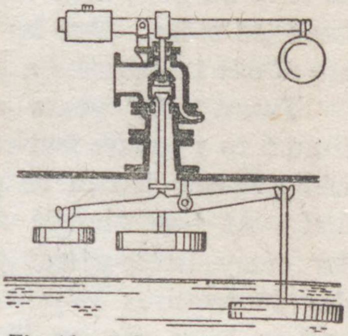


Fig. 46.—Safety valve with high and low-water floats

Prevention of Waste

We have considered the various contrivances which are necessary to raise steam with safety, and we shall now proceed to examine those which enable steam to be raised with economy. For every pound of coal burnt in the furnace 14,000 units of heat are produced, and the engineer is concerned to convey these to the engine with the least loss on the way. All of them he cannot retain. There must be some heat in the chimney gases, or the chimney would create no draught. The boiler must be warmer than surrounding objects, however carefully it is covered with badly conducting material; and so long as it *is* warmer, heat will flow in a continuous stream from its sides. But by the devices and methods we are about to describe a good deal of loss is prevented.

Twenty-five years ago a horse-power required from 6 to 7 square feet of heating surface in the boiler, while to-day it can be produced from 2 or 3 square feet. At that time 3 or 4 lb. of coal were needed for every horse-power produced by an engine; to-day it requires only from 1 lb. to 1¼ lb. Modern boilers, then, are smaller and less than half as costly to run as the old ones were. A manufacturer who was spending £2,000 a year on coal a quarter of a century ago is now obtaining the same power for less than £1,000. This result is achieved partly by improved design of boilers and partly by mechanical stoking, forced draughts, feed-water heating and regulation, and superheating, some of which also reduce the cost of labour.

Stoking

Probably most people would regard keeping the fire going merrily as one of the easiest things in the world—a job requiring merely moderate watchfulness and physical strength. And yet if the production of steam is to be maintained and coal is to be economised, there are few tasks which are more difficult. A careless stoker will allow the fire to burn too low and will then pile on coal to such an extent that the production of steam almost ceases for a time. And the excess of coal will result in a vast volume of black smoke consisting largely of combustible matter which ought to have been burnt before it left the furnace. Moreover, it is impossible for coal to be shovelled in without opening the door, and every time the door is opened there is a rush of cold air through the flues or tubes, reducing the temperature of all those parts which should be kept hot.

A really careful man will put on only small quantities of fuel at a time. He will place it near the door so that the volatile matters which come off are consumed as they pass over the hotter portion. Or he will scatter it lightly over the whole fire to secure the same effect. But no man can be so regular as a machine, and as fuel can be fed in with a machine without opening the door, all large well-managed boilers are fitted with mechanical stokers.

In one form a hopper, like a funnel, is fixed in front of the boiler in such a position that its lower end is level with the upper edge of the fire door opening. Below this hopper, and instead of a fire door, is a chamber fitted with a ram or piston which moves backwards and forwards in a horizontal direction. When the ram moves back coal falls from the hopper, and when it moves forward this coal is pushed into the furnace. The coal moves forward along the grate from front to back in short jerks, and by the time it reaches the end of the grate only the ashes remain.

Another kind of mechanical stoker consists of a chain grate, and is illustrated in connection with the Babcock and Wilcox boiler on Plate 3. In this case the fuel is fed from the hopper on to an endless chain composed of short, interlocking, cast-iron grate bars. This chain runs on rollers and is driven by a revolving drum at the front end of the stoker, while the shaft which drives the drum may be either overhead or underground. The movement of the chain can be started or stopped, or its speed varied, while the fire is burning. Small repairs, again, such as the renewal of a link, can be carried out without removing the grate, while for thorough overhauling or larger repairs the whole carriage, which runs on rails fixed on each side of the ashpit, can be withdrawn with ease. The necessary air for combustion of the fuel enters through the spaces between the links, which, however, are so close together that the smallest coal can be used. The coal is delivered over the whole width of the grate, and the depth of the fire is regulated by a vertical sliding door beneath which the chain passes.

There is a third type, more frequently seen in America than in Great Britain, in which a ram is used, but the coal is delivered in the middle of the furnace from below. As this is forced upwards it falls away in all directions, forming a mound of fuel which is more completely burned as it approaches the sides of the grate, though there is no grate in the ordinary sense of the word.

In a case known to the writer a set of four old-fashioned Lancashire boilers, requiring six men and three boys to manage them, have been replaced by Babcock and Wilcox boilers fitted with chain-grate mechanical stokers and other improvements. In accordance with modern practice the coal is conveyed to the boiler house by an endless belt, weighed, and delivered into the furnace without being touched by hand. Another travelling belt running underneath the boilers collects the ashes and conveys them to a tip. And the point to which heavy and unpleasant labour is avoided is indicated by the fact that the new plant is controlled by one man and one boy !

Mechanical stokers are used only with land boilers, and not with locomotives or on board ship, where the efficiency, in so far as it is determined by the method of stoking, depends entirely upon the intelligence of the man in charge.

Forced Draught

No one needs to be told that a fire burns more fiercely the more rapidly air passes through the bed of fuel. The use of the bellows to revive a dying fire in the household grate, or blocking up the front with a newspaper so that all the air which enters the chimney must pass through the fuel, are everyday examples. And everyone knows, too, that the higher the chimney the greater the draught, for a fire never burns so well in the topmost room of a house as it does in lower rooms. If the average temperatures inside and outside a chimney are 120° Fahr. and 50° Fahr., the air inside will weigh only seven-eighths of an equal volume of air outside, and the force tending to drive air up the chimney will be equal to one-eighth of the weight of a column of outside air, equal in volume to that contained in the chimney. Suppose the chimney to be 50 feet in height and 1 square foot in area of cross section, the force called into play would be nearly ½ lb.

The first man to use artificial means of increasing the draught was George Stephenson, who, in the locomotives he built for hauling coal at the Killingworth Colliery in 1815, conceived the idea of turning the exhaust steam into the chimney. This was effective in two ways. Firstly, since water vapour is lighter than the gases, it reduced the weight of the gases in the chimney; and secondly, as we have seen in the case of the injector, a jet of liquid or gas carries the surrounding gases along with it and creates a reduced pressure in its neighbourhood. The motion of a locomotive itself produces a draught. Air enters the front of the ashpit—is scooped up, as it were—and passes upwards through the firebars, and the draught is greater the higher the speed of the train. But notwithstanding this, all locomotives to this day take advantage of the exhaust steam to increase the fierceness of the fire; and the draught is so great that nearly 25 per cent. of the fuel is ejected through the flues in a partially burnt condition when the boiler is forced to high rates of evaporation.

In a stationary engine of any size no engineer would think of passing exhaust steam into the chimney, and on a ship fresh water for the boilers is too valuable to be used for creating a draught. Moreover, in a tall chimney the steam would condense, and the shower of falling drops of water would themselves tend to set up motion in the opposite direction to that required. The simplest device for securing forced draught is to fix a door on the ash-pit and to deliver air into it from a fan. In that case the doors have to be a good fit, and an arrangement made whereby the fire-door cannot be opened without first closing the air valve. Otherwise the fuel would be blown out through the fire door immediately it was opened.

On ships a different method is employed. The stokehold is enclosed, and air is forced into it by means of a fan or fans. The imprisoned air, in its efforts to escape, rushes through the firebars and causes the fuel to blaze briskly. The stokers are, therefore, working under increased pressure, though this is not very large.

For land installations the closed stokehold is not practicable, and there are two other alternative methods in common use. One is to place a fan in the flue near the lower end of the chimney, so that the gases are propelled forwards. It is, however, rather hard on the fan, and the hot gases have a serious effect on the bearings, which have to be cooled by water. The other plan is to place the fan outside the flue and to force air through a jet into the chimney. In this case the chimney in the neighbourhood of the jet must be of special form to render the jet effective. Twenty years ago artificial draught was only adopted in cases where the natural draught was bad; but to-day the demand for a high rate of combustion renders artificial means necessary wherever power is produced in large quantities.

Feed-water Heating and Regulating

Every pound of cold water delivered to the boiler must be heated to the boiling point before it is converted into steam, so that if some of the heat which fails to enter the water in the boiler can be utilised to warm the feed water, a great saving in fuel may be effected. Thus if the initial temperature of the water is 50° Fahr., or 10° C., and it is raised to 120° Fahr. or 48.9° C., before entering the boiler, the saving in fuel is nearly 6 per cent. Assuming the same initial temperatures, the following table gives the saving when the water is heated to a greater extent:

Temperature on entering boiler	*Saving of fuel*
140° Fahr., or 60° C.	7.65 per cent.
160° Fahr., or 71.1° C.	9.34 per cent.
180° Fahr., or 82.2° C.	11.04 per cent.

The heating of the feed water is accomplished by passing it through a nest of tubes placed in the flue leading to the chimney. There are several different forms, each claiming to offer some special advantage in cheapness, efficiency, or ease of repair; but the principle of all of them is the same. They are not employed on locomotives, but are to be found in all large land and in marine installations, and on account of the purpose they serve are usually called economisers.

A smaller, but not negligible, economy is effected by taking the control of the feed water out of the hands of the man in charge and rendering it automatic. There is one proper height for the surface of the water in the boiler, and only one. At this level steam is disengaged most readily from the surface with the least splashing, and it is freer from particles of water, which are useless for driving the engine. Moreover, in water-tube boilers it is very important that the supply of water should be maintained, in view of their small capacity. In power stations, where the load varies very greatly, there are corresponding variations in the demand for steam from the boilers, and—in the absence of any automatic arrangement—the water gauges have to be watched very closely.

There are a number of devices for regulating the feed water and maintaining a constant level. Most of them depend upon a float inside the boiler, or outside, in a separate chamber, which opens or closes a valve as it falls or rises; but there is one, at least, which acts upon a different principle. It consists of a small bulb divided into an upper and lower half by a partition, Fig. 47, Plate 5. The lower half is in communication with the steam and water spaces of the boiler, and the upper half is connected by a fine tube with the valve by which the feed water enters the boiler. The upper half and the thin tube are completely filled with distilled water. The apparatus is fixed so that the partition is at the correct level of the water surface in the boiler. If the level falls, steam gains admission to the lower chamber. As this is hotter than the water, the distilled water in the space above expands, the valve rod is depressed, and water enters the boiler more freely. When water is entering the boiler more rapidly than it is being evaporated, steam is cut off from the lower chamber, the water in the narrow tube contracts, and the supply is immediately decreased.

It is hardly possible to imagine a more beautiful contrivance than this. It is extremely sensitive, and while the engine is taking steam the valve is never at rest. It feels the pulse of the boiler with unerring accuracy, and never allows the level of the water to vary by an inch. For a task like this no man is equal to a machine.

The Delivery of Dry Steam

Between the engine and the boiler are the steam pipes, stop valves, reducing valves, dryers, traps, upon which engineers have been prodigal in their ingenuity, and we shall consider one or two examples of each in turn.

The simplest form of stop valve for opening or closing communication between the engine and boiler is the screw-down valve shown in Fig. 48. The valve is in the form of a circular disc, A, with three webs, B, beneath; these serve as guides while permitting the passage of steam when the valve is raised from its seating.[1] Opening and closing is effected by the wheel, C, on the top of the spindle, D, which has a thread working into a fixed bar, while the spindle passes into the valve chamber, E, through a stuffing box, F.

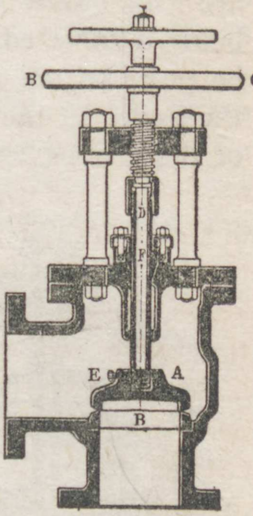


Fig. 48.—Simple stop valve

A valve of this kind is only suitable for small pipes and low pressures, because the full pressure of the steam acts on the upper side and renders it difficult to open. Thus a valve of only 2 inches diameter under a pressure of 100 lb. of steam would be held down by a force of 314 lb., while if it was 3 inches in diameter with a pressure of 160 lb. on the square inch the force would be 1,120 lb. To open a valve of 6 inches diameter against a pressure of 200 lb. on the square inch would involve a force of 5,655 lb., or more than 2½ tons! This is equivalent to a 2½-ton screw jack, fully loaded.

[1] The valve illustrated is simply a saucer-shaped disc without webs.

The case of large pipes or high pressures is met by the "double-beat" or equilibrium valve, shown in Fig. 49. Here one passage ends in a sort of blind alley, except for an opening top and bottom. There are two valves on the same spindle, the lower one being a little smaller than the other to enable it to be put in from the top. Since steam, passing from the boiler in the direction of the arrows, acts on the

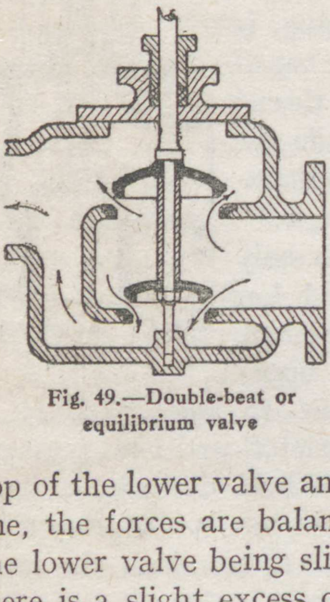


Fig. 49.—Double-beat or equilibrium valve

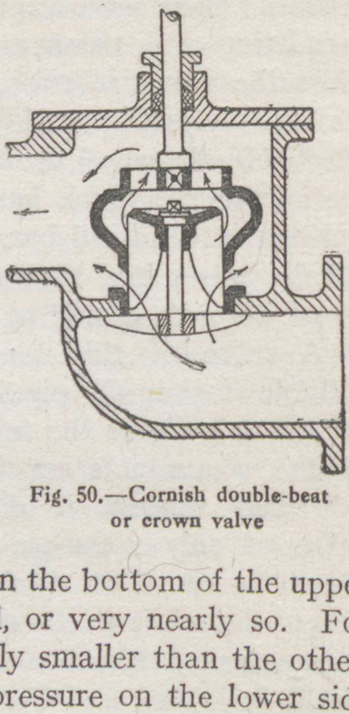


Fig. 50.—Cornish double-beat or crown valve

top of the lower valve and on the bottom of the upper one, the forces are balanced, or very nearly so. For the lower valve being slightly smaller than the other, there is a slight excess of pressure on the lower side of the upper valve. A still better form is the Cornish double-beat or crown valve, shown in Fig. 50. Here there is an opening in the partition between the two pipes, and a disc a little smaller than this opening is fixed, by means of a sort of claw stand, above it. The space between the opening and the disc is closed by a sleeve, which is raised or lowered by a wheel and screw in the ordinary way. This type of valve, by the way, is used for other purposes, and we shall meet with it again in the next chapter. The outline of the valve in elevation is not unlike a crown —hence the name, double-beat crown valve.

The objection to too small a valve in the steam pipe is that the flow of steam is hampered at the constriction, and the pressure beyond it falls. In other words, the steam is throttled. But provided the contraction of the pipe is gradual, narrowing slowly towards the smallest bore and widening at the same rate beyond it, the steam adapts its flow, as it were, to the shape of the pipe, and emerges beyond with an imperceptible reduction of pressure. On this principle Mr. Ferranti has designed a valve which, though having a very small area, is capable of passing a very large quantity of steam. A section of the valve is shown in Fig. 51. The shape is based on the form of the stream-lines in fluids when they pass through a small opening, and is determined strictly on scientific principles.

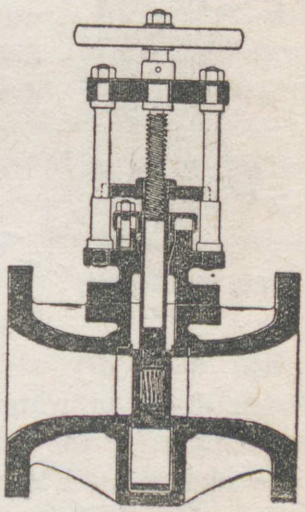


Fig. 51.—Ferranti's valve

There are occasions when a reduction of the boiler pressure is desirable. For example, a small engine, performing some special office, or a steam pump, may be supplied by a branch of the main steam pipe, and may require steam at a lower pressure than that demanded by the main engine. In this case a reducing valve is employed. An examination of Fig. 52 will explain how this operates. The valve is held up from its seating by a lever and spring, and the valve rod is attached near the bottom to a rubber diaphragm covered with water. If the steam pressure on the surface of the water exceeds a certain amount the diaphragm is depressed, the rod is drawn downwards against the effort of the spring, and the valve closes. Such a valve, therefore, only permits steam of a certain maximum pressure to pass.

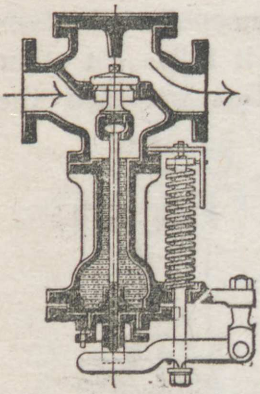


Fig. 52.—Reducing valve

Again, it is very necessary that the engine should be supplied with dry steam—that is, with steam free from drops of water. Many boilers are subject to "priming": the water foams and splashes up from the surface, and is carried to the engine by the rush of steam. And as water expands and contracts very little with change of temperature, it is capable of doing no work, and takes up heat from the cylinder during the latter part of the stroke, when the cylinder walls are warmer than the expanding steam. For the purpose of removing this water a steam dryer or separator is employed, and a simple form consists of a box with inlet and outlet pipes near the top on opposite sides, and a vertical partition suspended from the lid and reaching nearly to the bottom of the vessel, right in the path of the steam. The drops of water in the steam adhere to the partition, trickle down, and drip off the bottom. From time to time water is drawn off from the bottom of the vessel by a piece of apparatus called a steam trap.

A more effective dryer is that made by Hopkinson, of Huddersfield (*see* Fig. 53 on Plate 6). The direction of the steam is indicated by arrows. On entering the chamber A it meets spiral vanes attached to the sides, and is whirled round. The water drops, being heavier than the particles of steam, are flung against the vanes and sides, to which they adhere, and from which they trickle down into the chamber B. The dry steam flows through the chamber C to the exit. At the side is a water gauge, and the water can be run out from time to time through the pipe at the bottom.

Quite apart from the water which is carried along by the steam, there is always a certain amount of condensation in the pipes. However carefully these are covered with non-conducting material, heat always passes to the surrounding air, and consequently some of the steam is condensed to water. This water is removed by placing a trap at the lowest point in the pipes so that the water will drain into it. There are several varieties of trap, all arranged to discharge water automatically as it collects. The Geipel Trap, shown in Fig. 54, works on a very interesting principle. Two tubes, one of brass and the other of iron, are connected with a small brass vessel containing two compartments separated by a valve. The brass tube is connected at the other end with the steam pipe, and the iron tube leads to a waste pipe or drain. So long as steam is in the brass tube it is hotter than the iron and, having a higher rate of expansion, the brass tube causes the small brass box to bend upwards. The valve rod is then pressing against the lever above, and is held down on its seat. But as water collects in the brass tube the temperature falls, its length decreases, the valve rod falls away from the lever, and the valve opens. Water is then immediately blown into the iron tube, and steam again enters the brass one, with the result of closing the valve.

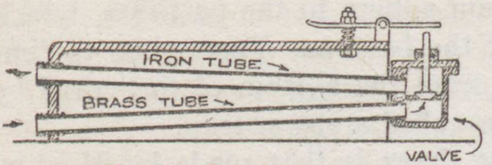


Fig. 54.—Geipel steam trap

Most other forms of trap depend upon a float. The water from the steam pipes drains into a box, and as it collects it raises a float which opens a valve and permits the water to escape. In these and other ways water is prevented from reaching the engine.

Superheated Steam

But the most effective plan is to raise the temperature of the steam from 100° Fahr. to 300° Fahr. above the temperature it reaches in the boiler. The value of superheated steam in the engine will be explained in Chapter V. Here it will suffice to say that the steam is caused to pass through tubes fixed in the flues or up-take so that the hot gases circulate round them. Not only are drops of water evaporated and condensation in steam pipes and cylinder avoided, but the steam increases in volume and a smaller weight is taken by the engine to produce the same power. For every 100° Fahr. of superheat—that is, for every 100° Fahr. by which the steam which reaches the engine is hotter than that which comes from the boiler—a reduction of 10 per cent. in the steam consumption is obtained.

In the case of Lancashire boilers the flue at the end of the boiler is the place usually chosen for the superheater. Reference to Plate 4 will show that the Babcock and Wilcox superheater is placed between the inclined tubes and the steam and water drum. In the Yarrow boiler it is fixed on the left-hand side between the circulating tubes and the up-take, as shown in Fig. 44. On that side, moreover, the number of circulating tubes is reduced in order to secure the same draught on each side of the furnace. Even if the steam has to be superheated in a separate furnace the gain is often sufficient to justify the expense.

Supplying the Feed Water

As the engine uses up steam, water must be continually supplied to the boiler. In Wātt's days a small hand pump was used, but this has given place to pumps worked from the engine shaft, or separate independent steam pumps, or injectors.

A simple form of feed pump is shown in Fig. 55. The piston or ram is a solid rod driven by an eccentric and connecting rod. The suction valves by which the water enters, and the delivery valve by which it leaves, the pump are clearly indicated. A pump of this kind would generally be fixed on the boiler, and the water would enter through a non-return or "clack" valve, close to the boiler side.

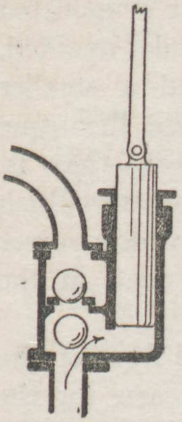


Fig. 55.—Simple feed pump

An independent feed pump, made by Hall, of Peterborough, is illustrated in Fig. 56. The steam cylinder A is at the upper end, the pump B at the lower, both piston rods being in the same straight line and connected together. Admission of steam to the cylinder is controlled by two valves.

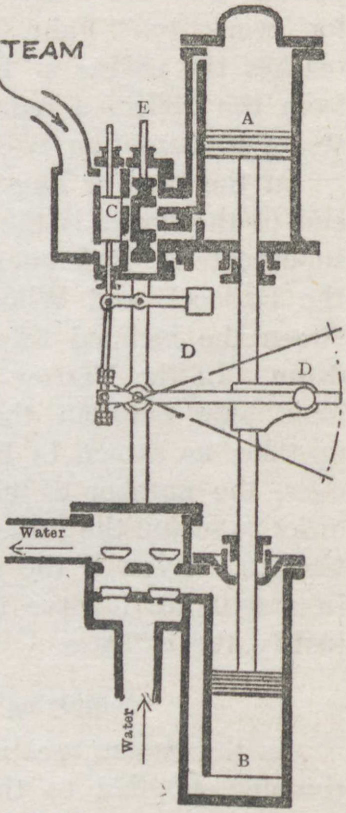


Fig. 56.—Hall feed pump

One of these, the impulse valve C, is worked by levers D from the piston rod, and regulates the flow of steam to the main valve, E, which is operated by the steam itself. In this way the waste of power in moving heavy levers is avoided, and the only mechanical friction outside the valve chamber is that produced in the small light levers which move the impulse valve. While the steam cylinder, A, valve chambers, and piston are made of cast-iron, and the piston rod of steel, the pump piston is made of gun-metal with ebonite rings, the liner, valves, and valve seatings of the same metal, and the pump rod of manganese bronze in order to resist the action of the water.

The pump is, as will be seen from the valves, double-acting, forcing water at every stroke. It is made in sizes ranging from one with a steam cylinder 4½ inches in diameter and a pump barrel of 3 inches, to one with a steam cylinder of 14 inches and a pump barrel of 10½ inches. The stroke of the smaller one is 9 inches and of the larger 2 feet, while the smaller pumps 600 and the larger 10,000 gallons per hour. Ten thousand gallons looks a large quantity for feeding boilers, but it is only 100,000 lb., and there are many boilers which will evaporate 30,000 or 40,000 lb. per hour, so that this pump would keep only two or three of them going.

It is far more striking when a week or a year is considered. Suppose, for example, the plant runs for an average of ten hours a day for six days a week for a year. Then the quantity of water required will be 100,000 gallons a day, 600,000 gallons a week, and 31,200,000 gallons a year. This would form a lake nearly 182 yards long, 100 yards wide, and 10 yards deep! It will be clear from this why manufacturers who employ only two or three large boilers like to be near a plentiful supply of water. It will be clear, too, why a manufacturing town requires such a tremendous supply of water, and why, for one reason, as we shall see later, the steam which has passed through the engine is frequently condensed and returned to the boiler.

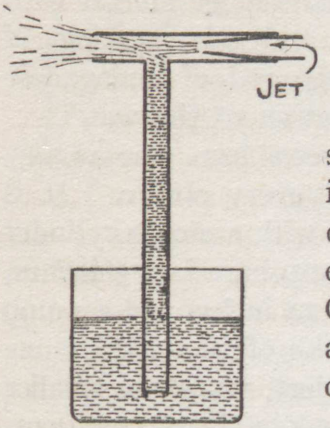


Fig. 57.—Principle of injector

There is only one way of feeding a number of boilers, and that is by pumps, but single boilers may be fed by an injector, one of the most wonderful contrivances used by the engineer. It was invented by Giffard about fifty years ago, and depends upon two principles.

The first is illustrated by the simple experiment shown in Fig. 57. A vertical tube dips into a vessel of water, and another tube is held horizontally so that the end is just over the nearest edge of the vertical tube. When air is blown through the horizontal tube it drags the air in the neighbourhood along with it, creating a reduction of pressure, so that water rises in the vertical tube and may even be blown out in the form of a fine spray. The second principle is that when a jet of steam issues from a suitably designed orifice, it has a velocity enormously greater than water or any other liquid would have under the same pressure. These two principles are combined in the injector, in which a jet of steam draws up water from the well, which must not be more than 12 ft. deep and preferably less—and forces it into the boiler from which the steam is derived.

There are a number of different makes, but the one illustrated (Fig. 58, Plate 6) is by Holden and Brooke, of Manchester. Steam enters at the top right-hand opening, which may be made larger or smaller or entirely closed by turning the lever at the top. The amount of the opening varies for different pressures, and the pointer on the right of the lever moves over a graduated circle which indicates the position for different pressures. The upper opening w on the left hand leads to the water tank, and the lower opening o allows for overflow.

The pressure required is anything between 20 lb. and 180 lb. on the square inch. The diameter of the steam channel at its narrowest point in the smallest size is about $\frac{1}{10}$ inch, and in the largest $\frac{4}{5}$ inch. The amount of water delivered depends upon the height from which it has to be lifted, the temperature, and the pressure of steam. With feed water at 115° Fahr. and a pressure of 160 lb. on the square inch the smallest size will deliver 141 gallons, and the largest 10,048 gallons per hour. That quantity is more than sufficient to satisfy the largest and most thirsty boiler that has ever been built, and the injector which will do it is as reliable as a pump, and it is lighter, cheaper, and more economical.

There are many inventions described as marvellous which are not half so wonderful. Everybody has heard of the boa-constrictor, which began to swallow itself, starting at the tail, and has exercised his imagination to picture what would happen when it got to the middle. But by means of the injector the boiler actually performs the feat. The clack valve is the mouth and the steam is the tail; and the tail continually lengthens out as it is swallowed up, taking a considerable quantity of water with it.

Now, having seen how steam is raised with due regard to safety and economy, and traced it from the boiler to the engine in which its energy is to be converted into useful work, we are ready to consider the details of those modern reciprocating engines by which the machinery of the world's workshops is driven.

CHAPTER V

The Modern Reciprocating Engine[1]

IN the first chapter we took a simple engine to pieces, as it were, found out what each part was like, why it was there, and what purpose it served. For its size it was a good engine. Fed by steam of low pressure, it worked well and used as little fuel as could be expected.

In the meantime, however, we have become acquainted with boilers that will produce steam at 160 lb. or anything up to 200 lb. on the square inch, at the rate of 30,000 or 40,000 lb. an hour, and we have realised that there may be not one, but ten or twenty boilers of this size in a modern power station, so that there must be engines of corresponding size to use up the steam they produce. It is necessary, moreover, that they should be capable of extracting the greatest possible amount of the energy conveyed to them by the steam. For they will be large engines, mostly, and their annual coal bill will represent a small fortune. A man who only burns 20 tons of coal a week doesn't always bother much about the £2 or so a week that a 10 per cent. increase of

[1] Reciprocating means "forwards and backwards," and the name reciprocating engine is given to one which has a piston working forwards and backwards in a cylinder.

efficiency would yield him; but the man who burns 1,000 tons in the same period is letting £3,000 a year slip through his fingers—or run down the drains, or into the canal or into some other place from which it is irrecoverable. The second man is often the servant of a public company, with inquisitive shareholders demanding higher dividends; or of a municipality with ratepayers who want long penny stages or low electric light bills. So, for his own sake, directly or indirectly, he demands to be provided with some of the boilers and accessories which have already been described and with engines having all sorts of refinements which reduce, each in its measure, the consumption of steam.

For nearly a hundred years after Watt's inventions the chief improvements in steam engines lay in the methods of manufacture—in the gradual replacement of the individual and variable skill of the workman by the automatic accuracy of the machine tool. Then engineers turned their attention to improving the invention itself. Stronger and more reliable materials, combined with increasing accuracy of workmanship, have enabled higher and higher pressures to be used; so that the 5 lb. or 10 lb. with which Watt had to be content in his day has been raised to 200 lb. or 250 lb. One problem, therefore, has been the construction of steam-tight joints which shall resist such pressures and, where superheated steam is used, a temperature of 600° Fahr. or 700° Fahr.

Newcomen made his pistons steam-tight by means of a layer of water on the top, and Watt, owing to his cylinders differing from a circular form by three-eighths of an inch or more, was obliged to use a soft packing to fill up the space. These methods soon gave way to "metal to metal" joints. There is bound to be some wear, and as the replacement of a whole cylinder would be a costly affair, it is provided with a "liner," which is cast separately and then pressed into the cylinder, which it fits only at the ends. It is of a harder, closer-grained iron than the cylinder itself, and it is very accurately bored to

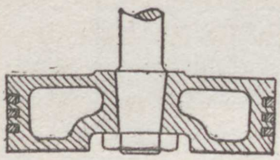


Fig. 59.—Piston for small engine

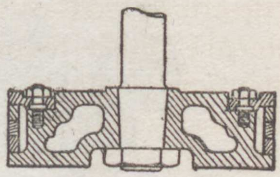


Fig. 60.—Piston with junk ring for large engine

receive the piston. The space between the liner and the cylinder walls forms a steam jacket which prevents condensation of the steam used to drive the engine.

The piston is usually of cast-iron, though it may be of cast or pressed steel. In small sizes it is in one piece, with two or three grooves cut in the curved face. Cast-iron rings, turned so as to be slightly larger than the bore of the cylinder or liner, are then sawn across diagonally at one point, and "sprung" into the grooves, as in Fig. 59.

In large sizes the rings are too stiff to be sprung on, and the piston has to be made with a single wide

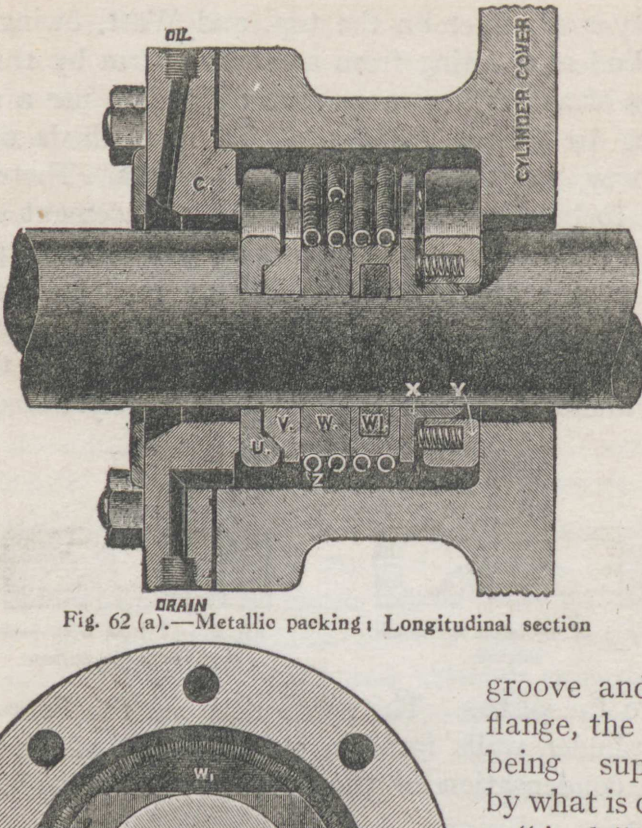


Fig. 62 (a).—Metallic packing: Longitudinal section

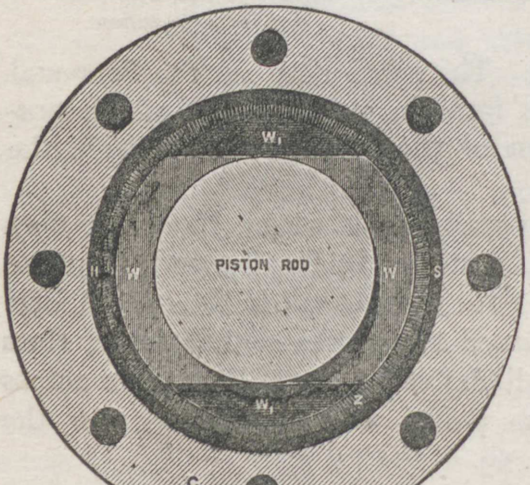


Fig. 62 (b).—Metallic packing: Transverse section

groove and one flange, the other being supplied by what is called a "junk" ring, bolted on after the rings are in place, as in Fig. 60. The rings are pressed outward against the liner by springs of which one of the best forms,

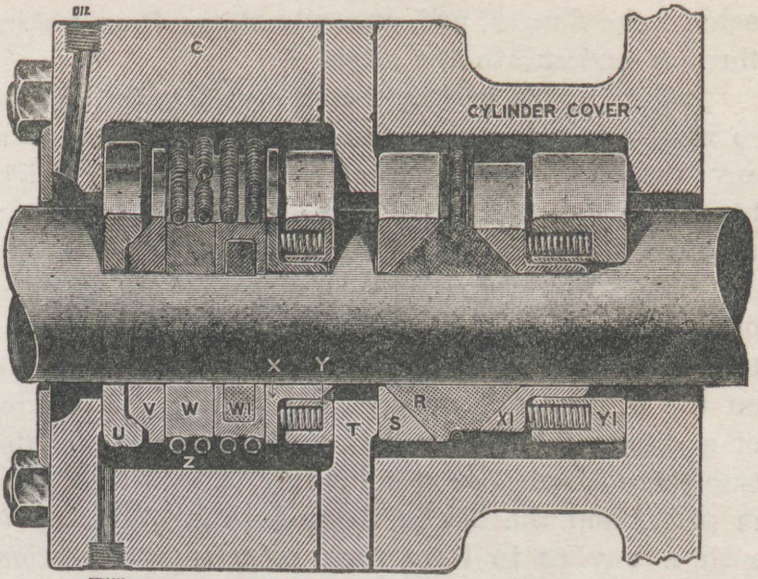


Fig. 63 (a).—Metallic packing for high pressures: Longitudinal section

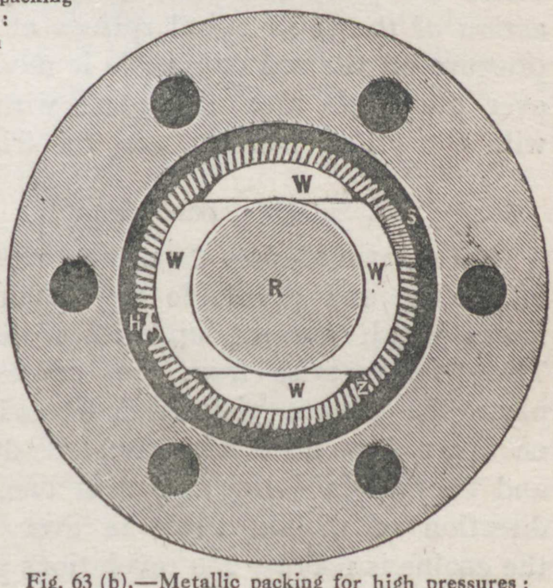


Fig. 63 (b).—Metallic packing for high pressures: Transverse section

made by Messrs. Lockwood and Carlisle, is shown in Fig. 61 on Plate 7. It will be noticed that the packing rings are so shaped on the inner surface that the internal spring forces them against the flanges, and prevents steam from leaking through underneath the rings.

Just as a soft packing became useless for pistons, so also it is going out of use for stuffing boxes—at any rate in engines using superheated or high-pressure steam. A good form of metallic packing is that made by Lancaster and Tonge, shown in Fig. 62. Here the stuffing-box contains blocks of metal fitting closely round the piston rod and held in contact by spiral springs. For pressures above 120 lb. on the square inch an additional length of packing of a different kind is used, as in Fig. 63. In this case there is only one spiral spring to hold the blocks in place, and the blocks themselves are built up in such a way as to form rings of triangular section. These are pressed closely against the rods by the action of the short spiral springs at the back. The pressure on the rod or spindle is much more uniform over the whole area of contact with metallic, than with the softer, packing, and the friction is less.

Balancing

Before considering expansive working it will be interesting and profitable to examine some of the forces which are set up within the engine itself. These forces arise from two causes. In the first place the piston, piston-rod, cross-head, and connecting-rod are all moving forwards during one stroke and backwards during the next one, changing their direction of motion twice in every revolution. If the engine is making 200 revolutions per minute there are 400 reversals of motion in that time. The movement is stopped partly by the crank, which exerts a push or a pull on the connecting-rod, and partly by the cylinder covers through the cushion of steam left in each end of the cylinder at the end of the stroke. The crank communicates the force to the engine bed through the bearings, and the cylinder covers do likewise through the cylinder.

The bed, therefore, is subject to stresses, now in one direction, now in the other, and vibration is only prevented by rigid connection with a heavy foundation. Anyone who has seen a small engine bolted down to a couple of planks and shaking as though it would pull itself to pieces, will realise what this means.

But that is not the point it is proposed to discuss in this section. Let the reader fix his attention, not on the reciprocating but on the rotating parts of a single-cylinder engine. Here we have the crank with the heavy connecting rod end being whirled round the shaft, now above, now below, now on this side, now on that. If a stone be tied to the end of a piece of string and whirled round in this way the string will become tighter the faster the stone is whirled, and if it be not strong it will break. If the string breaks or is cut the stone will fly on in a straight line in the direction it was going at the moment of release. All whirling bodies, in fact, exert a force outwards from the centre about which they are revolving, and this force is known as centrifugal force. In order to get an idea of the importance of centrifugal force in an engine we shall have to use a formula. It is only a simple one—not half so difficult as some of those worked by you fifteen-year-old schoolboys, so there is no need to be afraid of it. Here it is:

$$F = \frac{W \times v^2}{g \times r}$$

where W = the weight of the body in pounds;
v = the velocity of the centre of gravity of the body in feet per second;
r = the distance of centre of gravity of the body from centre of rotation in feet;
and g = the gravitational constant, 32·2.

Suppose that in a certain engine the moving parts weigh 100 lb., that r is equal to 1 foot, and that the engine is making 200 revolutions per minute. A point on the circumference of this circle of 1 foot radius will move $2 \times 3\frac{1}{7} \times 1 = 6\frac{2}{7}$ feet in one revolution, and $6\frac{2}{7} \times 200 = 1{,}256$ feet in one minute, or almost exactly 21 feet in a second. This is the velocity corresponding to v in the above formula. The centrifugal force due to the rotating parts is, therefore,

$$\frac{100 \times 21 \times 21}{32{\cdot}2} = 1{,}380 \text{ lb. approximately.}$$

This means that there would be a force of nearly 1,400 lb., or five-eighths of a ton, pressing the rotating shaft against the bearing, and not only tending to squeeze out the oil and thus to cause overheating, but exerting a pull, through the bearing, on the bed, now forwards, now backwards, now up, now down. If the bed were not securely bolted down to a heavy foundation it would tend to jump and slide about the floor. Should the holding-down bolts give way, it would become a very lively companion indeed for the man in charge.

Now the most important fact to be observed is that this force varies as the square of the velocity; that is, if the velocity is doubled the force is quadrupled; if the velocity is halved the force is reduced to one-quarter. Thus, in the engine in question, if the speed were reduced to 100 revolutions per minute, the force would be reduced to about 340 lb. On the other hand, at 300 revolutions per minute the force would become about 3,200 lb., or nearly a ton and a half.

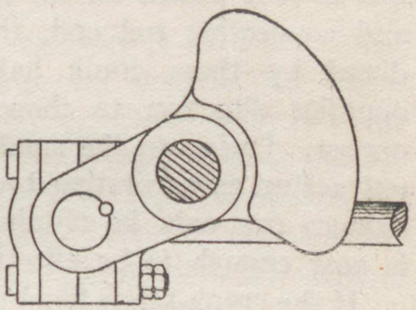


Fig. 64.—Balanced crank

An unbalanced engine running at high speed threatens, therefore, to tear itself to pieces. So long as engines were slow moving, these considerations were not important, but the tendency towards high speeds during the last thirty years has introduced problems of great difficulty and delicacy into the work of engine building. It is useless to put pounds' worth of material and months of labour into a machine that will rapidly accomplish its own destruction.

Fortunately, there are methods of obtaining an approximate balance which are neither very costly nor very difficult to adopt. Probably most readers will have observed that the sides of the crank are extended backwards in a fan-shaped block as shown in Fig. 64. This block is sometimes forged in the same piece with the crank, and sometimes of cast-iron, bolted in place. In size it is such that its weight multiplied by the distance of its centre of gravity from the crankshaft centre is as nearly as possible equal to the product of W and *r* in the case of the necessary unbalanced rotating parts of the engine; and as it is placed on the opposite side of the crank and connecting rod end, the centrifugal forces produced by these crank balance-weights act in the opposite direction to those which it is desired to oppose. Owing to the small effect of the connecting rod acting as a rotating body at the crank pin, the balance can only be obtained approximately, but it is near enough to be effective.

If the crank-pin is fixed on a disc it will be noticed that this disc is of a "lid" form, with the solid counterweight inside and opposite to the pin. Again, in a locomotive the weight is fixed between the spokes of the driving wheels; but this form of engine will be considered in detail later, and it will be better to consider now the general question of balancing in a two-cylinder engine.

At first sight it would seem that there was no need for any special device in an engine with two cylinders, when the cranks are set in opposite directions. The weight on one side of the shaft will certainly always be equal to the weight on the other; but the centrifugal forces will not be in the same straight line. If the two cranks are fairly close together, as in Fig. 65, or if they are at the opposite ends with bearings close up to them, as in Fig. 66, the vibration will generally be small. But if they are some distance apart, to some extent each end of the shaft will be alternately pushed and pulled, and there will be a tendency to twist the whole engine first in one direction and then in the other.

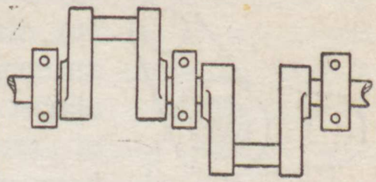


Fig. 65.—Crank for double-cylinder engine

So, however far apart the cranks, it is necessary in high-speed two-cylinder engines to employ balance weights on each crank. Moreover, the bearings should be as close up to the cranks as possible in order to avoid the shaft being bent.

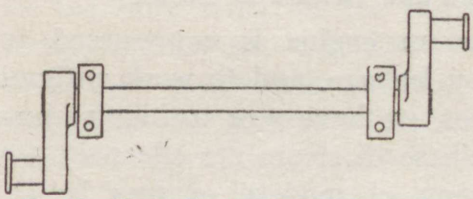


Fig. 66.—Crank for double-cylinder engine

As a matter of fact, double-cylinder engines are not always made with the cranks in opposite directions. Both cranks would then be on their dead centres at the same time, and there would be occasions upon which the engine would not start without assistance. The cranks, therefore, are more frequently set at right angles to one another (Fig. 67), because one of them is sure to be in the correct posi-

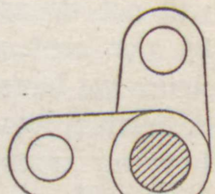


Fig. 67.—Two cranks at right angles

tion for starting immediately the steam valve is opened. With high speed engines provided with a flywheel

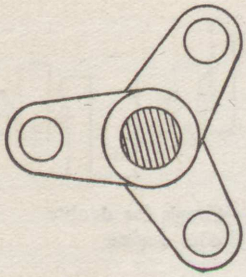


Fig. 68.—Three cranks at 120°

opposite cranks may be used without disadvantage. The cranks of an engine with three cylinders are almost invariably set at angles of 120 degrees, as in Fig. 68, because this arrangement facilitates starting, gives a more regular turning effort, and minimises vibration.

The Admission and Release of Steam

Having seen how an engine is constructed to avoid loss of steam by leakage, and to work without shaking itself to pieces, we have now to inquire how the admission and release of steam are effected ; for upon this the economy of modern engines largely depends. Of the 14,000 units of heat which are produced by every pound of coal, about 75 per cent., or 10,500, are transferred to the water. Many boilers will not do as well as this ; others claim to transfer 85 per cent. under favourable conditions, but the figure we have taken is near enough for our purpose. A further loss occurs on the way to the engine, for however carefully the steam pipes are covered it is impossible to prevent all loss, and the longer the pipe is, or the more exposed to cold winds, the greater this will be. So that if 10,000 units reach the engine we may consider ourselves fortunate.

As each unit of heat, when converted into work, is capable, theoretically, of performing 778 ft.-lb., the total energy to begin with was 10,892,000 ft.-lb., of which perhaps not more than 7,780,000 reach the engine; and as this exists in the form of hot steam the engineer has to arrange the engine so that it will do its work with the least possible quantity. For this purpose he makes the steam do work, not by exerting the full pressure as it leaves the boiler, but by expanding and pushing back the piston in order to occupy a larger volume. During this expansion the steam cools, and some of it is condensed to water, while the heat given up corresponds roughly to the work done on the piston. The steam then escapes from the cylinder at a lower temperature than that at which it entered, and the greater this difference the greater will be the amount of work which it has accomplished. If, on the other hand, the full boiler pressure were allowed to act during the whole stroke of the piston the exhaust steam would still be in the same condition as it was when it entered, hence its capacity for doing work at the expense of its own heat would remain unaltered. Compared with an engine of the same size cutting off at quarter-stroke, it would have used four times the amount of steam and done very little more work.

In order to admit and release steam it will be remembered that Watt used a complicated valve gear which we did not attempt to describe. This form survived for over a century for pumping engines of the Cornish type, but for other engines it was replaced by the D valve illustrated in Chapter I. This grew out of the original invention by Murdock, one of the ablest of Watt's assistants, in 1799, and is shown in Fig. 69. It consisted of a piece of semi-circular tubing, and plates at the ends of the flat side to form a passage between the steam and exhaust ports. It was gradually replaced in large engines by the long D valve. This is very similar to the short D valve, but flatter, and its mode of operation was exactly the same as that with which we are already familiar. The chief objections were the long travel, and the large amount of friction, which became more serious as the pressures employed increased.

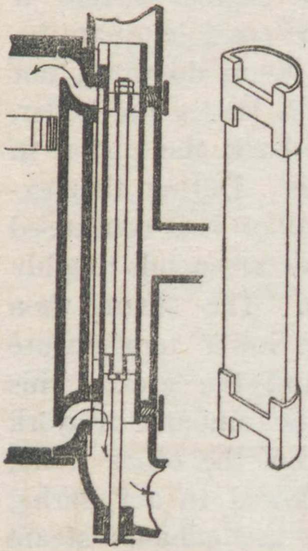


Fig. 69.—Murdock's D slide valve

A simple example of the pressure needed to move a valve will suffice to show how serious this was.

Suppose the valve to have a rubbing surface of 12 inches by 10 inches, or 120 square inches, the steam pressure to be 150 lb. on the square inch, the stroke to be 4 inches, and the number of revolutions 150 per minute. The total pressure on the valve face would be 120 × 150 = 18,000 lb. The force required to slide the valve backwards and forwards would be about one-tenth of this. The distance travelled in one stroke would be 4 inches, or one-third of a foot, and at 150 revolutions there would be 300 strokes per minute, so that the total distance the valve travelled in a minute would be 100 ft. The work done per minute, therefore, would be 180,000 ft.-lb., which is at the rate of nearly 5½ horse-power. True, the engine would probably yield 200 horse-power, so the loss would be less than 3 per cent., but even that is undesirably high. An engine which needs that amount of power to move one of its own valves is like a man whose joints are stiff with rheumatism!

It is one thing to discover a defect, and another thing to remedy it. The calculation we have made shows, however, that if the travel, or the area, or the steam pressure be reduced, the power required will be proportionately less, and the travel is reduced to half the distance by the double-ported valve shown in Fig. 70.

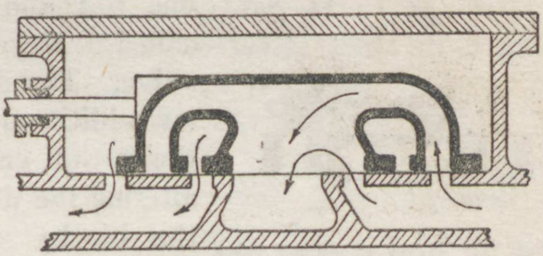


Fig. 70.—Double-ported valve

In this form it will be observed that each steam port has two openings into the steam chest, and that there are corresponding openings in the valve. The construction of this valve is difficult to show in a drawing, and still more difficult to describe in words in a way that will be understood; but the arrows showing the directions of the steam will assist any reader who wishes to obtain a clear notion of it.

The disadvantage of the ordinary D valve—apart from the power required to drive it—was hinted at in the first chapter. Steam cannot be cut off earlier than half-stroke without "wire-drawing" or throttling the steam as it enters.

This defect was not important until high-pressure steam began to be used, but then it was vital. It was overcome by the use of two valves, the lower one an ordinary D valve, but having ports right through it, which are opened and closed by two blocks sliding backwards and forwards on the top of the main valve. The whole arrangement is shown in Fig. 71. The two blocks are fixed on one rod, and form what is called Meyer's expansion valve. The rod is driven by an additional eccentric, and the cut-off can be varied by altering the distance between the blocks. With this arrangement the cut-off may be as early as one-tenth of the stroke.

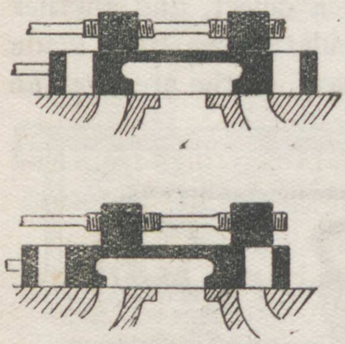


Fig. 71.—Meyer expansion valve

In order to avoid the friction which is produced when the whole pressure of the steam in the steam chest acts on the back of the valve, engineers have had to make fresh types, one of the most satisfactory of which is the piston valve (Fig. 72, Plate 8). The valve chamber, instead of being rectangular is cylindrical, or at any rate has a cylindrical liner. The ports which lead into this barrel are opened and closed by the movement of two pistons fixed a short distance apart on a rod driven by an eccentric. Steam is admitted to both ends of the liner on the outside of the pistons, or between the pistons, exhaust then taking place at the ends. This "inside" admission enables simple packing to be used in the stuffing box when steam at high pressure and high temperature is used. Moreover, the greater part of the steam chest is exposed only to relatively low temperatures and pressures, so that it can be made lighter and the joints of the covers give less trouble.

Whether the steam is admitted to the inside or outside of the pistons, the valve is "balanced," and the only friction is that which is necessary for steam tightness.

In order to prevent the packing rings from slipping into the ports, these are made in the form of grids instead of slots. No advantage is gained in respect of earlier cut-off, and though piston valves are expensive, yet they are very largely used on high-pressure cylinders because they fit well and take little power to operate them.

By this time the reader will imagine that we have done with valves—that every feasible and effective method of controlling the admission and release of steam has had its share of attention. Not a bit of it. The most ingenious, to those of a scientific turn of mind, have yet to be described. As, however, they are usually associated with a governor, it will be necessary to enlarge upon governors before proceeding to discuss them.

The simple form illustrated in Fig. 8 and Watt's governor were all right in their way, but they were not very powerful. They do not respond very quickly to change of speed, and have defects which it would require a good deal of mathematics to explain. A common modification is the Porter governor, which is like that shown in Fig. 8, but has a pear-shaped iron weight on the spindle which helps to keep the balls down. This enables a higher speed to be attained, and consequently makes the governor more powerful.

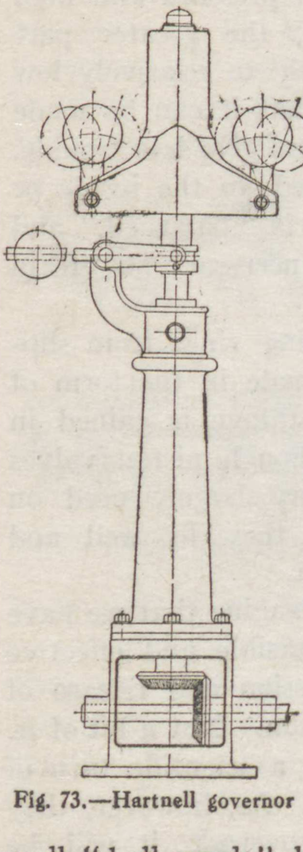


Fig. 73.—Hartnell governor

The Pickering governor, which was also described in Chapter I., and will be seen on the engine on Plate I, has the balls mounted on flat steel springs which offer some resistance to bending. These serve the same purpose as the weight on the spindle.

One of the best governors obtainable is that invented by Mr. Wilson Hartnell, of Leeds, over thirty years ago, and shown in Fig. 73. The balls are mounted on the ends of small "bell-crank" levers, the other ends being kept down by means of a spiral spring. The levers are mounted at the base of a bell-shaped cover which is fixed to the main spindle, and when the balls fly outwards they lift a collar by which the motion is transmitted to the throttle valve. Used either in this way or in the way to be described, the speed of the engine can be kept constant within $1\frac{1}{4}$ per cent. This means that an engine constructed to run at 200 revolutions per minute would not exceed $202\frac{1}{2}$, nor fall below $197\frac{1}{2}$ revolutions a minute.

But while throttle governing is the simplest, and can be effected with the smallest governor, in many engines the control is exercised directly upon the valve admitting steam to the cylinder. By altering the cut-off according to the speed of the engine the amount of steam obtaining admission to the cylinder is regulated with the greatest nicety at the latest possible moment. Fig. 74 shows how this is accomplished with a Hartnell governor and a Meyer expansion valve which has been shown diagrammatically in Fig. 71.

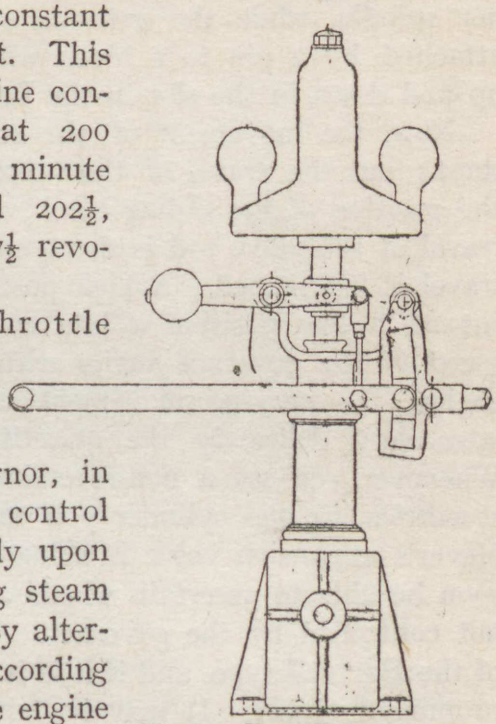


Fig. 74.—Hartnell governor controlling Meyer expansion valve

The rod of the eccentric which operates this valve is attached by pin joints to a link hanging from a pin on the stand of the governor. The valve rod, which has a pin joint just outside the stuffing box, is suspended by a small rod from the collar on the governor spindle, while the extreme end is forked, and attached by a pin to a block which is free to slide up and down in the slot in the link.

Now, the movement of the eccentric rod is constant; but the travel of the valve rod depends upon the position of the sliding block. If this is high, the travel of the valve rod is shortened; if it is low, the travel is lengthened. A high position gives an early cut-off, a low position a late cut-off. And as the speed of the governor varies with the speed of the engine, the varying movement of the valve regulates very delicately the quantity of steam used. Whenever you see a non-reversing engine with two eccentrics to one cylinder you may be sure that a Meyer's expansion valve is being used, and you will soon be able to ascertain whether this valve is or is not controlled by the governor. The latter may be of the Hartnell type, and if it is it may not be a very prominent object. It may be horizontal or vertical, and entirely enclosed, so that the rotating balls are not visible. But the slotted link will supply the clue.

Incidentally, it may be remarked that the chief difficulty in securing very fine regulation of the speed is the tendency of the governor to "hunt." When the engine increases suddenly in speed an appreciable interval occurs before the governor responds; and when it does act it goes too far and then has to come back again. In fact, a sensitive governor, when disturbed, tends to oscillate so that it always appears to be "hunting" for variations in the engine which do not really occur. To a great extent this is prevented by a dash-pot: a rod fixed to the governor operating gear is furnished at its lower end with a piston working in a small cylinder, as shown in Fig. 75. There is also an adjusting spring which enables the speed of the engine to be varied.

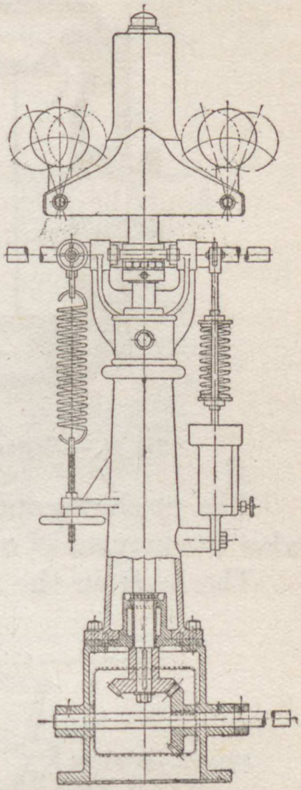


Fig. 75.—Hartnell governor with dash-pot

The most delicate control is obtained by using two separate valves for each end of the cylinder, one for admission and one for release of the steam at each end. They are of two kinds—Corliss and "drop" valves, and a diagrammatic section of a cylinder fitted with the former is given in Fig. 76. There is a steam chamber above the barrel and an exhaust chamber below. The valves, which are cylindrical, are opened and closed by turning them a little way round and then back again. They are fixed as near the ends of the cylinder as possible, so that the steam ports are very short, and there is an extremely small interval between the opening or closing of the valve and the effect on the piston.

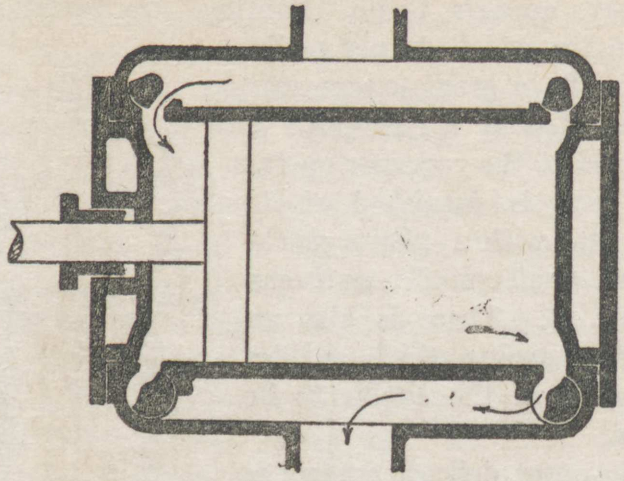


Fig. 76.—Diagram of a cylinder with Corliss valves

Fig. 77 shows one method of operating them and also the manner of controlling them by the governor.

The lever in the middle of the diagram is free to

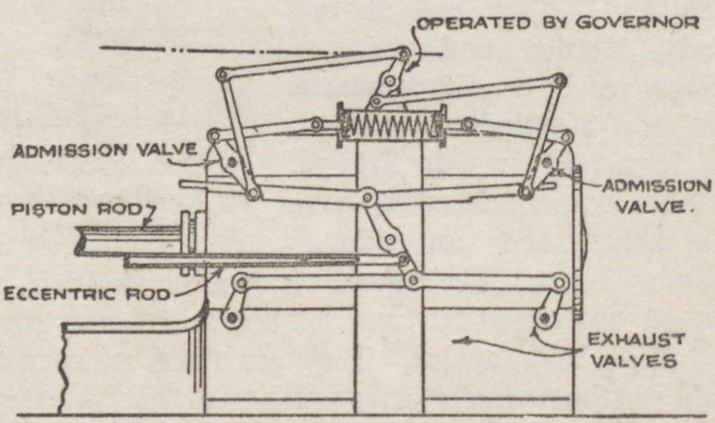


Fig. 77.—Corliss valve gear

rock on the pin which is fixed to the side of the cylinder. This rocking motion is communicated to the valves by means of the other levers. They are attached in such a way that during opening and closing the movement of the valves is very rapid, while at other times they turn very slowly.

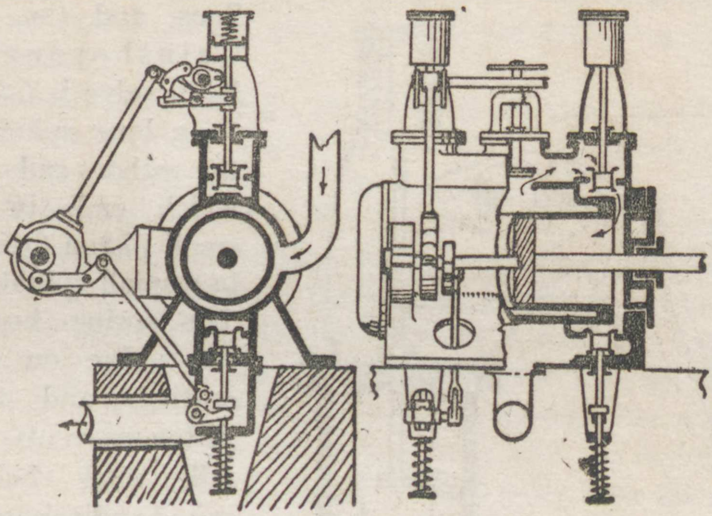


Fig. 78.—Transverse and longitudinal section through cylinder fitted with drop valves

This valve-gear was invented by C. H. Corliss, an American, about sixty years ago. Corliss valves are less frequently adopted nowadays than drop valves, mainly because they are more difficult to adjust for wear.

Now, drop valves are "balanced," or "equilibrium" valves, and, as was explained in Chapter IV., they are easy to work and easily reground or replaced. They are placed in precisely the same positions on the cylinder as the Corliss valves, but they open and close by being lifted from or allowed to fall upon their seats, upon which they are pressed by a spiral spring.

Fig. 78 is a diagrammatic section through the cylinder of a drop-valve engine made by Marshall, Sons, and Co., of Gainsborough. Each valve is fixed to a long spindle, the other end of which ends in a small piston fitting in a small cylinder. The spring keeps the valve on its seating, and the piston prevents its fall, after being raised and released, from being too rapid. It is, in fact, "cushioned" by the enclosed air. An arrangement of this sort is called a "dash-pot." It prevents the valve knocking itself to pieces.

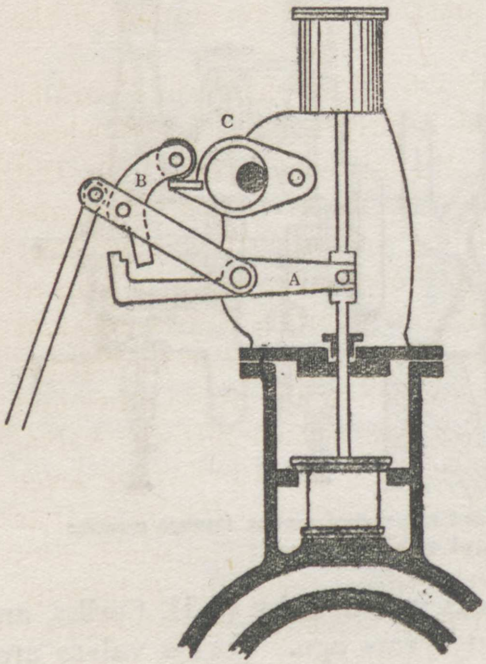


Fig. 79.—Mechanism of drop valve to larger scale

In order to explain how these valves are worked we shall require another diagram. In Fig. 79 there is a lever, A, which works on a pin fixed to a bracket on the valve chamber. The end inside the chamber is forked and rests just in a groove on the valve spindle. When the outer end, which is turned upwards, is pressed down the valve rises, and when it is released the valve falls to its seating again. What is required, then, is some means of pressing down the outer end of this lever during part of each revolution of the crankshaft.

Look again at Fig. 78. The shaft runs parallel with the cylinder and is driven by toothed wheels from the crankshaft at the same speed. On this shaft are two eccentrics for the admission valves and two cams for the exhaust valves. It will be clear from the diagram how the exhaust valve is worked from the cam, lever and rod pointing downwards and to the right. The rod pointing upwards to the right is pinned to a short lever which works at its other end on the same pin as the lever which lifts the valve. To this short lever is pinned a small bell-crank lever which is supported in a way shown in B, Fig. 79, so that one leg hangs over the end of the lever which lifts the valve. As the shaft turns, then, this bell-crank lever rises and falls, at each fall lifting the admission valve which it serves.

Now, continuing to look at Fig. 79, there is a new shaft close to the valve chamber, and on this shaft is an arm, C, which holds up the horizontal arm of the bell-crank lever. This shaft is turned round a little to right or left, and the arm holding up the bell-crank rises or falls, according to the speed of the governor. If the speed increases beyond that desired, the bell-crank lever is turned so that the lower arm slides off or misses completely the end of the lever which opens the valve. The duration of the opening, then, is under the control of the governor, because the governor determines the time during which the bell-crank depresses the lever. Such an arrangement is called a " trip-gear." It is quick, delicate, and reliable in its action, and regulates to a nicety the amount of steam which enters the cylinder at each stroke ; while the power required to drive it is much less than that needed for a flat valve, which is pressed upon the ports with the full force of the steam.

There are endless forms of drop valves and trip gear, and they are wonderful to watch, especially the " hit or miss " action by which the governor exercises its control. They are fitted on most large horizontal engines, but not on vertical engines, because the valves work most satisfactorily in a vertical position, and are, therefore, not easy to adapt to vertical cylinders. In some engines—those made by Galloway, Limited, of Manchester—the exhaust valve is a slide valve, because with low pressures the chief disadvantage of that form of valve vanishes ; and there are other modifications, of which we need describe only one, called the " Uniflow " engine.

In the ordinary slide or piston-valve engine the steam enters and leaves by the same passages, and even in the Corliss and drop-valve engines it follows the piston up and then comes back again. The result is that steam ports, cylinder covers, and portions of

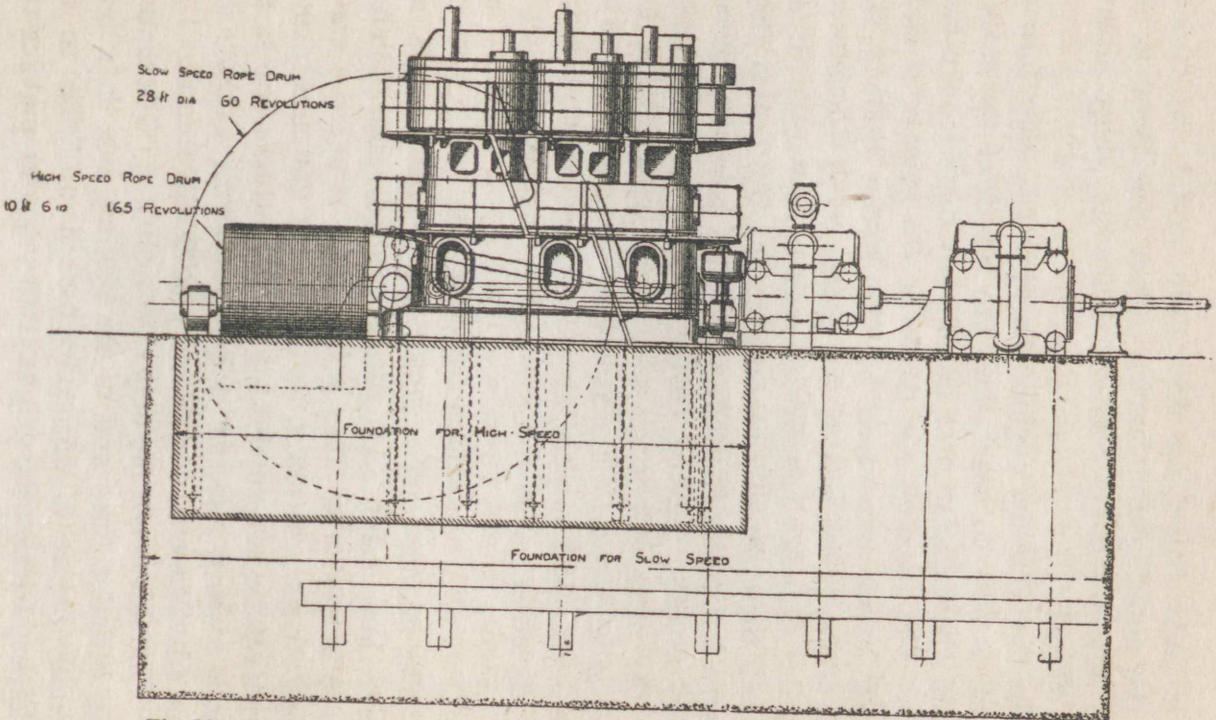


Fig. 80.—Horizontal and vertical engines of equal power drawn to same scale. Elevation

the cylinder barrel are alternately heated and cooled by the entering and leaving steam, and there is an unavoidable loss by condensation when steam enters the cylinder.

In the Uniflow engine the piston is very long—equal, in fact, to nearly half the length of the stroke—and the exhaust port is half-way between the two ends. The opening is in the form of a number of slots which, when uncovered by the piston nearing the end of its stroke, enable the steam to escape into an annular chamber running all round the barrel. Even though these are only uncovered for a short time, they offer a large area through which the expanding steam flows rapidly, leaving only sufficient to be trapped by the returning piston to serve as a cushion at the end of its stroke. The fact that the steam enters at the ends and flows out at the centre, never reversing its direction, gives the engine its distinctive name.

General Arrangements

The reader may wonder why some engines are made horizontal and others vertical, and whether there is any other reason than that of space. As to the floor space required for engines of the same power, there can be no question. Figs. 80 and 81 show to the same scale a vertical and a horizontal engine, and the advantage is undoubtedly with the former.

But this is not the only consideration. The wear of the cylinder liner and of the stuffing box in a horizontal engine is unequal; for in addition to the ordinary friction the weight of the moving parts is con-

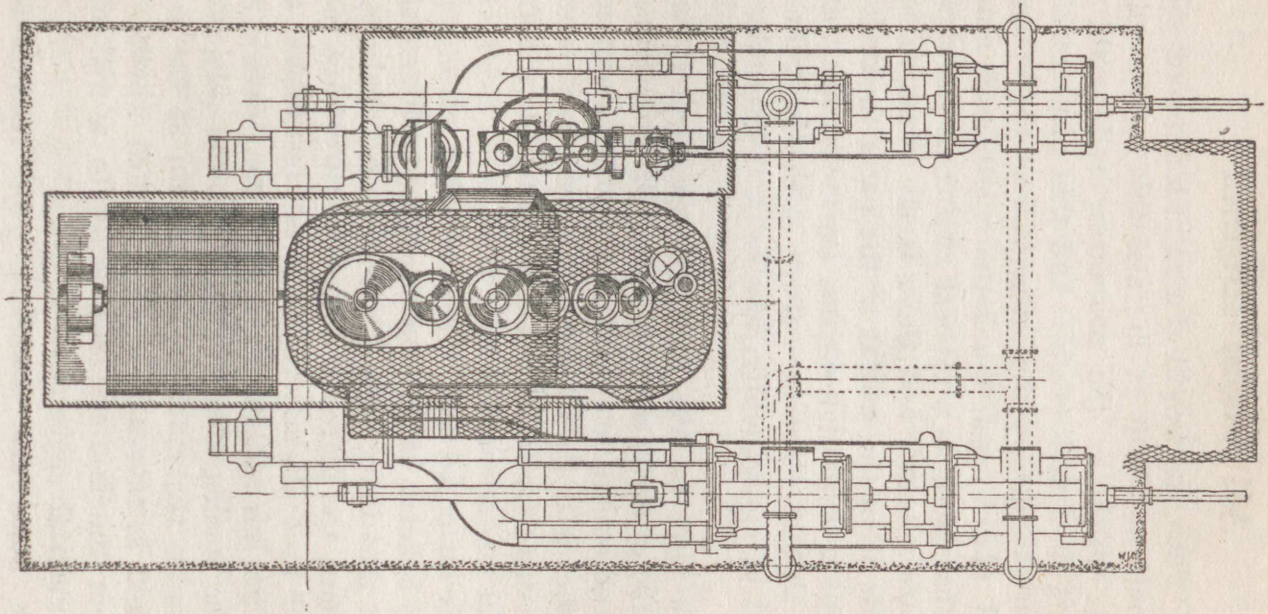


Fig. 81.—Horizontal and vertical engines of equal power drawn to same scale. Plan

siderable. Thus, the weight of a 12-inch diameter solid piston would be about 75 lb., and this only a small one; the weight of the connecting rod would be another 75 lb.; and so on. And this measures the increase of friction on the lower half of the cylinder liner and gland, and the lower cross-head guide. On the other hand, in a vertical engine all the sliding surfaces are vertical, and there is no excessive friction arising from the weight of the parts themselves. In any quick revolution engine, moreover, the steam is for a shorter time in contact with the cylinder walls and is, consequently, less subject to condensation.

If you were to ask the advocate of horizontal engines about these matters he would probably say that the objections are theoretical rather than practical, and that with the excellent materials available to-day the extra wear is infinitesimal. And the advocate of vertical engines would reply that, nevertheless, the friction is increased and the wear takes place. The man who believes in horizontal engines will probably point out that though the friction in a vertical engine may be less, the piston and moving parts have to be lifted and then allowed to fall every revolution, and that the lift has to take place when the steam is acting on the smaller area on the piston-rod side, while in his engine the moving parts remain at the same level. And in return he may be asked whether he can detect the faintest irregularity in a well-made modern vertical engine.

While there are doubtless good reasons why horizontal engines should be installed in some cases, the general tendency is towards high-speed vertical engines, totally enclosed, and provided with an arrangement whereby oil is pumped regularly at constant pressure between the rubbing surfaces. High speed gives the steadiest running, and is especially desirable in driving dynamos ; total enclosure keeps out dirt, and especially grit, which is liable to get between the rubbing surfaces and cause wear ; and forced lubrication, together with enclosure, renders the engine fool-proof. As an example of such a modern engine, we shall describe that made by Messrs. Belliss and Morcom.

The makers call this a quick-revolution, not a high-speed engine, for while it makes from 200 to 650 revolutions a minute, according to size, the shortness of the stroke enables this to be attained without requiring a high-piston speed. The reciprocating parts, therefore, are subject to smaller changes of motion than would be the case in an engine making the same number of revolutions a minute and proportioned as in horizontal engines. They are made with one, two, or three cylinders, and may be used either condensing or exhausting to the atmosphere. The first engine of this type—and the first engine to have forced lubrication—was made in 1890, and is still running for ten or twelve hours a day in the makers' works at Birmingham. It gives 20 horse-power at 625 revolutions a minute, and in the twenty-six years it has been at work it must have made 3,000 million revolutions.

Fig. 82 on Plate 9 shows a section through a "C" type compound engine made by Belliss and Morcom. The reader will notice that there is only one eccentric to operate the valves for both cylinders, and the direction taken by the steam can be traced by the arrows. He will also observe that the shapes of the pistons and cylinder covers are such as to give the least possible clearance space. The moving parts are wholly enclosed, and a small pump, shown separately in Fig. 83, forces oil from the crank case to every joint. The path of the oil to the bearings, cross-head, etc., can be traced by the small tubes and "dotted" passages. By this means oil at from 10 to 20 lb. pressure per square inch finds its way between all rubbing surfaces and prevents overheating or wear. The governor, which is placed at the end of the crankshaft (Fig. 82) and operates a throttle valve of the equilibrium type, will maintain the speed constant within 3 per cent.

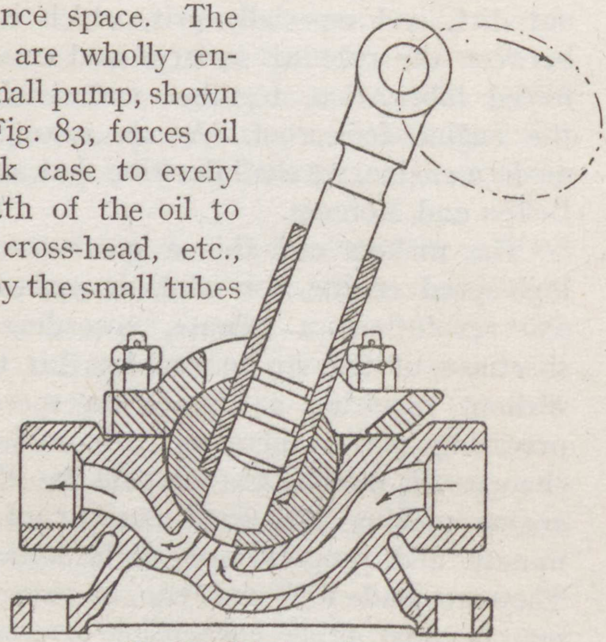


Fig. 83.—Valveless oil pump

This engine represents the acme of perfection among engines working on the plan rendered famous

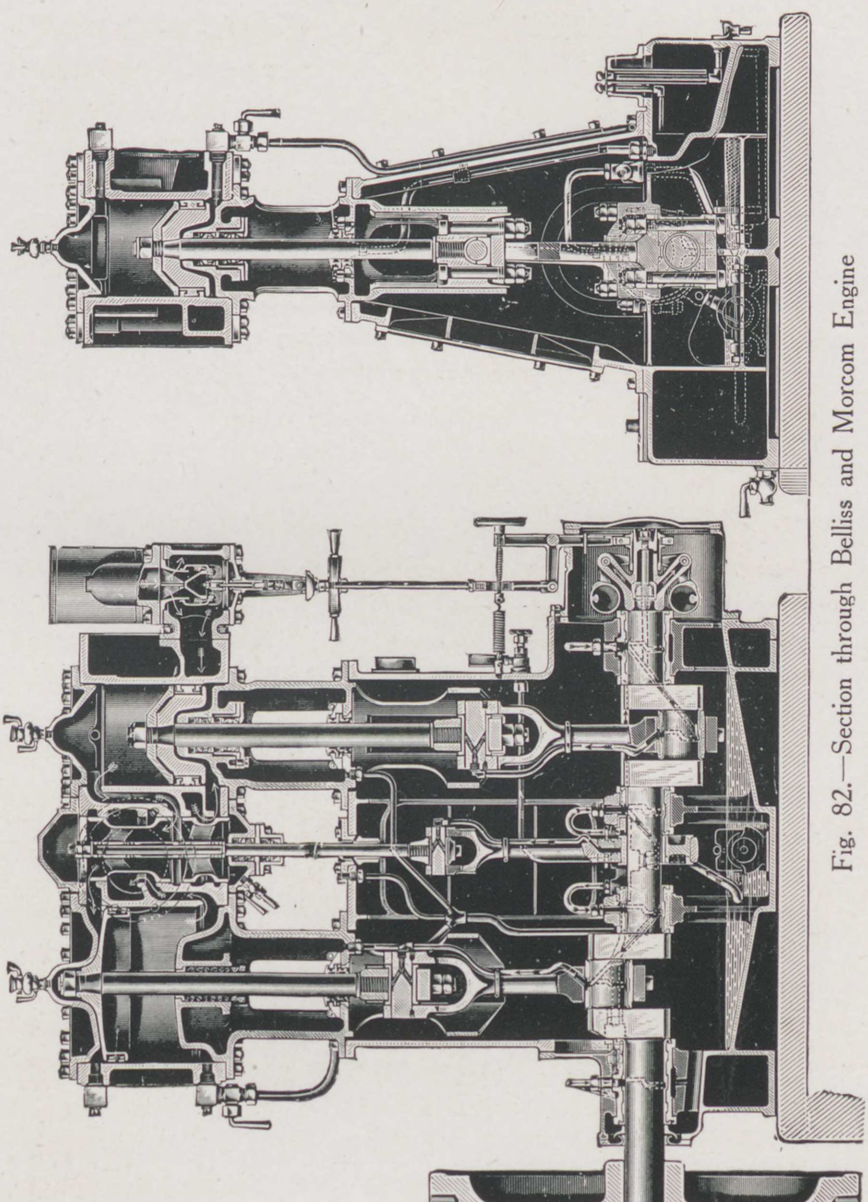
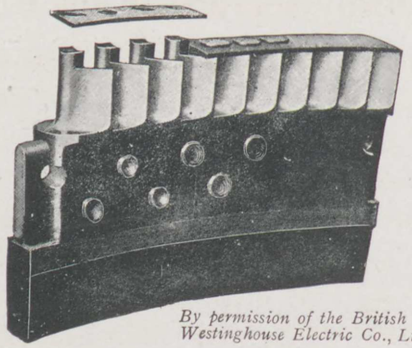
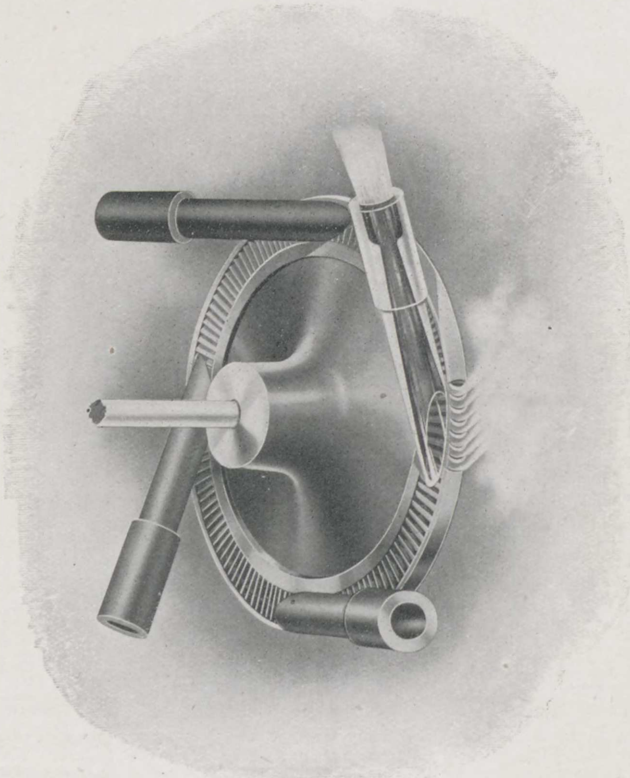


Fig. 82.—Section through Belliss and Morcom Engine



By permission of the British Westinghouse Electric Co., Ltd.

Fig. 93.—Construction of Blading on Impulse Turbine Wheel



By permission of Messrs. Greenwood & Batley, Leeds

Fig. 89.—Wheel and Nozzles of de Laval Turbine

by Watt nearly a hundred and fifty years ago. No reciprocating engine is more economical, none is less costly to maintain or less liable to get out of order. The forced lubrication and the exclusion of dust reduce wear to a minimum. Occupying but little space, and requiring but little attention, it is used for any and every purpose for which a steam engine is required, except for locomotives and ship propulsion.

Air Pumps and Condensers

The reader will recollect that in Newcomen's engine the steam was used to force the piston up, and that in order to hurry its descent the steam was condensed by the aid of cold water. At first this water was applied to the outside of the cylinder, but it was subsequently found that a jet of water within the cylinder was more effective. The earlier method is termed "surface" condensation, and the later one "jet" condensation.

Again, in James Watt's original experiment with a separate condenser (see Fig. 6) he used an air pump for the first time, and condensed the steam by drawing it through tubes immersed in cold water. In his later engines he found that the jet condenser* was more effective, because the water and steam came into closer contact with one another. But he continued to use an air pump for the following reasons. All natural waters contain air, which passes through the engine with the steam and does not condense like water. If it is not removed it exerts a back pressure

* In this, of course, the steam was condensed in a separate chamber.

on the piston and decreases the net effective pressure, tending to drive it forward. Further, the pump encourages the expansion of the escaping steam, lowers the back pressure, reduces the temperature, and therefore causes condensation to proceed more rapidly.

Whether a jet or surface condenser is used to-day depends upon the amount of good water available for boiler feeding. If this is plentiful then there is no disadvantage in mixing the

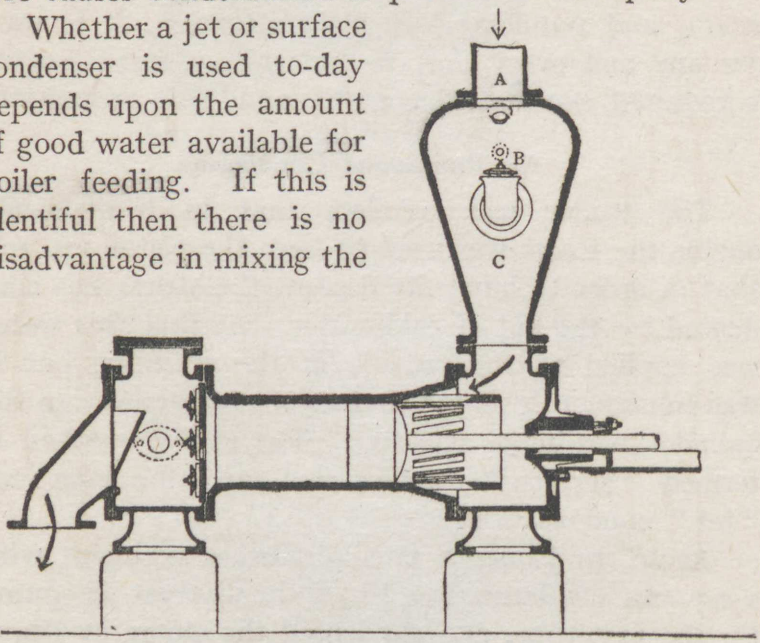


Fig. 84.—Combined jet condenser and air pump

cooling water with the exhaust steam, because this will not be needed for the boiler, and even an inferior quality of water may be used for cooling. If, on the other hand, good water is so scarce that the exhaust steam must be returned to the boiler, then it is essential that a surface condenser be employed.

A simple form of jet condenser, combined with an air pump, is shown in Fig. 84. This is fixed behind the cylinder so that the pump plunger is driven directly from the piston in the steam engine cylinder. The exhaust steam enters at A and the cooling water, in the form of a fine spray, at B. Condensation, therefore, takes place in the chamber C, and air is extracted with every stroke of the pump plunger.

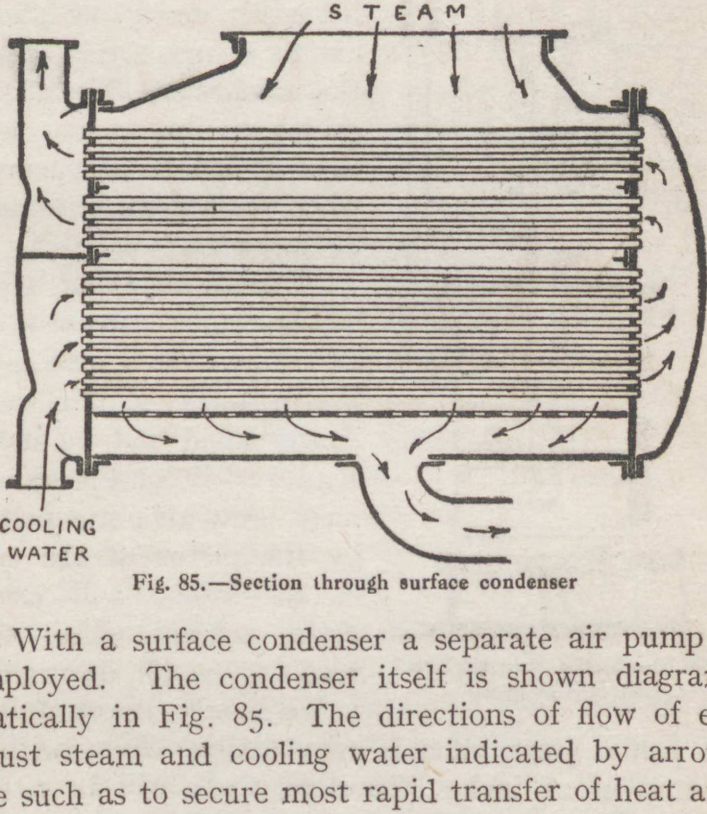


Fig. 85.—Section through surface condenser

With a surface condenser a separate air pump is employed. The condenser itself is shown diagrammatically in Fig. 85. The directions of flow of exhaust steam and cooling water indicated by arrows are such as to secure most rapid transfer of heat and the greatest uniformity of temperature. Moreover, brass, which is a better conductor than iron, is always used for the tubes and, as a rule, steel for the casing.

A diagrammatic section of an excellent air pump made by Messrs. Weir, Ltd., of Glasgow, is given in Fig. 86. It differs from a water pump mainly in the large size of the cylinder and valves. The inlet valves, moreover, must be very light, or they will not lift easily enough to allow air to escape freely from the condenser. Nowadays engineers aim at not less than 28 inches of vacuum when the barometer stands at 30 inches.*

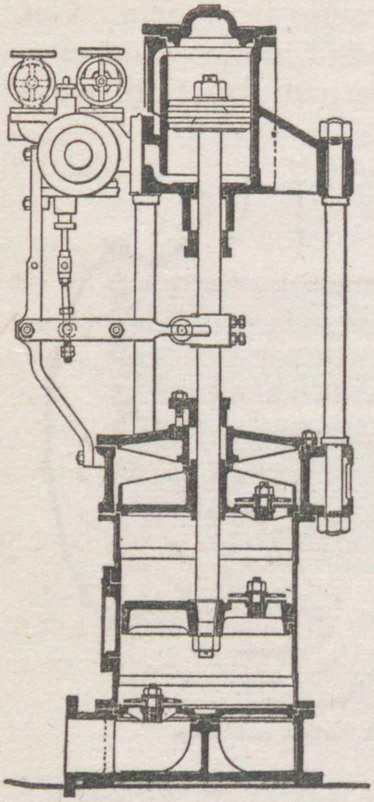


Fig. 86.—Section through Weir monotype air pump

This means that with an atmospheric pressure of 14·7 lb. on the square inch the pressure in the condenser must not be more than 0·98 lb. on the square inch. Any air not expelled by the piston at the end of its stroke will exert some pressure, which will tend to hold down the valves, and with an ordinary piston pump this is unavoidable. Even with a vacuum of 28 inches, therefore, there will be much

* Since the ordinary atmospheric pressure of 14·7 lb. on the square inch corresponds to a height of the mercury column in a barometer of 30 inches, pressure is sometimes spoken of in inches instead of in lb. per square inch.

less than 0·98 lb. per square inch available for lifting the valves.

The degree of vacuum obtainable, moreover, depends upon the temperature of the cooling water; the lower this is the higher will be the vacuum with a given pump and condenser. In this respect cold climates are more advantageous than hot ones, and the power station that can draw upon a plentiful supply of very cold water is better off than one which cannot do so. The Mersey Railway, for example, have to pump water continuously from the tunnel under the river, and even in the height of summer this is almost icy cold, so they use it in condensers.

Mr. Charles Day, when President of the Manchester Association of Engineers, quoted the following to illustrate the importance of workmen understanding the theory of engines they constructed.

A man was sent out to erect an engine and set it to work. After putting it together, he got up steam and started it running. But the vacuum gauge indicated only 26 inches instead of 28. He took the pump and condenser to pieces, refitted the parts, and spent two days in searching for a leak by which air could enter and reduce the vacuum. Now, if he had measured the temperature of the condensing water he would have found that it was too high to give the vacuum he desired. Since an engine is only guaranteed to give its full power at minimum steam consumption with condensing water at a specified temperature, the builders were not to blame.

The cooling water required is from 20 to 25 lb.

per pound of steam condensed, so that enormous quantities are required. Assuming that the engine takes 12 lb. of steam per horse-power per hour, the cooling water required will be 240 lb., and in an engine of 1,000 horse-power no less than 240,000 lb. or more than 100 tons of water per hour will be necessary. All kinds of pumps are used, but the centrifugal type is the most satisfactory, because it takes up little room and is capable of delivering large quantities of water in a steady, continuous flow.

The Compound Engine

When the best materials, the highest standard of workmanship, and the most scientific design have given us engines which run smoothly, with a minimum of friction, and wear well, and when all the operations of working have been rendered as far as possible automatic, the great problem which remains is the condensation of steam in the cylinder. More than a hundred and fifty years ago, when he was struggling to improve the Newcomen model, Watt realised that this was the principal source of loss; and he endeavoured to avoid it by two methods. In the first he effected condensation of the steam outside the cylinder, and in the second he surrounded the cylinder with a steam jacket. Both these methods are employed to-day, and in order to ascertain why they are not wholly successful it is necessary to inquire rather more closely into the changes which occur in steam while it performs its work in the cylinder.

Let it be borne in mind, first, that there is a tremendous advantage in working expansively—that is, in cutting-off at an early part of the stroke. During expansion the steam loses heat and falls in temperature, so that it is cooler at the end of the stroke than it was on admission. If the cylinder is not jacketed with steam, there is a great deal of condensation when the working steam enters the cylinder, because the walls of the latter have been cooled by the exhaust steam from the previous stroke; and there is further condensation during expansion. With a steam jacket the initial condensation is largely, but not wholly, prevented, and the ports and cylinder covers are not affected at all by the jacket. As the working steam expands it becomes cooler than the walls of the cylinder, and some of the steam condensed on the cylinder walls is re-evaporated by heat which flows in from the jacket steam. This is again a loss, but it is at the expense of the boiler, and does not compensate for the loss of the working steam.

The loss by heating and cooling is proportionately less in a large engine than in a small one, because the volume (that is, cubic contents) of the interior of a vessel varies more rapidly with its dimensions than does the area. Consider a hollow cube, with edges 1 foot long. The area, since there are six faces, is 6 square feet, and the volume 1 cubic foot. If the edge were 2 feet, the area would be 24 square feet and the volume 8 cubic feet, the one being four times and the other eight times greater than the corresponding figures relating to the first cube. Similarly, if the cube had edges of 3 feet, the area would be 54 square feet, and the volume 27 cubic feet, or nine and twenty-seven times respectively greater than the area and volume of the first cube. While a steam engine cylinder is not, of course, cubical in form, the same general relations between the area and volume of cylinders of different size holds good; so that it will be clear that surface condensation is of less importance in large cylinders than in small ones.

Again, in high-speed engines the steam is in contact with the metal surfaces for so short a time that the heating and cooling effect is much reduced. The jacket is most effective in small slow-running engines, and in large high-speed engines it is of very little importance at all. In any case the condensation is greater the earlier the cut-off, because the fall in temperature is greater; so that there is a very serious limit to the advantages obtained by expansive working. For example, in small engines there is no advantage in cutting-off earlier than $\frac{3}{4}$ stroke, while in large engines the cut-off may be $\frac{1}{4}$ stroke, but is more frequently $\frac{1}{3}$ stroke.

The engineer, however, is not beaten yet. He has superheated steam at his disposal. Consider a tall, cylindrical vessel with a little water in the bottom and a light, steam-tight piston above it. If the water is heated the temperature rises and a little vapour is formed which presses against the under side of the piston; for water yields vapour at all temperatures, and even the vapour from ice exerts a pressure which can be detected. When the temperature reaches 100° C. or 212° F., steam is vigorously produced. If, now, the temperature falls ever so little some of the steam is re-converted into water, and in the actual experiment the steam condenses on the relatively cooler walls and trickles down the sides. A vapour in contact with the liquid from which it has been formed is said to be *saturated*, and no matter what the temperature is, cooling always results in partial condensation. But if the heating is continued until all the water is boiled away the steam continues to expand, and the temperature, which has been constant during boiling, begins to rise. The steam is now said to be *superheated*, and cooling does not result in condensation until the temperature at which it all boiled away is reached.

The use of superheated steam was not possible in the early days, because neither the packing nor the oil used for lubrication would stand the temperature. Both of them would have charred. But the employment of metallic packing and the discovery of mineral oils capable of withstanding high temperatures enable steam to be heated to from 100° F. to 300° F. above the temperature in the boiler. Such steam does not suffer condensation on admission to the cylinder, and will undergo considerable expansion before condensation from this cause occurs. Unless, however, the boiler pressure is low or the range of expansion is very great, the exhaust steam will be at such a temperature that it is still capable of performing a considerable amount of work.

In practice there is a limit to the size, not of the cylinders which *can* be made, but which it is desirable to make; and since the boiler is most efficient when producing high-pressure steam, it is more satisfactory to share the temperature drop over several cylinders of moderate size. This forms a *compound engine*. It has two, three, or four cylinders, and the name "compound" is usually given to the first, the second and third being designated "triple expansion" and "quadruple expansion" respectively.

In the compound engine the steam first enters the high-pressure, or H.P., cylinder, and then exhausts into the steam chest of the low-pressure cylinder. Both cylinders have the same length of stroke, but the low-pressure, or L.P., cylinder has a larger diameter because the steam with which it is supplied, having expanded in the H.P. cylinder, has a larger volume.

In the triple-expansion engine there is an intermediate pressure, or I.P., cylinder between the H.P. and L.P. cylinders, the steam passing through each in turn. The quadruple-expansion engine, again, has two I.P. between the H.P. and L.P. cylinders. They may be arranged vertically or horizontally, the compound engine corresponding to either of the crank arrangements shown in Figs. 65 and 66, and the triple-expansion engine to that shown in Fig. 68.

The quadruple expansion engine, if horizontal, is sometimes arranged with the cylinders in pairs, tandem, driving a crank-like (Fig. 66); but in marine engines they are vertical and all in a row.

An additional advantage of the multiple-cylinder engine is that it is more easily balanced (see pages 109-116). In this respect three cylinders are better than two, and four are better than three. Whether more than two cylinders are desirable depends upon the pressure. For moderate pressures and moderate powers there is no need to go to additional expense for a third or fourth cylinder. But for the most powerful engines, using steam at 180 lb. to 225 lb. on the square inch, triple or quadruple expansion is fully justified and regularly employed. And in order to secure the advantages of four cranks over three in regard to balancing, and at the same time to avoid the construction of very large cylinders, triple-expansion engines are frequently supplied with two L.P. cylinders. If these are placed at the ends, with the H.P. and I.P. between them, the problem of balancing assumes its simplest form.

CHAPTER VI

Steam Turbines

THE primitive steam engines devised by Hero and Branca, which were described in Chapter II., differed from the engines which have just been described in the fact that rotary motion was obtained without the use of reciprocating parts. The use of a piston by Papin turned men's minds into another direction, and the success of Newcomen and Watt completely eclipsed for a hundred years the older ideas. But this does not mean that they were forgotten entirely. Most engineers would have admitted the disadvantage of starting and stopping the motion of heavy masses of metal twice in every revolution, and many—even Watt himself—sought long and earnestly for some means of converting the energy of steam directly into rotary motion. For nearly a hundred years the Patent Office Records were studded with unsuccessful efforts, and it was not until 1884 that anyone approached within measurable distance of success. In that year the Hon. C. A. Parsons patented a " reaction " turbine, and in the year following the Swedish engineer, Dr. Gustaf de Laval, patented one of the " impulse " type. The initial difficulties were very great, and for some years progress was slow and tentative. But when the difficulties of mechanical construction had been overcome and the theory had been worked out, it was rapid, and the increase of steam turbines, both in numbers and size during the last twenty-five years, forms one of the romances of applied science.

The simplest, but not, in point of time, the first successful, invention was that of de Laval. It depends upon the principle that when any gas escapes under pressure from a suitably shaped nozzle the pressure is converted into velocity—the same principle, in fact, that is involved in the injector. When steam escapes from a small hole from which it enters the atmosphere abruptly, its velocity is relatively small. The effect is as though it were "throttled." In fact, the velocity acquired, no matter how great the pressure may be, is approximately no greater than would occur under a pressure of 10·7 lb. per square inch, as shown by the gauge! In order to utilise larger pressures a nozzle, expanding towards the mouth, as in Fig. 87, is needed. In such a nozzle the steam expands during its passage, and if the inlet pressure is high, as in modern boilers, and the nozzle discharges into a condenser, a velocity of 3,000 feet to

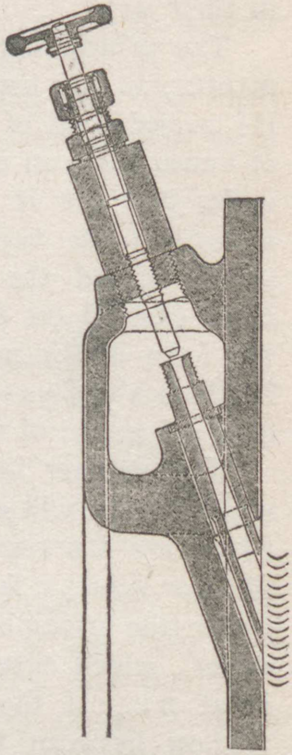


Fig. 87.—Section through nozzle of de Laval turbine

4,000 feet per second may be acquired. However light the particles of steam may be, they exert, by reason of their number and their high velocity, a considerable force upon any object which stands in their way.

The principle was employed, in a very imperfect manner, in the engine invented by Branca in 1619. He caused a jet of steam to strike against a number of vanes fixed on a wheel. As each little vane came under the jet it received an impulse—hence the name impulse turbine—and the succession of impulses caused the wheel to spin round. But the force exerted on the vanes depends so much upon the form of the nozzle—a fact that was not known in Branca's days—that his engine may have given only a fraction of the power of which it was capable.

The manner in which the steam exerts a force upon a vane will be understood by reference to Fig. 88. Here A B represents an edge view of a curved plate or vane; C is a nozzle from which issues a jet of water (the principle is just the same if steam replaces water), which enters upon the plate at A and leaves it at B E. If the surface of the plate is smooth, friction between the water and the plate will be small, and the water will move over the plate with practically no change of speed. Owing, however, to the change of direction which the water undergoes, a force is exerted upon the vane creating a tendency to move in the direction of the arrow.

So far the vane has been regarded as fixed. If it moves in the direction of the arrow the water, on leaving the nozzle, passes to another moving object, viz., the vane, and the speed at which it slides over the surface will be less than its speed at the instant of discharge—just as a man running to catch a moving train may be travelling at a great speed along the platform, and yet have only a slow rate of motion relative to the train.

Now, while the water is moving over the vane its speed over the surface will be practically the same at B as at A, and, in this respect, the action is the same for a moving as for a fixed vane. But the water is not merely moving over the surface —it is also following up the vane as it retreats. Its speed will be less than that of the original jet, and its direction will have been changed. It will not leave the vane exactly as it appears to do in the diagram, but will be thrown forward by the motion of the vane—that is, to the left. It is clear, therefore, that the resulting effect of the jet depends very much upon the inclination of the face at A and B, and it is here, more particularly, that scientific design is required.

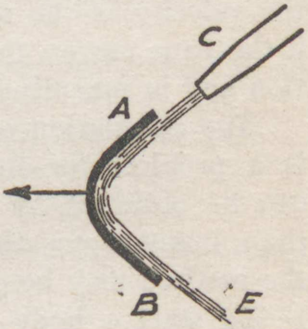


Fig. 88.—Diagram to explain principle of impulse turbine

From the foregoing account it follows that (i.) from the time the water or steam leaves the nozzle it suffers no change of pressure, and (ii.) the work is done by the water or steam upon the moving vane by virtue of the change, both in magnitude and direction, of the velocity of the substance. These two facts are characteristic of the impulse turbine, and because the work done is due to a change of velocity, impulse turbines are often referred to as "velocity" turbines.

They are so important that it is worth while repeating them in another way. There is no change of pressure from the time the steam impinges upon the vane to the time it leaves it. If the vane is fixed the velocity of the steam changes only in direction; if the vane moves, the velocity changes both in direction and in magnitude—it becomes lower.

The calculation of the force exerted upon a vane is a problem for the engineer, but a general idea can be obtained by the use of no more mechanics than many boys already know. An indication of the method may be given.

To start a body moving or to alter its velocity requires force, and as, according to Newton's Third Law of Motion, to every action there is an equal and opposite reaction, a moving body exerts force whenever its velocity is altered. The product of the mass and the velocity of a body is called its *momentum*, and the force exerted by a moving body is measured by the change which its momentum undergoes in unit time, or the rate of change of momentum. Thus, if m lb. of steam are moving with a velocity of v feet per second, its momentum is $m \times v$ units. If, however, the change of momentum is measured in this way, the force will be given in poundals, and to obtain its value in pounds it must be divided by

32.2, the gravitational constant. Engineers make this alteration at once by expressing momentum as $\frac{m \times v}{32{\cdot}2}$.

Suppose now that m lbs. of steam flow past the vanes per second, and that each particle in passing has its velocity *measured in the direction taken by the moving vanes* changed from v to v_2. At the beginning of a second m lbs. of steam have a momentum $\frac{m \times v_1}{32{\cdot}2}$, while at the end the momentum is only $\frac{m \times v_2}{32{\cdot}2}$. The force F lb. acting upon the vanes, tending to drive them round, will be, therefore,

$$\frac{m \times v_1}{32{\cdot}2} - \frac{m \times v_2}{32{\cdot}2}, \text{ or, } \frac{\text{F}\ m\ (v_1 - v_2)}{32{\cdot}2}.$$

This formula is of primary importance in turbine design.

In de Laval's turbine the vanes, or blades, as we shall call them in future, are fixed radially round the edge of a disc, as in Fig. 89 on Plate 10, and one or more nozzles (Fig. 87) are fixed so that they strike the ring of blades at an angle. Owing to the motion of the blades and their shape the jets are *deflected.* Suppose they could be arranged so that the steam impinging upon a blade with the wheel at rest was turned completely back upon its path. It would then exert its greatest force upon them, but no work would be done on the wheel so long as it did not move.

Next suppose that the wheel moved at such a rate that the blades had the same speed as the steam. The steam would pass through the blades without any change of velocity, and hence would exert no force upon them. If, however, the wheel moves at such a rate that the blades have half the speed of the jet, then the steam would leave the blades with no forward velocity relative to them. In other words, it would flow outside-ways, at right angles to the wheel. Thus, supposing the steam to have a velocity of 3,000 feet a second, and the blades were to move at 1,500 feet a second, then the force exerted on the wheel would be due to a velocity drop of 3,000 feet a second, for the blades are so shaped that the whole of the forward velocity would be destroyed at this speed. This is the theoretical condition of the highest efficiency of an impulse turbine.

Now in order for the blades on an impulse turbine wheel, 1 foot in diameter, to have a velocity of 1,500 feet a second, it would need to make more than 475 revolutions a second, or 23,000 revolutions a minute. Such a velocity is not attained, mainly because no known materials will stand the enormous bursting action which would be set up by centrifugal force in the wheel. Only by employing the very finest steel for the purposes combined with scientific design of the highest order was de Laval able to obtain running velocities of 1,100 to 1,200 feet per second, and this must be regarded as the high-water mark. The smallest turbine makes 30,000 revolutions a minute, but the wheel is only about 6 inches diameter, so that the speed of the rim is only 875 feet a second: the largest make 9,000 in the same time.

It is worth while pausing for a moment to consider what these figures mean. If you trundle your 2-foot hoop at the easy pace of 5 miles an hour it covers $6\frac{2}{7}$ feet at each turn, and makes nearly one turn a second, nearly fifty-five turns a minute, or 3,405 turns an hour. The 5-foot driving wheel of a locomotive covers $15\frac{5}{7}$ feet for every turn, and at sixty miles an hour it will make 5·6 revolutions a second, 336 revolutions a minute, 20,160 revolutions an hour, 3,986,880 revolutions in a week of 168 hours. In that time it would have travelled 1,080 miles, or two-fifths of the distance round the world; but if a 6-inch de Laval turbine wheel, rotating at 30,000 revolutions a minute, could be set on a rail, and could keep up its speed, it would cover nearly 9 miles a minute, or 540 miles an hour, or about 90,000 miles in a week of 168 hours. In about forty-six hours it would have gone completely round the earth and arrived again at its starting point. This beats Jules Verne hollow; for he, riding full tilt on the wings of his imagination, occupied eighty days upon the journey!

Very interesting details of construction follow from the enormous speeds which are obtained in the impulse turbine. From what has been said in Chapter V. about balancing it will be seen that this is of tremendous importance where such high speeds are involved. Recalling the formula, $\frac{M\ v_2}{g\ r}$ which gives the force produced by a body rotating around a centre (see p. 112), and remembering that even in a disc the whole of the mass acts as though it were concentrated at a point called the centre of gravity, it will be seen that if the centre of gravity is not concentrated at the geometrical centre of the shaft, very large forces indeed are called into play.

If the force were 1 lb. at 100 revolutions per minute it would be 4 lb. at 200 revolutions, 9 lb. at 300 revolutions, 16 lb. at 400, 25 lb. at 500, 36 lb. at 600, 49 lb. at 700, 64 lb. at 800, 81 lb. at 900, and 100 at 1,000 revolutions per minute. Quite insignificant at low speeds, this force would become sufficient at 30,000 revolutions a minute to tear the machine to pieces. Not only, therefore, has the disc to be most accurately balanced, but it must be made of the finest quality of steel to resist the stresses set up in the material, and the blades must be securely fixed lest they be flung off by centrifugal force.

But there is a more wonderful phenomenon arising from high speed than even the forces which are brought into play. When a shaft is supported between bearings it sags a little, and when it is rotated there is a tendency for it to whirl round as though it were a bow. This effect becomes very marked in the neighbourhood of a certain speed, called the critical speed, which depends upon the length and thickness of the shaft. In a long, thin shaft this speed is low, and in a short, thick shaft it is very high. As a matter of fact, there are several critical speeds for each shaft, but as a rule only one is important. When the critical speed is passed whirling becomes less, the shaft straightens, and the motion becomes steady.

Now the speed of a de Laval turbine is so high that it is practically impossible to avoid whirling. By making the shaft long and thin, however, the critical speed is low, and when the turbine is started the danger point is passed rapidly. Thus the diameter of the shaft in a 5-horse-power turbine is only $\frac{1}{4}$ inch, and in the 300-horse-power turbine only $1\frac{1}{8}$ inches. But the bearings must be flexible —a condition which is secured by making the bushes* spherical in form, and there must be plenty of room in the casing. In the reaction turbine, which will be described later, this clearance space would be a disadvantage; but in the impulse turbine it is of but little consequence. The steam expands in the nozzles, so that pressure is converted into velocity, and it is this velocity, not pressure, which forces round the vanes. Each vane, as it passes a nozzle, receives a tap or impulse which forces it round.

No machine—not even an electric generator—needs to be driven round at from 10,000 to 30,000 revolutions a minute, and though they could be driven at this rate they would have to be specially built, and would be costly in consequence. So the de Laval turbine is generally connected with the machine it is to drive by toothed gearing, a small wheel on the turbine shaft, and a large wheel on the shaft of the electric generator, which reduces the number of revolutions by ten or more to one. The toothed wheels used for this purpose are very wide on the face, the teeth are small and are cut spirally

* Bushes are the brass blocks or cylinders which form the bearing.

—that is to say, they do not run straight across from side to side. The force exerted by one wheel or the other is, therefore, continuous and more uniform than when the teeth run parallel to the shaft.

In order to avoid the enormous velocity obtained in the de Laval turbine, Rateau and others invented turbines in which the full force of the steam was exerted not upon one ring of blades but upon several rings in succession. Thus the rings of blades in the Westinghouse modification of Rateau's turbine are mounted a short distance apart on the curved face of the disc, and the spaces between are occupied by rings of blades on the rims of discs or diaphragms which are attached to the casing and which, therefore, do not rotate. Fig. 90 shows, diagrammatically, this arrangement. In each ring of fixed blades the steam expands and acquires velocity, which enables it to give a succession of impulses to the moving blades. The amount of expansion at each stage, and, therefore, the velocity acquired, depend upon the shape of the fixed blades. With a parallel flow the pressure never drops to less than ·58 of the original pressure; with an expanding orifice the drop may be greater; with a contracted orifice the drop may be less. From an exact knowledge of

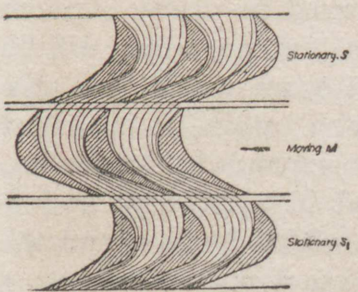


Fig. 90.—Diagram of blades of impulse turbine

the relation between the fall in pressure and the shape of the fixed blades the total velocity obtainable from the steam may be split up into a series of stages, and the velocity which is characteristic of the single wheel of de Laval's turbine is reduced accordingly. Turbines with more than one stage can be used to drive electric generators and other machinery directly, without the intervention of toothed gearing.

With these preliminary explanations the general arrangement, method of working, and construction of an impulse turbine will be clear from the following plates and diagrams. Fig. 91 shows a section through a small Westinghouse-Rateau turbine with a single velocity wheel having three rings of blades, and made in sizes from about 40 to 300 horse-power. Fig. 92 is a half-section through a larger high-pressure turbine having one velocity wheel, A, with two rows of blades, and six velocity wheels, B, carrying a

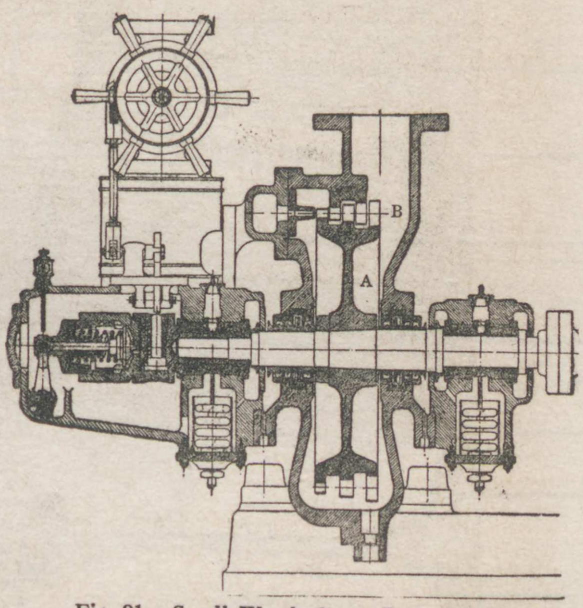


Fig. 91.—Small Westinghouse-Rateau turbine

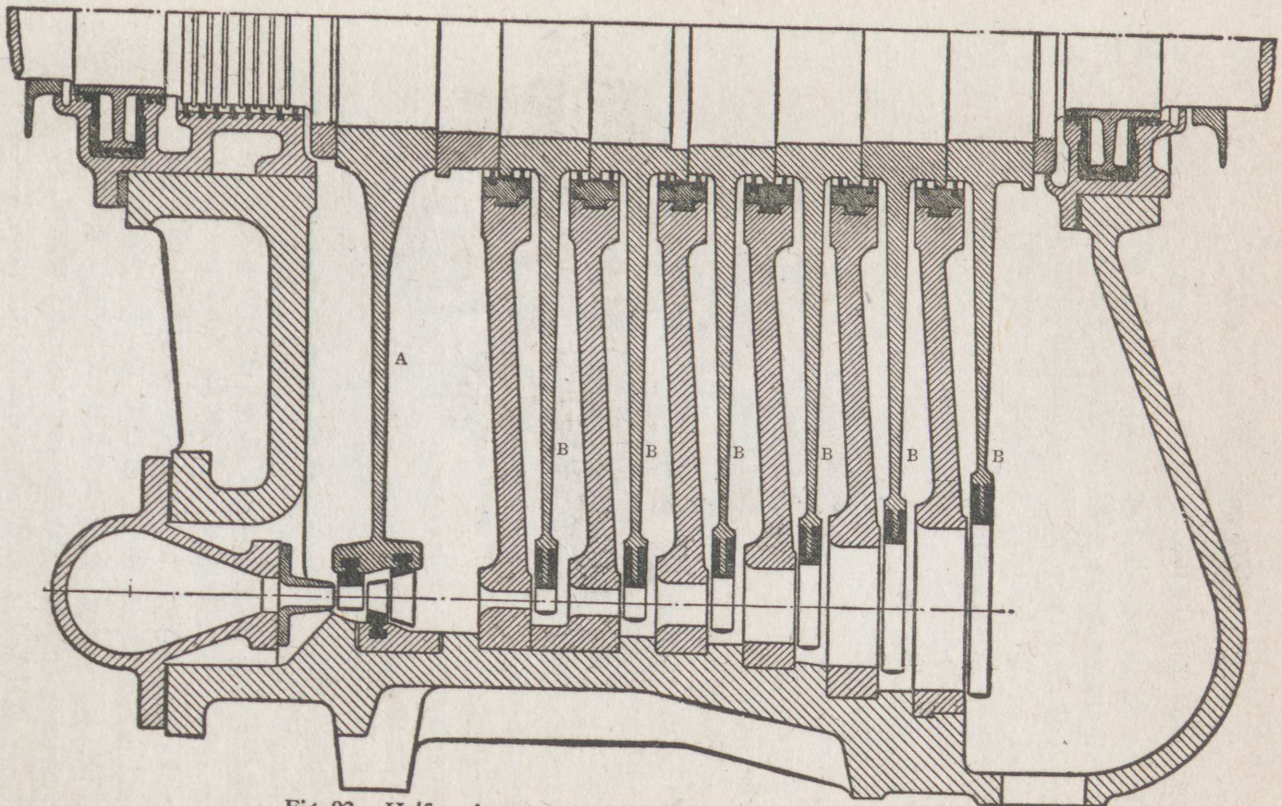
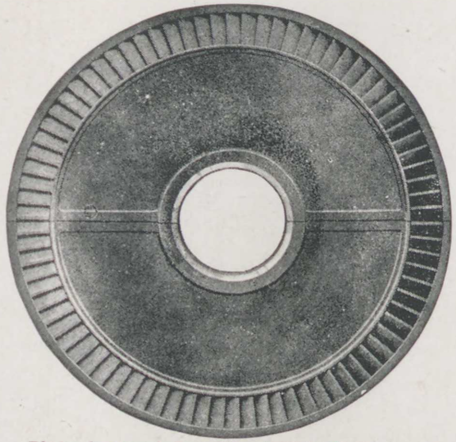


Fig. 92.—Half-section through large Westinghouse-Rateau turbine



Photos by permission of the British Westinghouse Electric Co., Ltd., Manchester

Fig. 94.—Complete Wheel of Westinghouse-Rateau Turbine

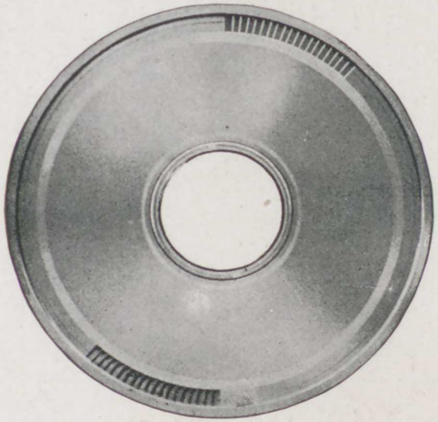


Fig. 95.—Diaphragm at high-pressure end

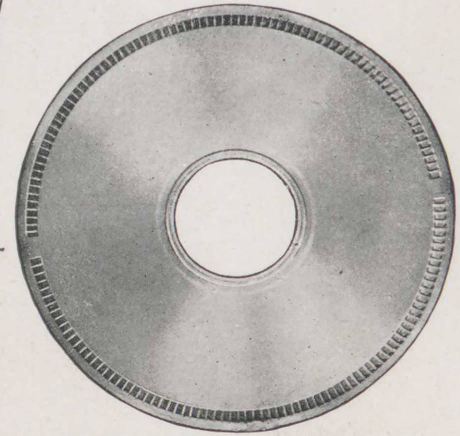
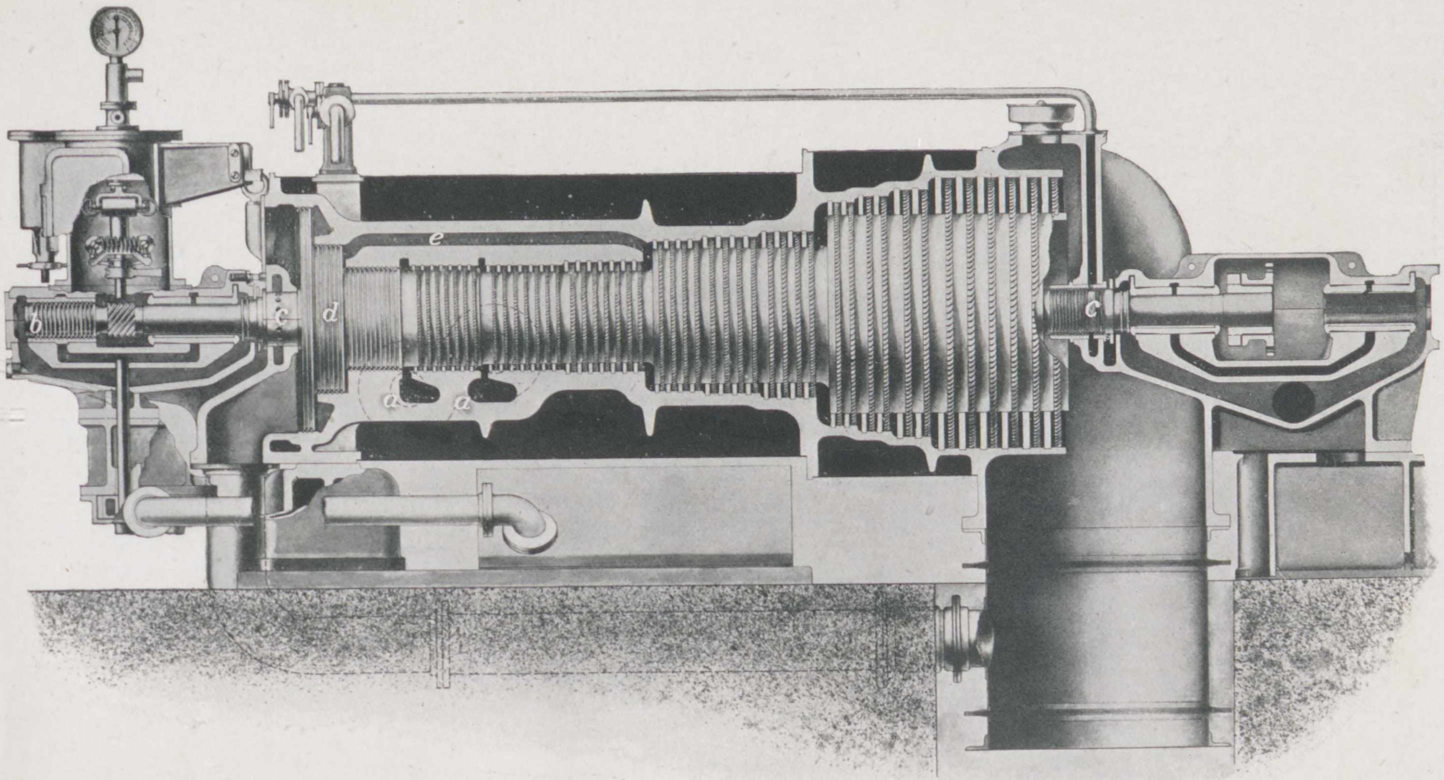


Fig. 96.—Diaphragm at low-pressure end



By permission of Messrs. C. A. Parsons & Co., Ltd.

Fig. 102.—Section through Parsons Turbine

single row of blades. Steam is directed upon the blades of the first wheel through three nozzles, one of which is shown on the diagram. Each nozzle can be opened or closed separately, so that the supply of steam may be adjusted for one-half, or full load, or over load. If the condenser is not in operation all three nozzles must be open for full load. At each end of the casing are glands to prevent the escape of steam. The bearings are not shown; on the left-hand side is a registering block, consisting of a bearing fitting over a portion of the shaft provided with ribs, and having similar ribs on its interior surface to prevent endwise motion of the shaft. At one end of the shaft is the safety governor, about which something will be said presently, and there is a flexible coupling connecting the turbine shaft with the shaft of the electric generator, pump, or other machine which it is intended to drive.

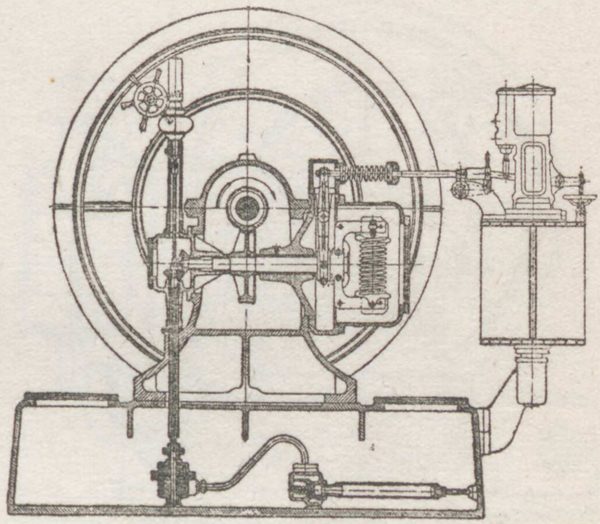


Fig. 97.—Section through governor

The construction of the blading is shown in

Fig. 93 on Plate 10, and a complete wheel in Fig. 94, Plate 11. Just as the high velocity of the steam when it enters the turbine rendered three nozzles sufficient for admitting it to the velocity wheel, so in the case of the earlier wheels steam is not admitted all round the diaphragm. Fig. 95 on Plate 11 shows the diaphragms used for admitting steam to the earlier single-bladed wheels, and Fig. 96, Plate 11, shows the diaphragm used in the later stages.

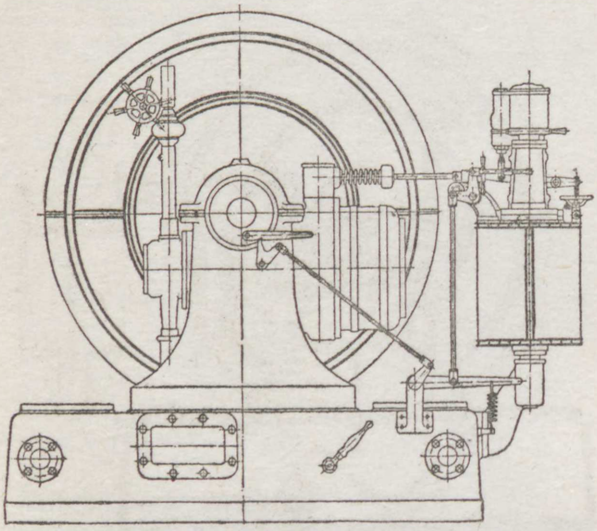


Fig. 98.—Outside view showing governor

Now let us glance at the governing arrangement. Fig. 97 shows a section through the governor end of the turbine, and Fig. 98 an outside view. A worm on the turbine shaft drives a toothed or worm wheel on the governor spindle, which is horizontal, and any change in speed affects the governor valve and varies the opening to steam. There is also an emergency, or overspeed safety device, which operates if the ordinary governor should fail to act, and shuts off steam if the speed becomes dangerously high. This is shown in Fig. 99. It will be seen that a small rod G is held in position in a hole in the shaft by a spring. As this rod has its centre of gravity a little nearer to the top of the diagram than the centre of the shaft, it tends to fly out when the shaft is rotating. For normal speeds this is prevented by the spring; but if the speed becomes excessive the rounded end of the rod projects beyond the surface of the shaft and presses upon the small lever Q, releasing the trip lever A. How the release of this trip lever closes the governor valve will be seen from Fig. 98.

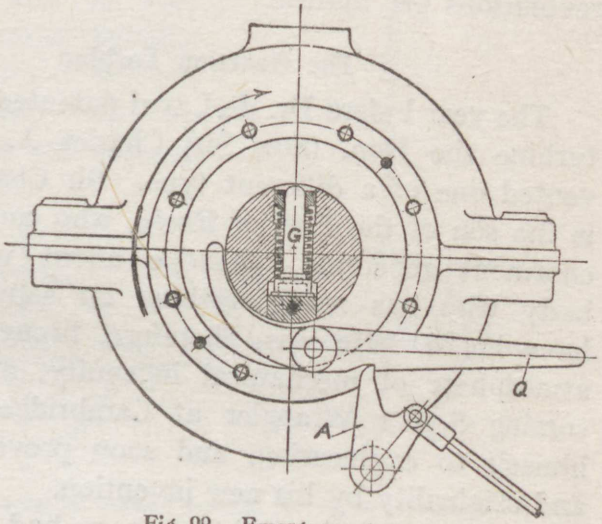


Fig. 99.—Emergency governor

The position of the oil pump is also shown on Fig. 97. It is situated in the oil well into which all the oil used for lubrication drains, and from which it is pumped to the bearings and other parts requiring lubrication. A bevel wheel on the end of the spindle which drives the governor serves to drive the pump. It is worth noting that no oil is used inside the casing of a turbine, so that no oil becomes mixed with the steam. The condensed steam, therefore, is practically free from oil and can be used to feed the boilers — a great advantage where pure water for boiler feeding is not easily obtained. These turbines are made in sizes from 20 to over 12,000 horse-power, and run at speeds from 750 to 4,000 revolutions per minute.

The Reaction Turbine

The year before Dr. de Laval patented his impulse turbine the Hon. (now Sir) Charles A. Parsons invented one of a different type. Sir Charles Parsons is the son of the Earl of Rosse, who constructed the enormous reflecting telescope about which everybody who has read anything on astronomy must have heard. He was, therefore, brought up in an atmosphere of mechanical ingenuity, and after becoming Senior Wrangler at Cambridge he devoted himself to engineering, and soon proved his power and originality by his new invention.

Just as the Swedish engineer had adopted the same principle as Branca, with that special modification of the form of the jet which is based on scientific knowledge of the properties of steam which has been discovered long since Branca died, so Sir Charles Parsons adopted the principle employed by Hero, and brought to bear upon the problem the mathematical and scientific knowledge built up by 2,000 years of human genius and human industry. What the impulse principle is, and how it is applied has already been described, and we have now to examine in greater detail the reaction principle.

Suppose the vessel shown in Fig. 100 to be suspended by a thread and to be filled with steam which can only escape through the nozzle. Now the expansive force of the steam is exerted equally in all directions, and it will, therefore, press equally over the interior surface of the vessel. But at the nozzle it will escape,

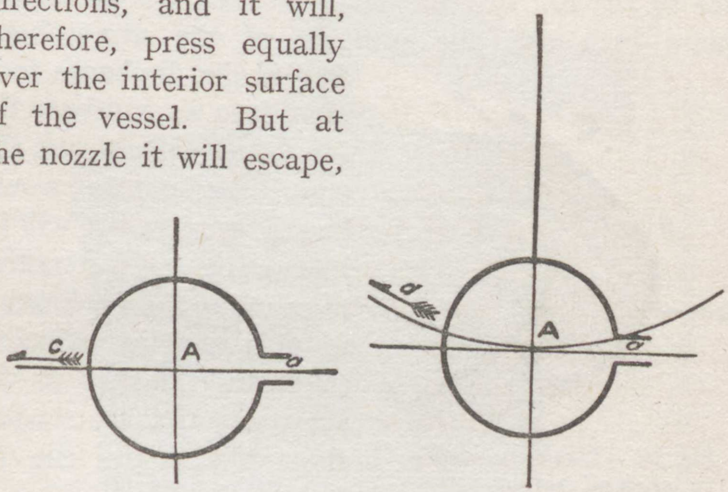


Fig. 100.—Diagram to explain reaction due to jet of escaping steam

and since, according to Newton's Third Law of Motion, "to every action there is an equal and opposite reaction," the force exerted on the escaping steam will create an equal and opposite force on the vessel, causing it to swing backwards in the direction shown by the arrow. To give a concrete example. Suppose the pressure of the steam in the vessel to be 200 lb. on the square inch. Then, with the type of nozzle shown in the diagram, the pressure at the nozzle will be only 116 lb. on the square inch, or ·58 of the original pressure, and if the nozzle is 1 square inch in area there will be a pressure of 84 lb. per square inch, tending to force the vessel backwards in the direction of the arrow. With a properly designed nozzle, however, it would be possible to increase this difference to 185 lb., the difference between 200 lb. on the square inch and the pressure of the atmosphere. And if the discharge took place into a condenser the force tending to thrust the vessel backwards would be still greater. It will be interesting and instructive to examine the application of this *reaction* principle to steam turbines in the same way that we studied the application of the *impulse* principle.

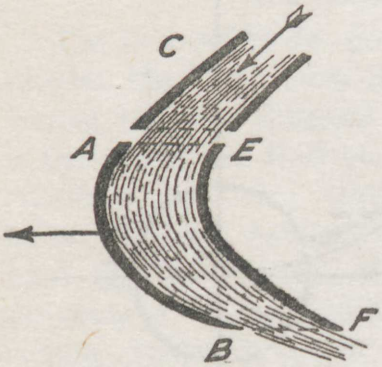


Fig. 101.—Diagram to explain principle of reaction turbine

Suppose C in Fig. 101 to represent a nozzle conveying the working fluid (in a scientific sense, as you know, the term fluid includes both liquids and gases) to the vanes or blades A B and E F, which themselves form practically a curved nozzle, which is seen in section. If the blades are regarded as fixed, it is clear that the fluid will tend to force the blades in the direction of the arrow. But whereas in the impulse machine the pressure at inlet and outlet is the same and, except for a small friction effect, the speed of the fluid over the surfaces does not change,

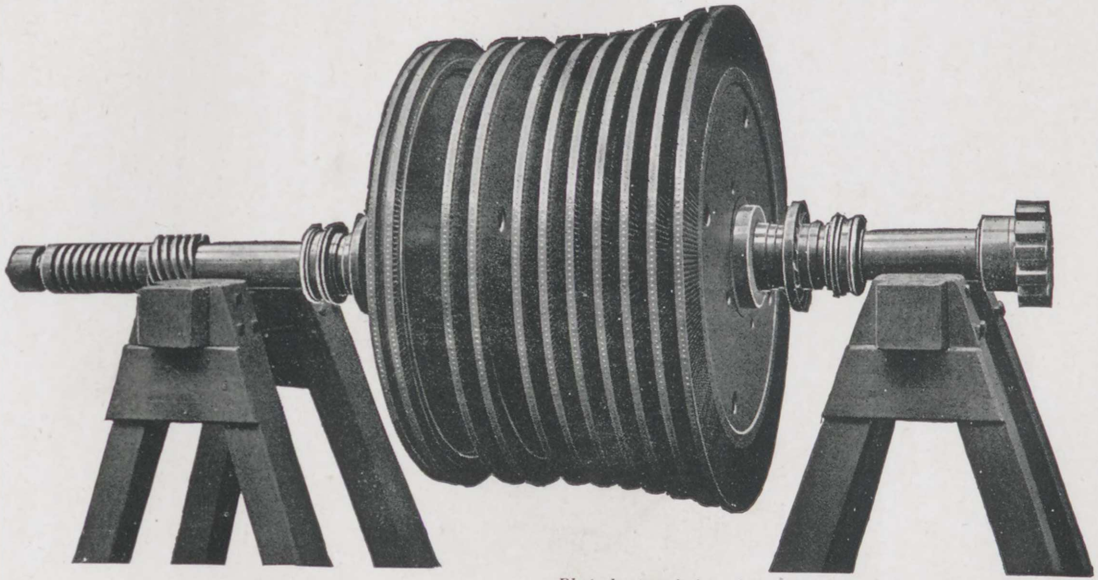


Photo by permission of the British Westinghouse Electric Co., Ltd.

Fig. 103.—Drum of Modern Reaction Turbine

PLATE 14

Fig. 104. — "Balance" or Double-flow Arrangement of Turbine Blading

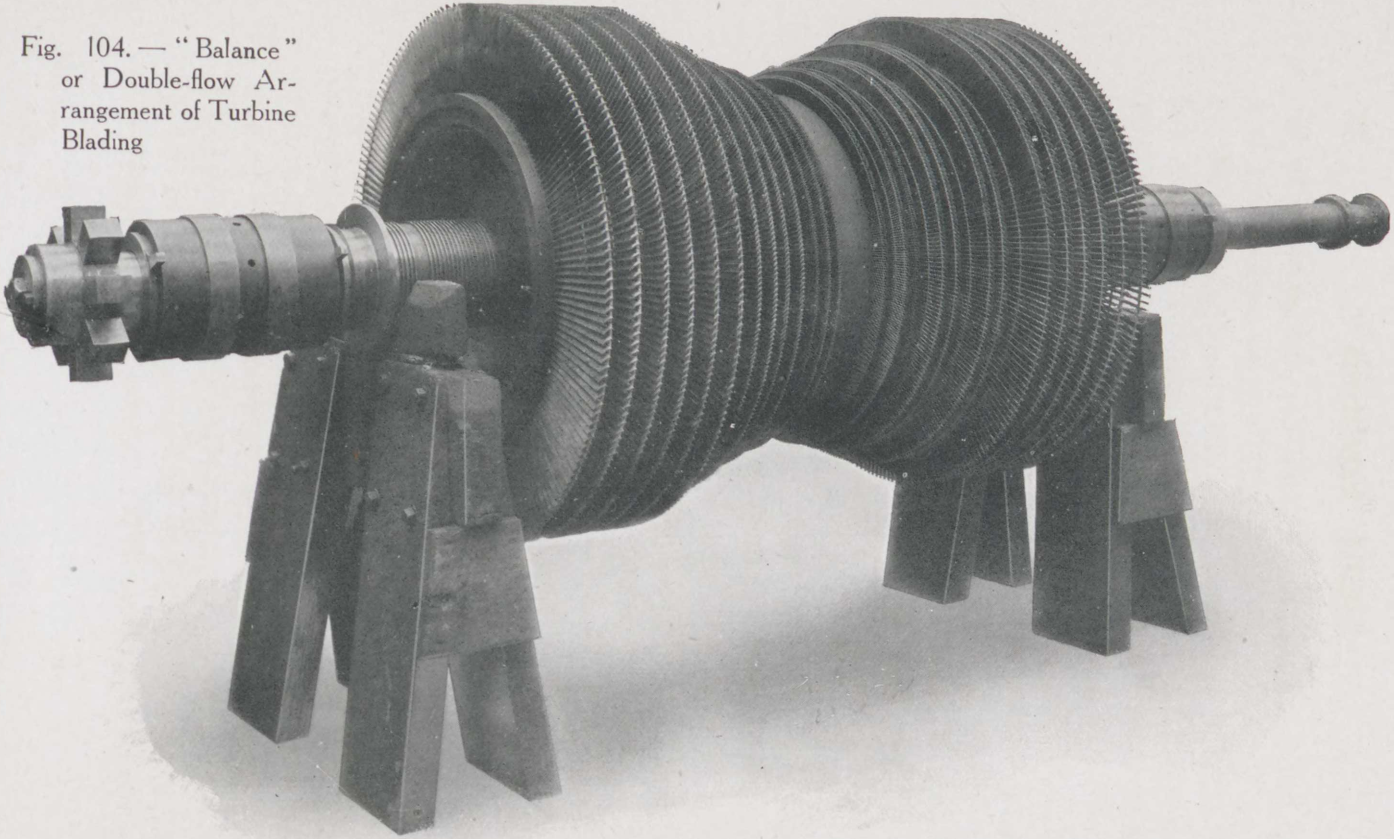


Photo by permission of Messrs. C. A. Parsons & Co., Ltd this is not so in the reaction machine. Owing to the form of the blades in the latter, the pressure at B is less than that at A, and hence under the fall in pressure the speed over the blades increases as the fluid moves from A to B. In other words, it acquires momentum just as in the case of the suspended vessel in Fig. 100 ; and for this reason the blades are urged in the direction of the arrow exactly as in the case of the suspended vessel by a force which depends upon the difference of pressure between inlet and exit of the nozzle. The result is precisely the same when the blades are free to move, though the angles have to be proportioned suitably to the speeds.

A little further thought will show that the behaviour of the steam in the moving blades of a reaction turbine is similar to its behaviour in the fixed blades of an impulse turbine. And since the fixed and moving blades of a reaction turbine perform similar purposes they are similar in form. Further, as the fixed blades of both impulse and reaction turbines perform the same office, it is in the moving blades that the differences exist.

The essential features of the reaction turbine are (i.) the steam undergoes a fall in pressure, and consequently expands as it passes through the moving blades, and (ii.) work is done as a result of the change of momentum suffered by the steam in passing through the moving blades as in the impulse type, and this arises partly from the expansion within the vanes. On account of the fact that there is a fall of pressure in the moving blades, reaction turbines are often referred to as *pressure* turbines.

In the Parsons turbine the moving blades are fixed in grooves round a drum, and between each ring of these blades there is a fixed ring of blades attached to the turbine casing. The space between any two consecutive blades forms a nozzle, and the blades are so designed as to give these nozzles the desired shape.

As the steam passes from end to end of the turbine the pressure falls to that of the condenser, and there is none left to convert into velocity. It will be almost at rest relatively to the turbine casing; and as for every pressure there is a corresponding temperature it is clear that the turbine does work by abstracting heat from the steam with which it is supplied.

The turbine is a heat engine just as Watt probably understood the ordinary reciprocating engine to be, and in its broad outline it is subject to the same laws. But instead of steam expanding in a cylinder behind a piston having only a straight line motion backwards and forwards, necessitating cross head, connecting rod, and crank, we have steam expanding between innumerable thin blades and applying an even, continuous turning motion to the shaft. Moreover, there are no eccentrics, no sliding valves, no masses of metal to be alternately heated and cooled, and no narrow passages through which the steam has to escape after expansion.

Since in the impulse turbine it is the velocity of the steam which is being used to produce motion, the wheels need not run very closely either to the fixed blades or to the casing. But in the reaction turbine, in which the expansive force of the steam is being utilised, leakage past the blades must be, as far as possible, avoided. A slight endwise movement of the shaft, or an increase in the temperature of the superheated steam, may lead to what is called "stripping," that is, both fixed and moving blades are torn from their grooves and deposited in a heap at the bottom of the casing. While the impulse turbine was not free from such accidents in the early days, they were very serious and not infrequent causes of failure of reaction turbines. In fact, the huge drum, weighing often several tons, and the thin blades a few inches in length and a fraction of an inch in thickness, form an unusual combination of strength and weakness, and much ingenuity has been exercised in overcoming the mechanical defects which were so apparent in the early days. The result is that all parts upon which superheated steam plays are now made of steel, and the blades are invariably thinned off at the outer ends, so that if by any mischance they do come into contact with the interior of the casing they are rubbed over and not torn out of their sockets.

So much for the principle involved. Parsons' first turbine, constructed in 1884, was of only 6 horse-power. It drove a dynamo, and after running for several years it was deposited in the South Kensington Museum. It was the first turbine in which the drop in pressure was distributed over a series of wheels or rings of blades. During the next four years—up to the end of 1888—a number of similar turbines were built, but none of them was of larger size than 150 horse-power. In 1889 the Heaton works of C. A. Parsons and Co. were founded in order to allow of more and larger turbines being built under the direct supervision of the inventor. Unfortunately, at this point there were legal troubles in regard to the validity of the patents, and Sir Charles Parsons was not permitted to manufacture his parallel-flow turbine until 1894. Thus while 60,000 horse-power had been constructed by 1889, the horse-power produced between that year and 1894 was only 10,000. From 1894, however, the inventor came into his own.

Nearly every year saw an increase in the power of individual machines and an increase in their economy of working. The 150-horse-power turbines to which reference has been made were constructed in 1886, and ran at 4,800 revolutions per minute. The first turbine over 150 horse-power was made in 1891, and the first over 200 horse-power in 1892. By 1894 500-, by 1899 1,500-, by 1906 6,000-, by 1908 10,000-horse-power turbines were at work. The earlier turbines were non-condensing, and took about 20 lb. of steam per horse-power per hour ; the later ones, fitted with the most effective air pumps and condensers, required only about 9 lb.

The general construction of the Parsons Turbine will be understood from the section given in Fig. 102 on Plate 12. Steam enters by the two channels, AA, shown in black near the left-hand of the drum. In order to provide room for the gradually expanding steam, both the diameter of the drum and the length of the blades increases as the exhaust is approached. The thrust bearing, B, to prevent the shaft from moving endwise, will be seen on the extreme left. At each end of the shaft is an arrangement, C, for preventing the escape of steam from the casing. These consist of grooves, on the shaft into which project thin strips of brass, while exhaust steam from the governor serves as a "packing." Dummy pistons, D, constructed much in the same way, and with steam acting upon them in such a way as to oppose the endwise push on the blades, serve to "balance" the thrust, so that the thrust bearing itself is mainly a safeguard. Above the first two sets of blades will be seen a passage, E, through which steam can act on these dummies.

The governor and the method of driving it will be readily understood from the section. It does not operate the throttle valve directly, but admits or prevents the admission of steam for this purpose. The valve is never quite still, and a little steam is always being used to operate it. It is this steam which is used for "packing" the glands. There is also an emergency governor which acts in a way not very different from that described on page 161. It only comes into action when the speed exceeds the normal by 10 or 15 per cent.

The blades in the first few rows are of copper, because that metal resists most satisfactorily the action of high-pressure steam. The others are of brass. All are rolled and drawn to the required section and highly polished to reduce friction with the steam. They are thinned at the tips for reasons which have already been given. Two methods are employed to fix them into position in the grooves. Either they are fixed singly or made up in sections, and afterwards tightly wedged in position. On one edge near the outer end is a small slot in which a wire or strip is hard-soldered to keep them the right distance apart.

The drum of a modern reaction turbine is shown in Fig. 103 on Plate 13.

The drum has the effect of stiffening the shaft, so the problem of whirling does not enter here as it does in the de Laval turbine. The speed is always below the critical speed (see page 156), but danger arose from the difficulty of lubrication. When two rubbing surfaces have a large relative velocity the film of oil tends to break up, and what is called discontinuity occurs. The method adopted by Sir Charles Parsons in his earlier turbines, and still followed when the speed is 3,000 or more per minute, is to use several concentric bushes or tubes fed with oil under pressure. If the friction between the shaft and the inner bush increases—as it will increase if rupture of the film occurs—the bush is dragged round with the shaft and overheating is prevented. The arrangement has the additional advantage that vibrations due to the shaft being slightly out of balance are effectively damped. The oil films form a cushion.

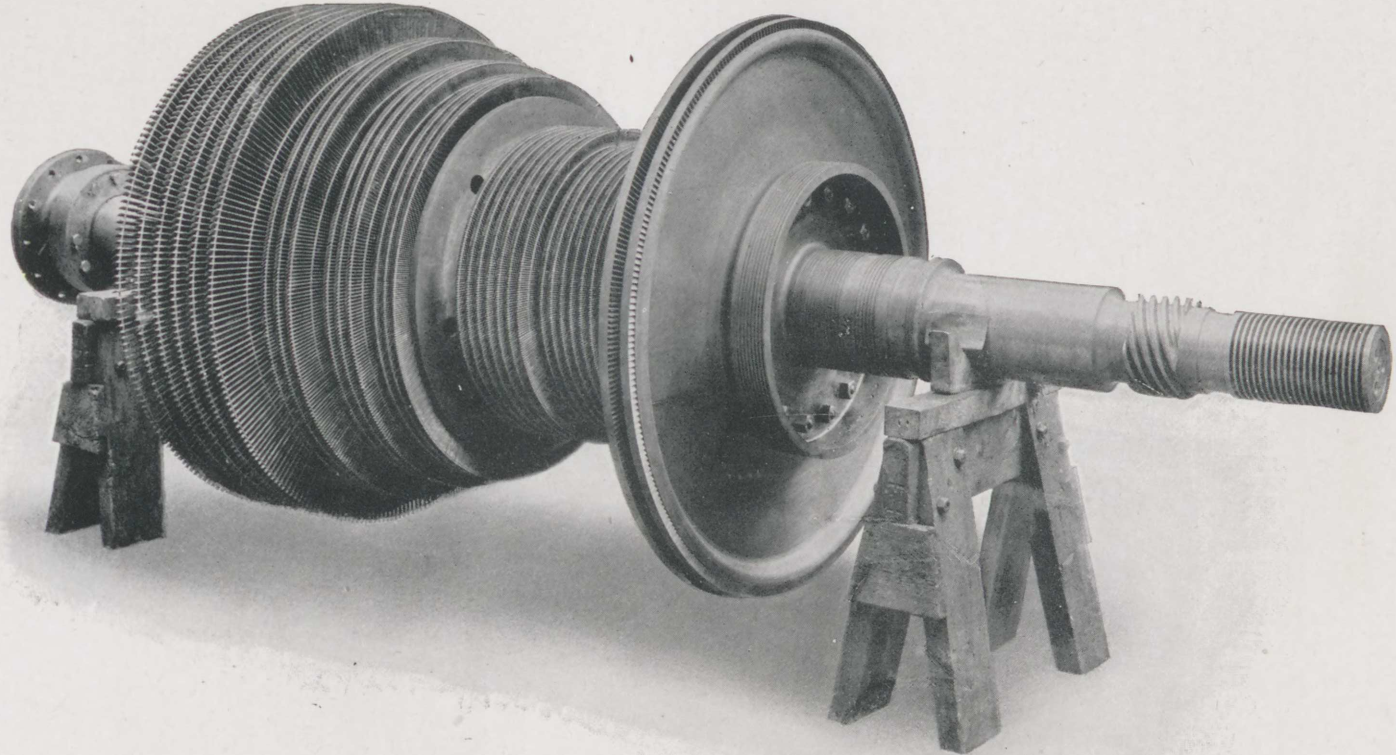


Photo by permission of Messrs. C. A. Parsons & Co., Ltd.

Fig. 105.—Reaction Turbine with Impulse Wheel at high-pressure end

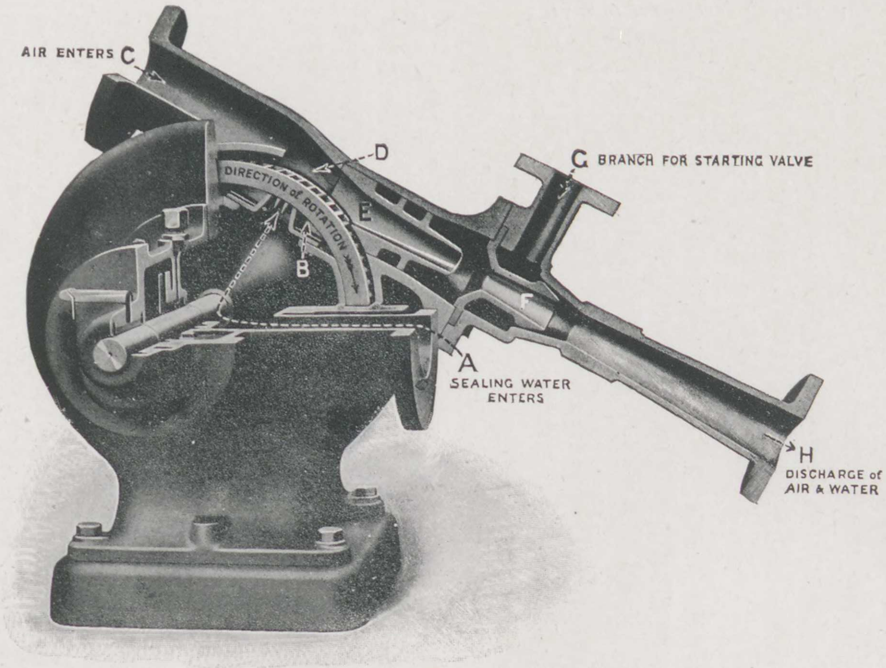


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Fig. 108.—Leblanc Rotary Air Pump

The larger turbines are often constructed in tandem—that is to say, there is a high-pressure drum and a low-pressure drum on the same shaft, in separate casings, and the steam passes by a large pipe from one to the other. As there is a bearing between the two the portions of the shaft are shorter and stiffer than if the whole power were obtained from a single drum. The high-pressure casing is then usually made of cast steel and the blades of copper. Where only low pressures are to be employed the blading is often in two sets, as in Fig. 104, Plate 14. The steam enters at the middle and flows through the two sets of blading in opposite directions; but the blades in each half are, of course, set so that the turning effect on the shaft is always in the same direction. With this arrangement there is no end thrust. Another plan followed by many makers is to use both impulse and reaction blading in the same turbine, as in Fig. 105 on Plate 15. The steam first acts upon one or more impulse wheels, and then flows through reaction blading.

The Most Powerful Steam Turbine in the World

The largest steam turbine in the world was constructed by C. A. Parsons and Co. in 1913 for the Commonwealth Edison Co., of Chicago, and therefore has the additional interest that it was made by a British firm for a great American company. Constructed to give over 35,000 horse-power, it is guaranteed to require only 8·1 lb. of steam per horse-power per hour, or only 40 per cent. of that required twenty-five years ago. This in itself constitutes a record.

The whole plant includes a high-pressure and low-pressure "rotor" or drum on the same shaft, coupled to a huge electric generator with a small one used as an "exciter" at the extreme end. The total length is 76 feet 2 inches, the greatest width is 18 feet, and the depth from base to top is 10 feet. Just below the low-pressure casing is an enormous surface condenser reaching 20 feet below the floor level. The shaft is nowhere less than 16 inches in diameter, and is in three lengths of not less than 20 feet. The low-pressure casing alone weighs 150 tons. When working at full power it will require 281,250 lb., or 125½ tons, of steam, and about 5,600,000 lb., or 2,500 tons, of condensing water per hour!

Steam is generated at 200 lb. per square inch and superheated by 200° Fahr., making the temperature about 600° Fahr. It enters the steel casing at the high-pressure end, and passes through sixty-four rows of blades in six sets. These blades vary in length from 2¾ to 6½ inches. Thence it passes to the low-pressure turbine, which is of the double-flow pattern, the steam entering at the centre and flowing towards the ends. The pressure is here 25 lb. per square inch absolute, or 10 lb. per square inch above that of the atmosphere. In each half there are twenty-four rows of blades, or forty-eight rows in all, varying in length from 2¾ to 19 inches. Having done its work, the steam flows to the condenser through a rectangular orifice, 21 feet long and 12 feet wide, large enough for a crowd of men or a motor-car to pass through with ease.

This condenser has a surface of 39,300 square feet, and is built of steel plates, with all the stiffening girders on the outside in order to avoid interrupting the free flow of steam. The tubes are 1 inch in external diameter. This is rather larger than is usual, but there is less danger of them becoming choked by deposit than with smaller tubes. They are arranged in two "nests," one in the upper part and one in the lower part of the casing.

The circulating water enters the lower compartment through a rectangular opening, 5 feet 9 inches by 2 feet 2 inches, and after passing through both compartments flows out through a tube 4 feet in diameter.

Exhaust, Reducing, and Back-pressure Turbines

So much for high-pressure turbines. An additional merit of this form of prime mover lies in the fact that it is very efficient with a low pressure of steam.

There are no narrow ports as in the ordinary reciprocating engine, except at the point where steam is admitted, and the steam passes through openings of gradually increasing size on its way to the condenser.

The power that is obtained by increasing the vacuum in the condenser from 28 inches to 29 inches is greater than that obtained between 27 inches and 28 inches. Consequently, with a good air pump and condenser a turbine will give a good deal of power when fed with steam at or about atmospheric pressure. Either the impulse or reaction type may be used for this purpose, and the steam is usually obtained from the exhaust of reciprocating engines.

Mixed pressure turbines (Fig. 106) have two sets of wheels and blades in the same casing, but with different inlets for exhaust or live steam. Thus, in the power station of the Mersey Railway, which connects Liverpool with Birkenhead and other places in the Wirral peninsula, the main engines are 2,000-horse-power vertical reciprocating, and there is a 1,200-horse-power mixed pressure turbine which usually works on exhaust steam from the main engines. A governor prevents the speed rising above 1,800 revolutions a minute, but if for any reason the supply of exhaust steam becomes insufficient to maintain this speed, the governor opens a valve and admits live steam just to the extent which is necessary to maintain the speed. Such an arrangement is extremely valuable where there is a variable load, as is the case in winding engines, rolling mills, etc.

Another type, intermediate between the high-pressure and exhaust steam turbines, is known as a reducing turbine. It is used in paper mills and chemical works where a large quantity of low-pressure steam is required for heating purposes, and electricity for lighting and driving machinery. For various reasons boilers are most economical when producing high-pressure steam, and advantage is taken

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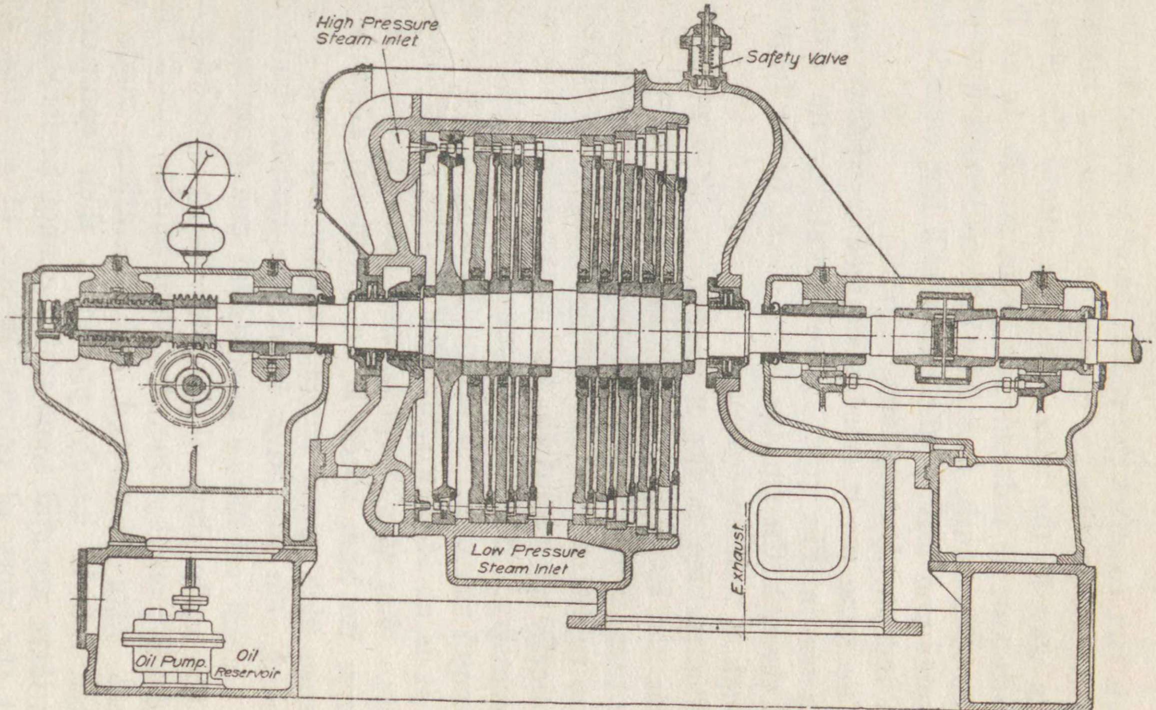


Fig. 106.—Mixed pressure Westinghouse-Rateau turbine

of this fact to effect the reduction of pressure to that required for heating by passing it through a turbine on its way to the vats. By this means the steam pressure can be reduced, say, from 200 lb. to 20 lb. on the square inch, furnishing a considerable amount of power and leaving the steam still hot enough for most industrial operations.

The same result can be obtained in another way, as shown in Fig. 107. Here the steam can either pass through the turbine or go direct to the heaters through a reducing valve.

The turbine is the most perfect form of steam engine for large powers. It has a low steam consumption, it occupies a relatively small space, and owing to the absence of reciprocating parts there is practically no vibration, and heavy foundations are unnecessary. Since the steam exerts a turning effect all round the wheel or drum, the motion is uniform, and it is an ideal machine for driving electric generators. For this purpose, and also for centrifugal pumps, its high speed is an additional advantage, because high speed enables weight and size to be reduced. On the other hand, the turbine demands the highest excellence in material and manufacture. In the early days there were many breakdowns. Gradually, one by one, and with infinite labour, the causes were discovered and alterations made in design which largely prevented their recurrence. But there are still some which cannot be forecasted. And the story of patient labour, of scientific and mechanical skill, of hope and disappointment and

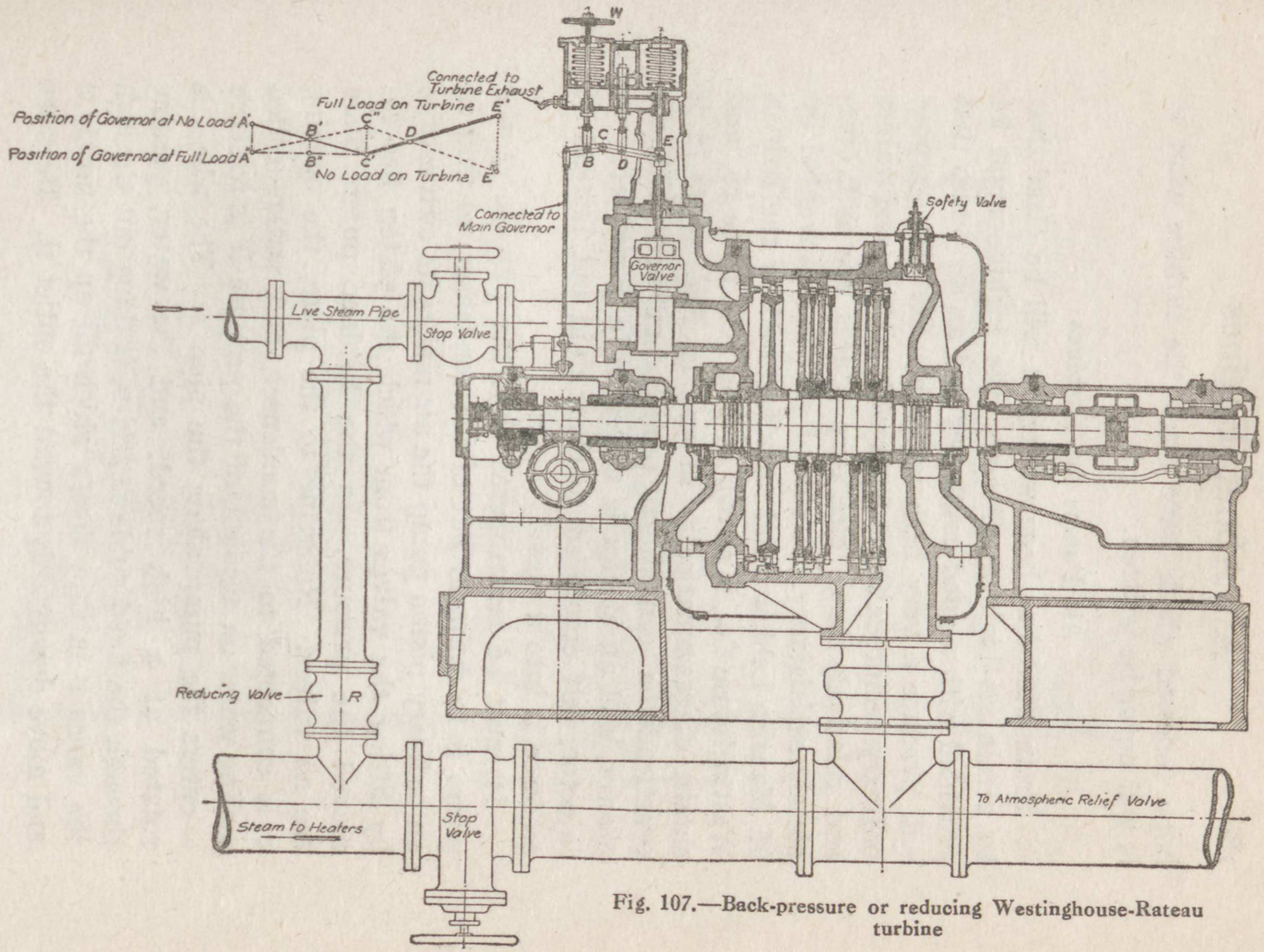


Fig. 107.—Back-pressure or reducing Westinghouse-Rateau turbine

hope renewed which have made the turbine what it is will never be written.

Air Pumps for Turbines

From what has been written it will be clear that to attain its highest efficiency the turbine must be provided with a good condenser and an air pump that will produce a very high vacuum. For this purpose ordinary reciprocating pumps with pistons and valves and relatively large clearance spaces are not completely satisfactory. A rotary air pump, invented by M. Maurice Leblanc, and manufactured by the British Westinghouse Co., is shown in Fig. 108, Plate 16, and shown diagrammatically in use in Fig. 109. It is practically a centrifugal pump combined with an ejector, and an ejector is the same in principle as an injector, but employed to draw fluid out instead of to force it into a vessel.

It must be remembered that the purpose of the pump is to draw air out of the condenser, so that in an ordinary piston pump the air makes its own escape by lifting the valves from which the piston has removed the pressure. In the Leblanc pump there are no valves. Referring to the plate, the opening C is connected to the condenser, and water—called sealing water on account of the purpose it is to serve—enters the pump along the pipe A. The wheel is rotated at a high speed, and the water, passing through the fixed guide nozzle B, is flung out through the vanes D in thin sheets which fill up the nozzle E and move downwards toward the outlet H. Between

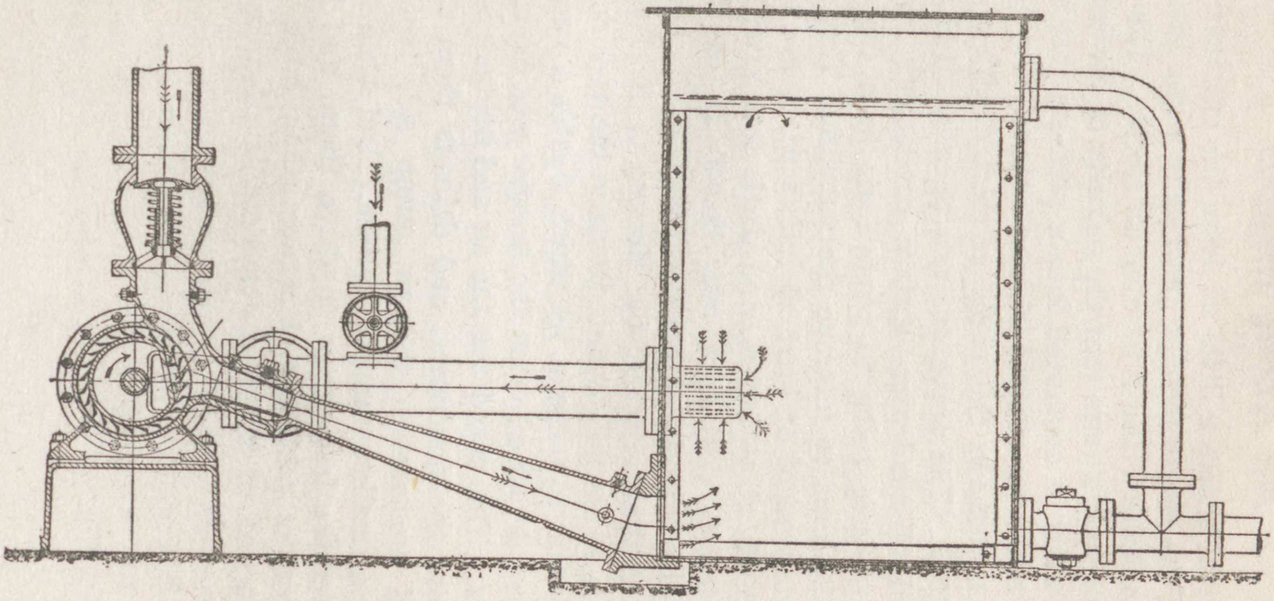


Fig. 109.—Rotary air pump with sealing tank

each pair of sheets a little air from the entrance C is trapped, the sheets forming practically water pistons, and the nozzles E and F forming an ejector. The outlet H is of such a form that the velocity of the issuing air and water is converted into a pressure just sufficient to overcome that of the atmosphere.

Fig. 109 shows the pump connected with a self-sealing tank. The apparatus can be associated with any kind of condenser—surface condensing or jet, its sole purpose being to remove air from the condenser and thus to improve the vacuum. They will give a vacuum of at least 28 inches when the barometer stands at 30 inches, and single sets have been constructed to deal with over 80,000 lb. or about 36 tons of condensed steam per hour.

The method adopted by Messrs. C. A. Parsons and Co. is to use an ejector. Between the turbine and the air pump is a steam jet which creates a vacuum in the way described when the injector was explained on p. 102. This withdraws the air and uncondensable gases from the condenser, and delivers them under increased pressure to the air pump side, thereby enabling a smaller pump to be used. And since small pumps require less power to drive them, and have lighter valves and less clearances than large ones this reduction of size is a considerable advantage.

CHAPTER VII

The Gas Engine

THE idea of an engine which should be self-contained, an engine which should need no boiler, is a very old one. Papin and others tried, at the end of the seventeenth century, to produce power by exploding gunpowder inside a cylinder and arranging for the piston to do work as it fell by its own weight. At odd times in the eighteenth century, and very frequently in the nineteenth century, men worked at the problem of the internal combustion engine, trying now gases and again highly inflammable volatile liquids. The Patent Office records bear witness to the ingenuity and persistence of these early inventors, and the history of applied science indicates their failures by naming Lenoir, a Frenchman, as the first to achieve any degree of success, in 1860.

Lenoir's engine was intended to use gas from the town supply, and its manner of working shows, by comparison with present-day engines, how feeble and uncertain was man's control over the forces which he sought to harness in his service. The cylinder, like that of the earlier steam engines, was set vertically, with the shaft above the upper end of the cylinder, and the piston was very heavy, lest by the explosion of a mixture of gas and air underneath it should be blown out of the top. This piston, moreover, was not connected to the shaft by a connecting rod and crank in the ordinary way. There was a connecting rod, but it was provided with teeth all the way along the upper half, forming a rack, and the shaft was provided with a toothed wheel into which the teeth of the rack fitted. When an explosion occurred the piston rose rapidly, and the rack, acting on the toothed wheel, caused the shaft to spin round. Having arrived at the top of its stroke, the rack disengaged with the wheel, fell away from it, and allowed the piston to return to the bottom of the cylinder without affecting the rotating shaft. During this return stroke the exploded gases were swept out through the exhaust valve, and in the interval between the strokes a heavy flywheel kept the shaft in motion.

Crude in design, cumbrous in action, and irregular in speed as the Lenoir engine was, a great many were made before, in 1876, Dr. Otto invented a far more perfect form—the parent of the gas engine of to-day. Its mode of operation is shown diagrammatically in Fig. 110. The first outward stroke of the piston draws in a mixture of air and gas, the valves being opened just long enough for the right proportion of each to enter. As the shaft continues to rotate the piston makes its return stroke, and as the gas and air valves are now closed the mixture is compressed. The efficiency of the engine increases with the degree of compression, but it must not be too high or the explosion will take place prema-

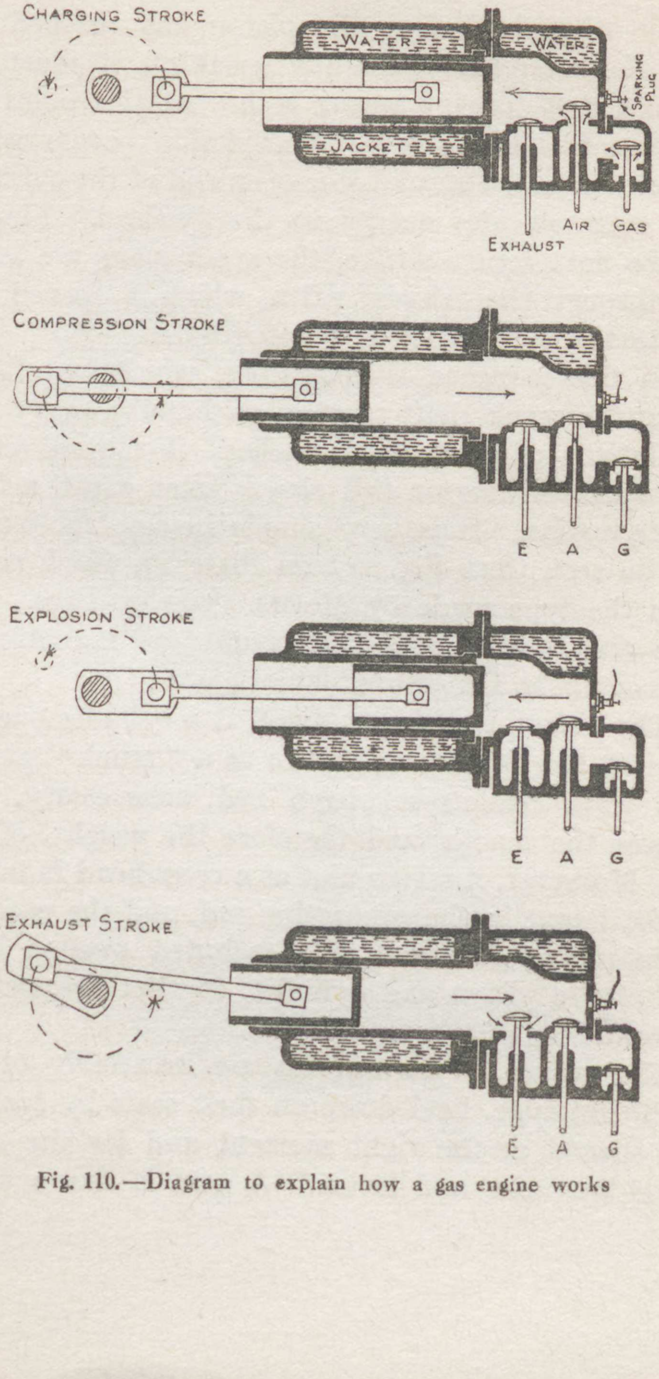


Fig. 110.—Diagram to explain how a gas engine works

turely—that is, before the piston has reached the end of its stroke. Generally speaking, it must not reach 125 lb. on the square inch. At this point the mixture is ignited, and an explosion occurs which drives the piston towards the open end of the cylinder, and communicates energy to the flywheel. Finally, on the next return stroke, the spent gases are swept out through the exhaust valve, which is opened just before the former stroke is completed.

In this sequence of operations, which is called a cycle, the crank shaft receives an impulse every two revolutions or every four strokes. For that reason an engine working on this plan is often called a four-stroke engine. It is very simple in construction, as will be seen from Fig. 111 on Plate 17, which represents the type made by Messrs. Crossley Bros., who were the first firm in this country to manufacture engines under Dr. Otto's patent.

The piston, it will be noticed, is a cylinder open at one end, the type being known as a " trunk " piston. This form renders a piston rod unnecessary, and reduces the length, and therefore the weight, of the bed. Moreover, it serves also as a cross-head in taking up the thrust in the connecting rod, and the pressure produced in this way is distributed over a large area of the piston and cylinder, so that the wear is uniform.

The valves of gas engines are invariably of the mushroom type, held down on their seats by springs, and opened at the right moment and for the right period by cams and levers. A cam is like a small

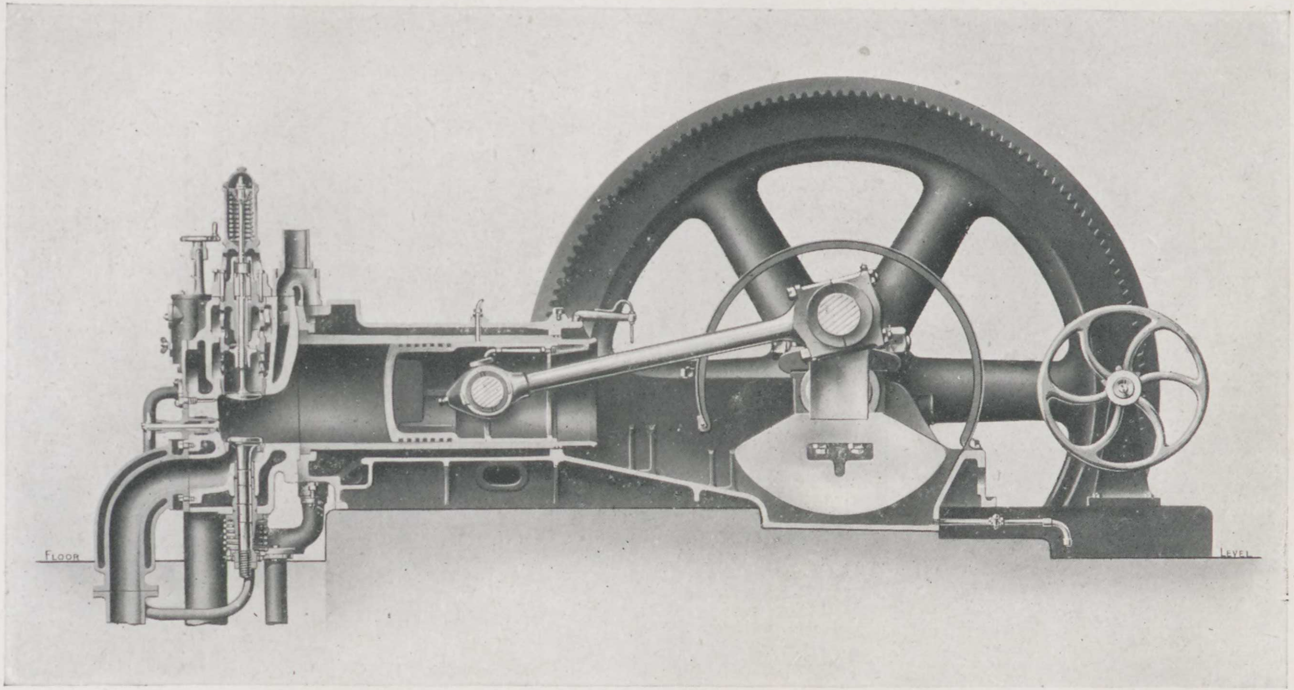
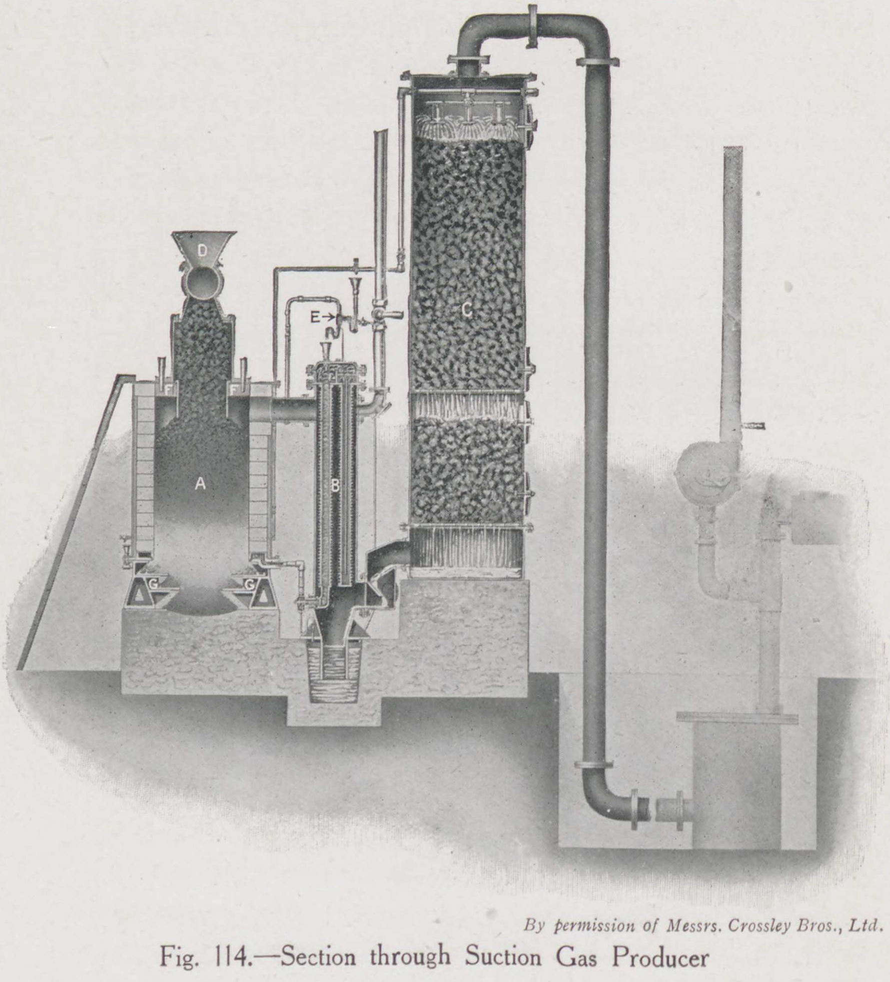


Photo by permission of Messrs. Crossley Bros., Ltd.

Fig. 111.—Section through a Gas Engine

PLATE 18



By permission of Messrs. Crossley Bros., Ltd.

Fig. 114.—Section through Suction Gas Producer

eccentric without the strap. One for each valve—air, gas, and exhaust—is fixed on a shaft parallel to the engine bed, and driven from the main shaft by bevel wheels or by worm gearing at half the speed. This ensures that each valve shall be opened once in every two revolutions of the main shaft. In small engines the cams may be in direct contact with the valve spindles, but the usual plan is for the motion to be communicated through levers. Other kinds of valve have been tried, but none are so satisfactory as these. Slide valves do not work well under the high temperatures which occur during explosion, and rotary valves are not easily adjusted for wear.

Ignition of the mixed gases in the original Otto engine was effected by means of a hot tube. The tube was closed at one end, the open end communicating with the interior of the cylinder. It was kept hot by a flame which played upon it all the time the engine was working. At each compression stroke the mixture of gases was forced into the tube and became ignited. Sometimes the ignition occurred prematurely, but not as a rule, because there always remained some of the spent gases from a previous explosion. For many years it was the only plan which worked satisfactorily, but in recent years it has been replaced entirely by the electric spark.

For producing the electric spark there are two methods—an induction coil and a magneto machine or small dynamo. Both are good, but the magneto is cheaper than a really good coil and less liable to get out of order than a cheap one. Moreover, for the coil accumulators are necessary, and they must be kept charged or a duplicate set must be held in readiness. For large engines, where the cost of accessories is less important, the arrangement devised by Sir Oliver Lodge is frequently used. This gives a very powerful spark, which is certain and effective in its action. By whatever method the electricity for the spark is generated, it is produced inside the cylinder between the ends of two wires fixed in a sparking plug. This is easily removable for cleaning or renewal.

The gas engine needs to be governed just as a steam engine does, or it would "race" when the load was decreased or removed. The governor itself is practically the same as a steam engine governor, but the method by which it controls the speed of the engine may differ. Many of the early gas engines were fitted with a "hit and miss" governor. Between the cam and the gas valve spindle was a small rod which when the engine ran too fast was lifted out of the way. When this occurred the gas valve did not open, no charge entered, and no explosion occurred.

Missing a whole explosion is rather a drastic method of reducing the speed, especially when there is only one explosion in two revolutions; and the modern practice is to employ a "throttling" governor, which controls very delicately the quantity of gas drawn into the cylinder on each occasion. One of the neatest devices for effecting this is that adopted by Messrs. Crossley Bros., and shown in Fig. 112.

It will be noticed that only one valve is used to admit both gas and air, that no additional throttle valve is used, and that the amount of gas and air entering is controlled at the moment of admission to the cylinder. The curved bar pinned to the top of the valve spindle acts as a lever, the fulcrum of which is a "radius rod," actuated by the governor. The amount of movement given to one end of the curved bar by the cam is constant; but as the speed of the engine varies the radius rod swings to right or left, alters the length

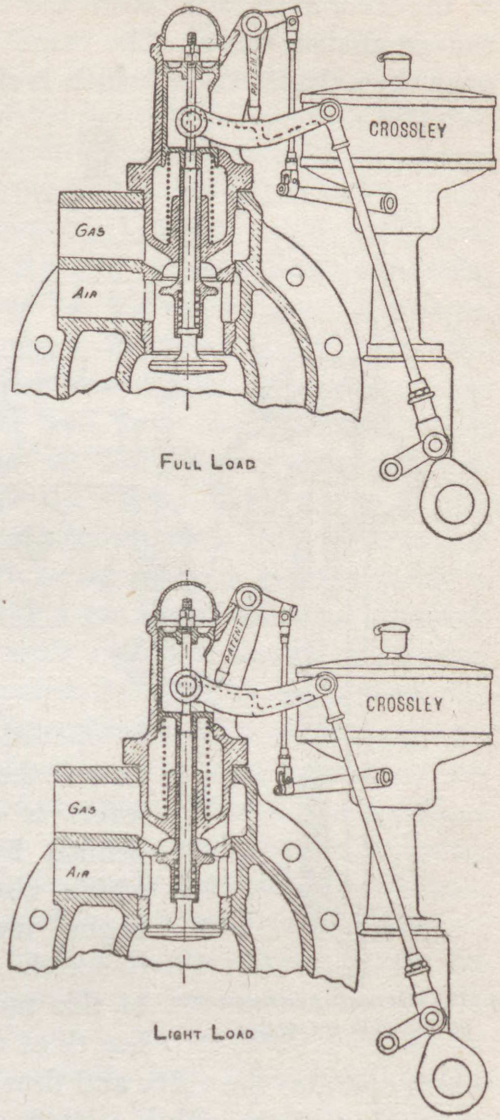


Fig. 112.—The governing arrangement of a Crossley gas engine

of the lever arms, and varies the extent of opening of the admission valve. The same cam also serves to open the exhaust valve, which is situated immediately below that by which air and gas are admitted.

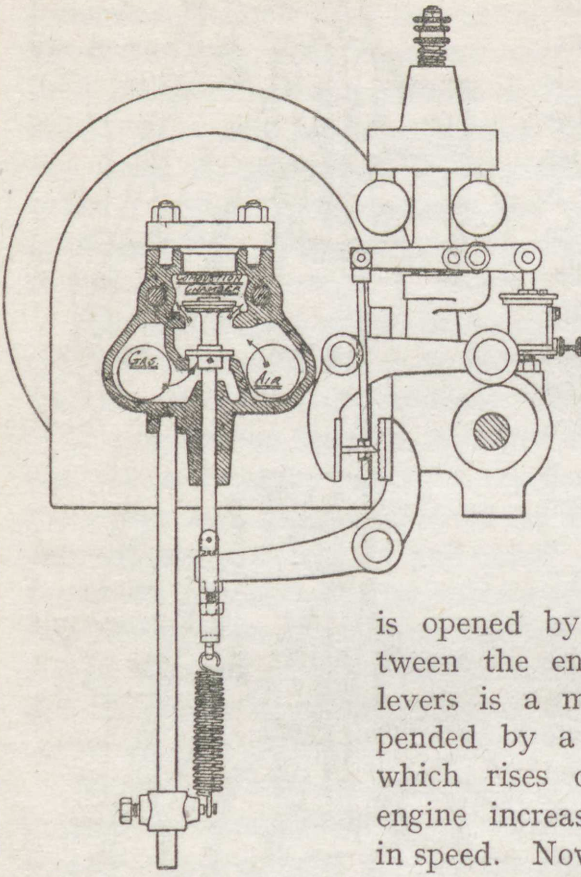


Fig. 113.—Governing arrangement of National gas engine

Another very interesting method of governing is that adopted on the National gas engine and illustrated in Fig. 113. The cam operates one bent lever, and the valve is opened by another. Between the ends of the two levers is a metal plate suspended by a rod to a lever which rises or falls as the engine increases or decreases in speed. Now the movement of this metal plate alters the length of one arm of the lever which operates the valve and thus controls the amount of opening of the valve. Both (Figs. 112 and 113) are very pretty pieces of mechanism.

While the cylinder of the steam engine had to be kept warm by means of a steam jacket, that of the gas engine must be kept cool by means of a water jacket. The walls of the cylinder are double, and cold water is maintained in constant circulation—sometimes naturally and sometimes by the aid of a pump. If this were not done the valves would soon wear out, and the piston would expand and jam owing to the heat produced by the explosions. Moreover, the combustion chamber—the small space behind the piston into which the mixed gases are compressed—would become so hot that the mixture would explode immediately on admission, with the certainty of damage to the engine, and probably also injury of the man in charge. With the steam engine the absence of steam in the jackets means merely a loss in efficiency; with a gas engine even an interruption to the flow of water means a smash. And even when the cooling system is working effectively the gases which escape from the exhaust are hot enough to render very useful service. In some cases they are employed to produce hot water. Thus about 2 gallons of boiling water can be obtained for each horse-power per hour, and the waste heat from a 50-horse-power engine will produce 100 gallons per hour.

Having now learnt how a gas engine works, let us see what advantage it possesses over the steam engine. In the first place, it occupies less space. No boiler is required, and the heat is produced in the same chamber in which it is to be utilised. There is no loss of heat by radiation from the surface of boiler or steam pipes, and the cost of these, together with stop valves and other accessories, is saved. It is cleaner, and though coal and ashes have to be handled at the gas works, this can be done on a large scale which justifies employment of labour-saving machinery. The gas engine utilises from 25 per cent. to 30 per cent. of the heat obtainable from the fuel, while the steam engine converts less than 15 per cent. into useful work. But town gas is rather an expensive fuel, and for many years the engines were small, so that their use was in consequence limited. How it has developed during the last thirty years deserves a separate section.

The Food of the Gas Engine

The disadvantages of the early gas engines were their dependence upon a supply of town gas, the cost of this form of fuel, and the fact that the piston received only one impulse for two revolutions of the shaft—that is, for one-quarter of the time the piston drove the shaft, and for three-quarters of the time the shaft drove the piston. Consider the fuel question first.

Coal gas is made by heating coal out of contact with air in closed retorts. The result is :

(*a*) Gas.
(*b*) Ammoniacal liquor.
(*c*) Tar.
(*d*) Coke.

In order to obtain gas of the highest illuminating value the process of distillation cannot be carried out in the cheapest way. When the gas engine was first introduced—and, indeed, for many years afterwards—the value of coal gas lay in its illuminating value, so that it was a dear fuel. But in 1878 Mr. J. Emerson Dowson showed not only how to produce a cheaper gas, but also how this gas could be produced wherever it was required, so that a town supply was no longer necessary. The principle was this: that if coal burns in an ample supply of air it forms carbon dioxide which is no longer inflammable, while if the air supply is limited, carbon monoxide is formed, and this gas will burn with a further supply of air, producing carbon dioxide. Thus, in a fairly deep fire, red hot throughout, a lambent blue flame will frequently be seen playing over the top. The oxygen in the air entering the lower part of the grate produces carbon dioxide, and this, passing through the red-hot carbon in the upper part, takes up carbon and forms carbon monoxide. Those who have learnt a little chemistry will recognise the equations corresponding to the two processes:

$$C + O_2 = CO_2$$

$$CO_2 + C = 2CO$$

The nitrogen, which forms four-fifths by weight of the atmosphere, passes out unchanged with the carbon monoxide, and the mixture is known as *producer gas*.

The apparatus consisted of a deep cylindrical furnace charged with coke fed by a hopper from the top. It was of sheet iron, lined with firebrick, and there were dampers at the bottom to regulate the supply of air, and poker holes in the top to enable the red-hot fuel to be stirred occasionally. At the meeting of the British Association for the Advancement of Science, at York, in 1881, it was shown driving a 3-horse-power gas engine, and created a great deal of interest. It occupied no more space than a boiler and produced no smoke, burning the coke completely away to fine ashes, which were raked out at the bottom from time to time.

A gas with a greater calorific, or heating value, free from nitrogen, can be obtained by passing steam through red-hot coke. The result in this case is a mixture of carbon monoxide and hydrogen. Unfortunately, the steam would soon put the fire out, so the process has to be stopped every few minutes while air is blown in to raise the temperature again. In spite of the fact that the process is intermittent, *water gas*, as it is called, has been made in gasworks for many years for mixing with coal gas. The carbon-dioxide gas, formed when air is blown through, is allowed to escape into the atmosphere, and the water gas alone is employed for this purpose. To the student of chemistry the equation

$$C + H_2O = CO + H_2$$

will again be familiar.

A tremendous advance was made in 1889 when Dr. Ludwig Mond found that if air and steam were used together a mixture of producer gas and water gas was obtained, which was better than producer gas, while the process could be worked continuously. He found, moreover, that small coal, which is cheaper than coke, could be used, and that the ammoniacal liquor from which a valuable fertiliser is made, could be recovered. The sale of this by-product reduced the cost of fuel in some cases to 3s. 6d. a ton, and it was evident that here was a source of power which rendered gas engines independent of the town supply. Engineers began at once to study the possibilities of large engines, and whereas engines of 100 horse-power had been the largest before they soon began to be made of 500 and 600 horse-power.

But improvements in gas producers did not cease with Mond's invention. In the earlier ones the air and steam were forced in, and the engine had to take what came, whether the load and its appetite were large or small. But in the modern producer the engine sucks gas just as fast as it requires it, like a baby with a bottle, and there is no fear of choking.

In the sectional illustration of one of Messrs. Crossley Bros.' suction gas producers (Fig. 114 on Plate 18) it will be seen to consist of three parts: the producer proper or gas generator A, the vaporiser or steam raiser B, and the scrubber or gas cleaner C. The gas generator is a steel casing lined with fire brick and having a hopper on the top through which the fuel is admitted. The vaporiser consists of a metal box containing a number of tubes which have "gills" in order to encourage the transfer of heat. The hot gases from the producer pass through the box, and as water flows through the tubes the steam which is necessary for the process is generated. The gases then pass up through a tower filled with lumps of coke over which water is continually flowing. In this way they are freed from dust, which, if it entered the engine, would choke up the valves and lead to undesirable wear. As the coke in the lower portion of the scrubber comes first into contact with the gases it needs to be renewed more frequently than that in the upper portion. Each portion, therefore, rests on a separate tray, so that one can be renewed without interfering with the other.

One great advantage of the suction gas producer, as compared with the earlier form, lies in the fact that the pressure inside is less than that of the atmosphere. Carbon monoxide is an extremely poisonous gas, and is exceptionally dangerous because it has no smell. There is no simple chemical test by which its presence in the air can be detected, and it is a common plan to use a bird or a mouse as a sentinel. These little creatures are much more sensitive than human beings, and fall into a stupor long before a man would be affected. But with a suction gas producer there is practically no danger.

The fuel employed may be anything that will burn. Good results are obtained with coke, but the best are given by anthracite. From this fuel at 30s. a ton, gas equal in heating value to the best town gas can be produced at 11d. per thousand cubic feet. The stand-by losses are also small. When the engine is not working, just sufficient air is allowed to pass through to keep the fire in, and the coal consumed in a 100-horse-power plant during an all-

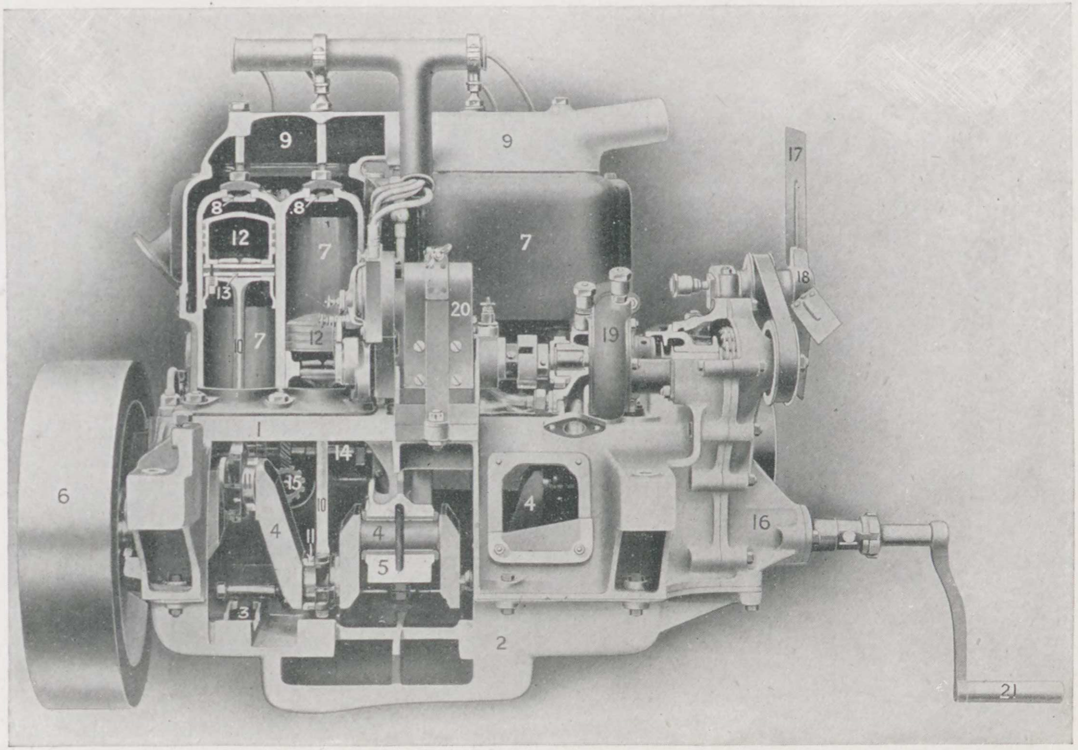


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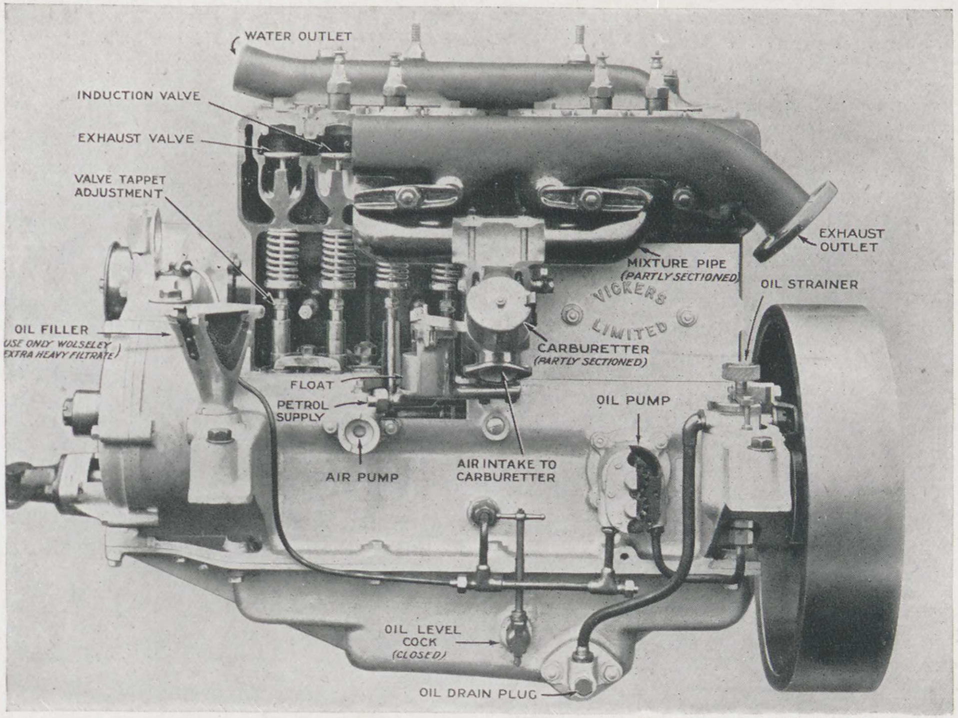
Fig. 121.—Section of a 4-Cylinder Motor

1, Crank case; 2, Oil base; 3, Oil troughs for connecting rods; 4, Crank shaft; 5, Crank shaft bearing blocks; 6, Fly-wheel; 7, Cylinders; 8, Cylinder plugs; 9, Water outlet pipe; 10, Connecting rods; 11, Connecting rod bearings; 12, Pistons; 13, Gudgeon pins; 14, Cam shaft; 15, Oil pump driving wheel; 16, Engine chain cover; 17, Fan blades; 18, Fan centre and pulley; 19, Water pump; 20, Magneto machine; 21, Starting handle



By permission of Wolseley Motors, Ltd.

Fig. 122.—Section of a 4-Cylinder Motor, showing Carburettor and Oil Pump

night stoppage of twelve hours amounts to less than 40 lb. The plant can be started again in from ten to fifteen minutes.

When bituminous coal is used the plant must be fitted with a tar extractor, otherwise the scrubber would soon get choked up, and the tar would get into the engine and cause trouble. Provided this precaution is taken, then with fuel at 10s. a ton the cost of power amounts to only about one-sixteenth of a penny per horse-power per hour. It is not necessary, however, to use coal at all. Wood waste, sawdust, bark, spent tan, coir dust, coconut shells, mealie cobs, rice husks, sugar-cane refuse, cotton seed, olive refuse, and other material that tends to accumulate and prove a nuisance may be burnt in a gas producer. In this way many industries, especially those concerned with the preliminary processes of manufacture from the products of the soil, can obtain power practically at no cost for fuel, and at the same time get rid of stuff which can only be destroyed by burning. From being tied to the town the gas engine has spread to the outskirts of civilisation, lightening the labour of the pioneer, increasing his output, and providing more cheaply those things for which people in the Old Country have need.

During the last twenty years a new source of food for gas engines has been discovered in which fuel is not specially burnt for the purpose at all. The process of obtaining iron from its ore consists essentially in heating the oxide of iron with carbon in the form of coke, using a blast of air to raise the temperature. The gas, which was formerly allowed to escape freely from the top of the furnace, contains rather more than 30 per cent.—chiefly carbon monoxide—which is combustible, and at night the blaze could be seen for miles around. It was suggested by the late Mr. B. H. Thwaite in 1892 that this waste should be prevented, and the gas used in gas engines. For every ton of coal charged into the furnace more than 120,000 cubic feet of gas is produced, and, taking the whole country, there is sufficient energy to yield 750,000 horse-power continuously all the year round. Three years later, in 1895, the Glasgow Iron Company adopted the suggestion, and their example was followed by many other firms, especially in Germany and the United States.

The Growth of the Gas Engine

When, after 1889, cheaper gas became available the problem of the large engine arose. There were two principal difficulties. One lay in constructing the cylinder, and the other in keeping the piston cool. The gas engine cylinder is rather a complicated casting, and owing to explosions inside and cooling water outside great strains are set up, so that it is liable to crack. The difference of temperature of two points an inch apart may be 50°, and even though iron has not a high rate of expansion, this difference between points so near together sets up very severe strain. Engines giving 1,000 horse-power for one cylinder have been made, but they are not numerous, and for anything over 200 horse-power engineers usually prefer to employ two or more cylinders. English makers for a long while arranged them side by side, while Continental firms preferred the horizontal tandem arrangement with one cylinder behind the other.

All large gas engines are started by means of compressed air, which is produced by a separate engine of relatively small size. The flywheel is barred round until the piston and valves are in the correct position for starting, then compressed air is admitted, and as soon as the engine has fairly started the compressed air is cut off and the gas supply turned on. The absolute necessity of some such aid as this for large engines will be realised by anyone who has seen even a 20-horse-power engine started by hand. It is due both to the fact that with only one explosion in four strokes a very heavy flywheel is necessary to equalise the motion, and to the force required to compress the charge before an explosion can take place.

When very large cylinders are necessary they are often cast in four or more parts and then bolted together before being bored. All castings, and especially large ones of complicated form, are subject to strains which are set up during the process of cooling in the mould. This strain would disappear in time, especially if the whole of the "skin" could be removed. But the shape of a gas engine cylinder is such that it cannot be machined all over, and while the strain is there it is a source of weakness.

Again, in engines of small size the water jacket is effective in keeping the piston cool, but not in a large one. The central portion of the end, continually exposed to explosions, is too far removed from the cooling influence of the jacket to be affected. It is not only liable to excessive stresses, but the temperature may rise so high that it jams in the cylinder. It is necessary, therefore, to make the head of the piston hollow and to keep it supplied with water by means of jointed pipes which follow the motion of the piston. This all adds to the initial cost and possibility of breakdown. Up to a certain point the rise of the big gas engine was rapid, and then unexpected difficulties such as these held it back, so that it has failed to compete with the steam engine for higher powers.

Increased power is not obtained, however, merely by an increase in size, but also by devices which secure that there shall be more than one explosion every two revolutions. In 1881, when the gas engine was yet in its infancy, Mr. Dugald Clerk patented a method of obtaining an explosion for each revolution; but the Otto cycle had too strong a following, and no one would take the matter up. Years afterwards Koerting and others in Germany revived the two-stroke engine and met the demand for large powers without a corresponding increase in size. To understand how this is done, recall for a moment the operations in the Otto cycle. In four successive strokes there are (1) charge drawn in, (2) compression, (3) explosion, (4) exhaust. In order to provide for an explosion every revolution, two of these operations must be carried out in such a way that they do not occupy a stroke, and this is achieved by arranging ports in the cylinder walls which shall be uncovered by the piston on its outward stroke. Through these ports a blast of compressed air is driven, which sweeps out the waste gases and leaves sufficient air for the next explosion. Towards the end of the stroke gas is admitted, so that by the time the piston is ready to return the new charge is there to be compressed.

From the two-stroke to the double-acting engine is only a step. Using a piston of the ordinary type, like that of a steam engine, with a piston rod and cross head, and putting a front cover on the cylinder, the operations of a two-stroke engine can then be performed both in front of and behind the piston. The engine then looks—and acts—more like a steam engine, but explosions replace the steady, persistent force of expanding steam.

The large gas engine has been an attractive field for inventors, and numerous attempts have been made to overcome the disadvantages produced by high temperatures, suddenly applied pressures, and the great weight of the parts. In several engines, for example, the explosion does not take place between the fixed end of a cylinder and a moving piston, but between two pistons, free to move in opposite directions and each communicating its energy to the same or a neighbouring crank. Attempts have also been made to produce a gas turbine, but so far the problem has defied solution. There is, however, one invention which deserves description by reason of its simplicity, its originality, and its success. And that is

The Explosion Pump

The explosion pump was invented by Mr. H. A. Humphrey, who was one of the pioneers of the large gas engine in Great Britain. Suppose a large U-tube open at both ends, as in Fig. 115, to be filled with water or any other liquid, and suppose pressure to be suddenly applied to the surface of the water in the left-hand limb. The liquid will fall in that limb and rise in the other, and as soon as the pressure is released it will flow back past its original level until it rises nearly as high in the left-hand limb as it reached, under pressure, in the right. But it will not stop there. It will swing again in the direction in which it was originally driven, and then back, several times, the swing gradually decreasing in extent until the liquid comes to rest. The internal friction of the liquid, the friction on the walls of the tube, and the work done each time in pushing back the atmosphere gradually destroy the motion.

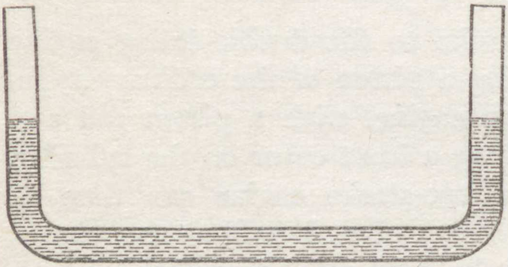


Fig. 115.—Diagram to explain principle of Humphrey pump

Now this swing or vibration, or oscillation, is exactly like the swing of a pendulum. So long as the swings are not very large their magnitude does not matter: they each take the same time. But for our purpose the time of swing is not of much consequence. The essential fact is that if you give water in a tube of this form a push, it will always come back again. And that is just what a gas engine piston linked up to a crank will do. So that this column of water, once it is set in vibration, will draw in, or

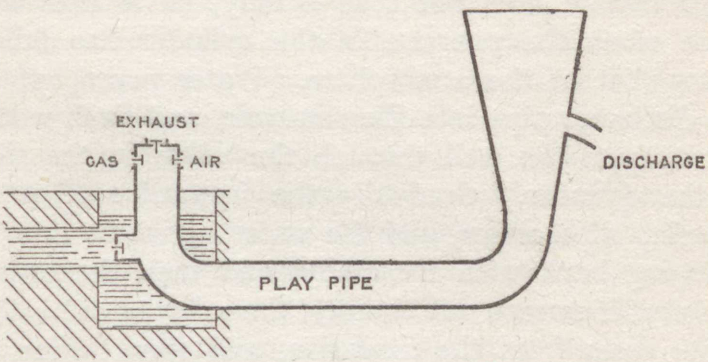


Fig. 116.—Diagrammatic section of the Humphrey pump

compress, or expel gases just like the solid piston of an ordinary gas engine.

At the Chingford Reservoir of the London Water Board there are five pumps constructed on this plan and represented diagrammatically in Fig. 116. The horizontal portion, called the play pipe, is of cast iron, 6 feet in diameter and 60 feet long. The left-hand limb, forming the pump proper, is 7 feet in diameter and 10 feet long. It is provided (*a*) with gas and air inlet valves, and (*b*) with exhaust valves, in the upper end, and with a water inlet valve in the side to admit water from the well into which it is built, and which is supplied with water from the River Lea. The right-hand limb is open and has a discharge pipe through which water flows into the reservoir.

The mode of operation is as follows: A mixture of gas and air is exploded above the surface of the water in the cylinder, the water being driven forward along the play pipe and up into the right-hand limb. When once a large body of water is set in motion it does not stop readily, so it does not cease when the pressure in the cylinder has fallen below that of the atmosphere. Water pours out of the discharge pipe into the reservoir, and fresh water enters from the well through the valve in the side of the cylinder. Gradually the forward motion in the play pipe ceases, and the water begins to return. Swinging back with increasing and then decreasing velocity, it sweeps out through the exhaust valve the waste gases from the explosion, and then begins to flow forward again towards the reservoir. During this stroke gas and air are admitted to the cylinder, the water flows back and compresses them, an explosion occurs, and the whole cycle of operations is repeated.

While the pump is at work no attention is required. There are no rubbing surfaces to be lubricated, the valves are self-acting, held down on their seats by springs, and locked when not in use by the action of a small water motor. Unlike the ordinary gas engine, all the strokes in a cycle are not of the same length. They have different duties to perform and are made under different conditions. So long as the supply of gas does not fail and the ignition device is in order the pump will go on working week after week, month after month, year after year, delivering with unfailing regularity from 12 to 14 tons of water per stroke. Four of the Chingford pumps are capable of lifting 40,000,000 gallons through a height of from 20 to 25 feet every twenty-four hours.

Sidney Smith describes an old woman who took a cottage on the west coast that was liable to be invaded by the sea; and when the waves came rolling in she stood at the door, broom in hand, resolutely prepared to sweep back the Atlantic Ocean! She would have been safer had she lived to-day, for she might have dug a deep ditch and emptied it between tides by the aid of an explosion pump.

But there is a more important rôle for this pump if tradition and vested interests do not stand in the way. Suppose a town with a hill close at hand and a lake or river curling round the lower slopes. With a Humphrey pump, working under more ideal conditions of constant load than is possible with any other form of prime mover, the water could be pumped up into a reservoir on the top of the hill, and thence it could flow down, through pipes, to drive water turbines. And these turbines, constituting the most perfect form of drive for generating electricity, would be coupled to dynamos, providing all the light and heat and power that the town required. Such is an ideal arrangement which the Humphrey pump has brought within the range of practicability.

CHAPTER VIII

The Petrol Motor

HARDLY any other invention has had such an important and immediate effect upon habits of life and methods of warfare as the petrol motor. For more than a century men had dreamed of a horseless carriage propelled by mechanical power, and their efforts had all fallen short of success for want of an engine at once light, reliable, and sufficiently powerful for the task. For twenty years a few daring spirits made perilous experiments in aerial flight, but lacked an engine light enough to be mounted on their machines. During several hundred years there had been isolated attempts to construct a submarine boat, but no means of mechanical propulsion were available which could be used under water. The same space of twenty years witnessed a new method of locomotion on land, and saw man acquire the power of navigating both the ocean of air and the still depths of the sea.

The early inventors of internal combustion engines did not confine their efforts to the use of gaseous fuel, though it was by this means that success was first attained. They tried various liquids and devised all sorts of contrivances to get these liquids to burn. But it was not until 1884 that the difficulties were overcome. In that year Gottlieb Daimler, who had been manager of Dr. Otto's gas engine works in Germany, patented the engine which is the parent of the petrol motors of to-day.

Petrol, or gasolene, as it is called in America, is a constituent of petroleum, which is pumped up from wells in the United States, Canada, Mexico, the Caucasus, Rumania, Persia, and other parts of the world. When heated in retorts it gives off vapours, and the temperature at which it boils rises gradually. By collecting the materials at different temperatures the following are obtained :

(*a*) Gases which liquefy at about the temperature of ice.

(*b*) A clear colourless light oil, known as naphtha or mineral naphtha, to distinguish it from that obtained by the distillation of wood.

(*c*) A yellow oil used in lamps and called kerosene or paraffin.

(*d*) Oils useful as lubricants.

(*e*) Paraffin wax.

(*f*) Coke, pitch, or asphalt.

When the naphtha is again heated, the portion which boils away first is gasolene or petrol, and it is this substance which is used in small internal combustion engines. In spite of the source it is *not* oily. It is clear, colourless, easily converted into vapour on heating, and both the liquid and the vapour are highly inflammable.

In order to form an explosive mixture with air, the petrol must either be vaporised or in the form of a fine spray, and the first main difference between a petrol engine and a gas engine is the necessity, in the former case, of what is called a curburettor. A typical one is shown diagrammatically in Fig. 117. It consists of a small vessel into which petrol flows by gravity from a reservoir at a higher level. Inside is a float, attached to levers and a needle valve in such a way that when the float rises beyond a certain point the valve is closed. By this device the petrol in this chamber is always at the same level, and the pressure under which it flows along the passage to the nozzle is always the same. The nozzle is in a space to which air has free access, and which is warmed—at any rate, when the engine is running—by a surrounding jacket of hot water from the cylinder jackets or hot gases from the exhaust. In the cold, when starting, the petrol leaves the nozzle in the form of spray, but when running it is rapidly vaporised and mixed with the air also drawn in by the suction of the engine. Ordinarily, in the type of carburettor shown, the air needed for combustion enters the orifice at the bottom, but when running at high speed additional air is obtained through the small valve on the right.

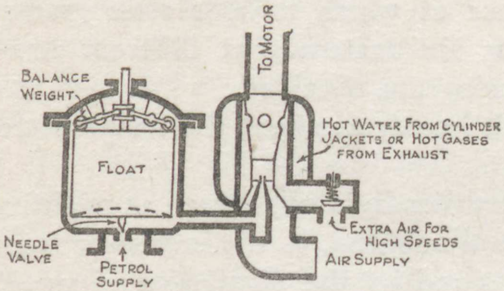


Fig. 117.—Diagrammatic section of a carburettor

Apart from this contrivance there is no difference in principle between gas and petrol engines; but in compactness and lightness of construction they are completely unlike. Generally, too, the petrol engine is wholly enclosed in order to exclude dust and dirt. A general idea of the arrangement of parts and their interdependence will be obtained from Fig. 118, which shows the position of the piston and valves at a certain stage of the Otto-cycle. It will be observed that the cylinder is water-jacketed in order to prevent the temperature rising beyond about 185° Fahr. The water for this purpose may circulate naturally by the heating effect of the cylinders, or it may be pumped through. After leaving

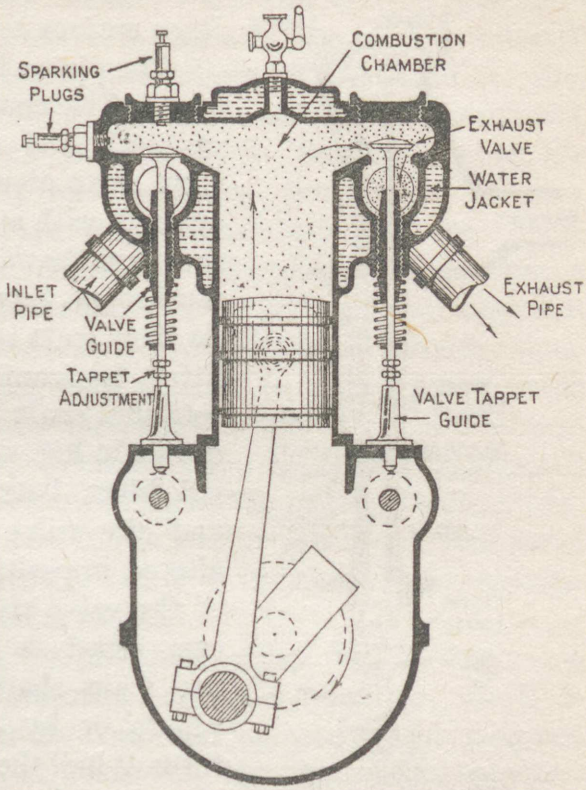


Fig. 118.—Diagram of petrol motor

the engine it passes through a great length of tubing called a radiator, in which it is cooled. The cooling effect is greatly increased by thin "fins" fixed to the tubes, and offering a large surface to the air.

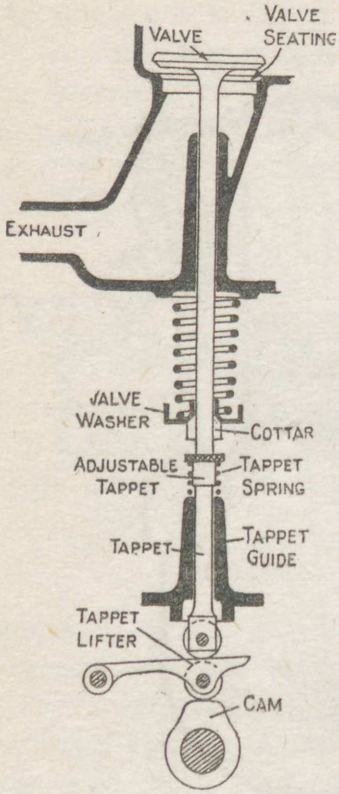


Fig. 119.—Adjustable valve tappet

The piston is of the trunk type. The connecting rod is of steel, and is of such a form as to give the requisite strength with maximum lightness, and the valves are of the mushroom type, held down on their seats by springs and lifted by cams fixed on a rotating shaft or shafts as shown in Fig. 119. The tappet lifter, between the cam and the valve rod, can be altered in position as the end of the valve rod wears. The cam shaft is driven from the main shaft by toothed wheels or by a chain, and turns at half the rate. Originally the inlet valve was not operated by a cam, but was held down by a rather weak spring and opened by suction of the engine. The cylinder is bolted directly to the crank case, which may be of thin malleable iron or aluminium alloy. Oil is supplied to the rubbing surfaces by a pump and flows into crank case.

In the early engines the explosive mixture was fired by a hot tube, but with the improvement of electrical apparatus this has been completely replaced by the electric spark. This is produced between the ends of a rod and one or two wires of nickel, nickel-steel, or platinum, fixed in a plug which is screwed into the end of the cylinder. The rod down the centre is insulated from the metal body by mica washers. Sometimes, for high speeds, two sparking plugs are used to ignite the explosive mixture at two points and secure a more rapid explosion. If, for example, an engine is running at a thousand revolutions a minute, then, since there are two strokes to a revolution, each stroke takes only three-hundredths, or ·03 of a second. The explosion, therefore, must be extremely rapid if it is to have any effect upon the piston, which, immediately it has passed the end of the stroke, will move away at an average rate of a thousand feet a minute, or nearly 17 feet a second.

The spark is produced either by an induction coil and accumulator or by a magneto, which is really a small dynamo having permanent magnets instead of electro-magnets for the field magnets. The armature is wound to give a high-tension current, and the magneto is driven from the main shaft. The spark is produced by a metal stud on a rotating ebonite disc making contact with a fixed stud, and in view of the high speed of the piston it must be accurately timed. For if the explosion takes place before the piston has finished its stroke a "back fire" occurs and the engine reverses. Usually the "timing" can be varied. In order to avoid a "back fire" when starting, it should be retarded; but when the engine is running at full speed an increase of power is obtained by advancing the spark.

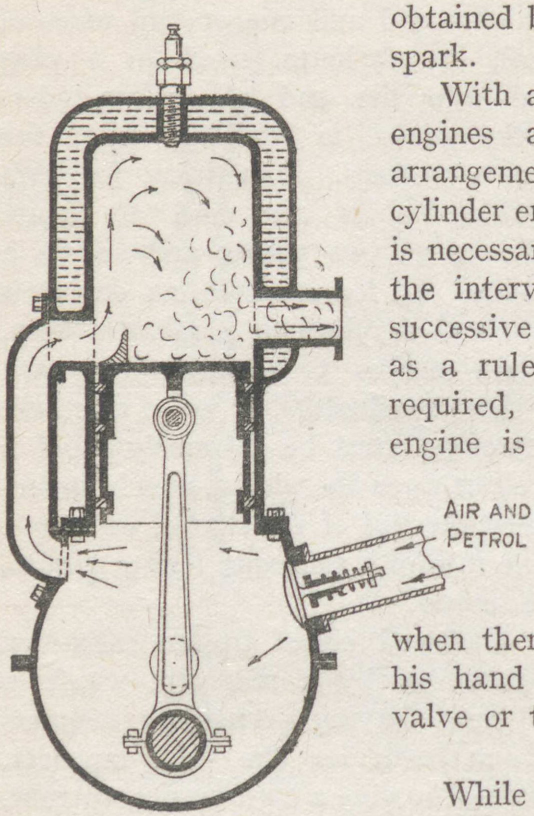


Fig. 120.—Diagram of two-stroke petrol motor

With all single-cylinder engines and with some arrangements of double-cylinder engines, a flywheel is necessary to carry on in the intervals between the successive impulses. But, as a rule, no governor is required, since the petrol engine is rarely used for any purpose in which the load is suddenly reduced at a time when there is no one with his hand on the throttle valve or the brake.

While the foregoing description covers the majority of petrol engines there are a few variations from general practice to which reference must be made. First as to valves. The poppet or mushroom type has the disadvantage of being noisy, especially if the "lift" is large, and there is a tendency for them to knock their heads off. In order to secure silence some engines have rotary valves, not unlike the Corliss valves shown in Fig. 76; others have piston valves; and in others there is a sliding, or sliding and turning, sleeve between the piston and cylinder, provided with holes which at the right moment coincide with ports in the cylinder itself. Thus the Itala and Daracq are rotary valve engines, and the Argyll and Daimler companies make sleeve engines. There is, further, an engine open at both ends with two pistons between which the explosion takes place.

But the most important departure in principle is the substitution of the two-stroke for the four-stroke cycle. The plan adopted is the same as in the two-stroke gas engine to which reference has already been made in Chapter VII., except that the crank case is employed as a sort of receiver. In the diagrammatic view in Fig. 120 it will be seen that the admission and exhaust ports are in the side of the cylinder and are opened and closed by the movement of the piston itself. As the crank case is air-tight the upward movement of the piston draws in the explosive mixture from the carburettor. The downward movement first compresses this charge, and then, when the port is exposed, forces it into the upper half of the cylinder, where it displaces the waste gases from the previous explosion. The return of the piston closes both ports and compresses the mixture. Explosion then takes place and the whole process is repeated, the piston thus receiving an impulse for every revolution of the crank. We can now leave the general principles and proceed shortly to examine engines for motor-cars, motor-boats, and aeroplanes.

The enormous extension of motor traffic during the last fifteen years has made heavy demands upon the world's supply of petrol, and the price of this fuel rose from 8d. to 1s. 9d. a gallon even before the war. It was natural, therefore, for owners of petrol engines to look around for a cheaper fuel, and among those most easily obtainable were paraffin, benzol or benzene, and alcohol. Paraffin is ordinary illuminating oil, such as is used in lamps. Benzol is produced when coal is distilled, in the manufacture of coal gas, and alcohol is obtained when vegetable matter ferments. All are inflammable, but do not vaporise so easily as petrol, while there is such a heavy duty on alcohol that the price is prohibitive. Before the war benzol, which was only two-thirds the price of illuminating oil, and paraffin, which was still cheaper, were both used. The only disadvantage is that the engine will not start with them. Once, however, the carburettor has become warmed up they work very well.

Many engines are made to start on petrol and then work with paraffin or benzol. Other engines are made to work with paraffin or benzol altogether, and are provided with a vaporising chamber which can be heated up by a lamp. This is surrounded by a jacket through which the exhaust gases pass, so that when once it has been heated it remains hot enough to vaporise the fuel as long as the engine is working.

There is also a form of mechanical vaporiser, in which the spray produced is so fine that it forms a mixture with air which is easily ignited. Engines fitted with a vaporiser of one form or another are intermediate between the petrol engine proper and the oil engines to be described in the next chapter. They differ from petrol engines only in the means for converting a less volatile liquid fuel into vapour.

Engines for Motor-cars

The number of makes of motor-car engines is so great that if details were discussed it would be difficult to know where to stop. We shall, therefore, confine attention in this section to one well-known type, selecting for that purpose the engine made by Wolseley Motors, Limited, of Birmingham. On Plate 19, Fig. 121, will be found a view, half in section, of the 16-20 horse-power four-cylinder Wolseley engine, as seen from the water pump and magneto side. Each important part is marked on the drawing with a figure, and the index to parts will enable the construction and mode of operation to be understood without difficulty. Fig. 122, Plate 20, shows a similar view from the carburettor and oil-pump side. For the sake of the reader who wishes to examine the construction a little more closely a line drawing of the complete section is given in Fig. 123. In this drawing three pistons are shown in outside view, and one—that on the left—in section.

It will be noticed that the crank case carrying the bearings is in two parts, bolted together and

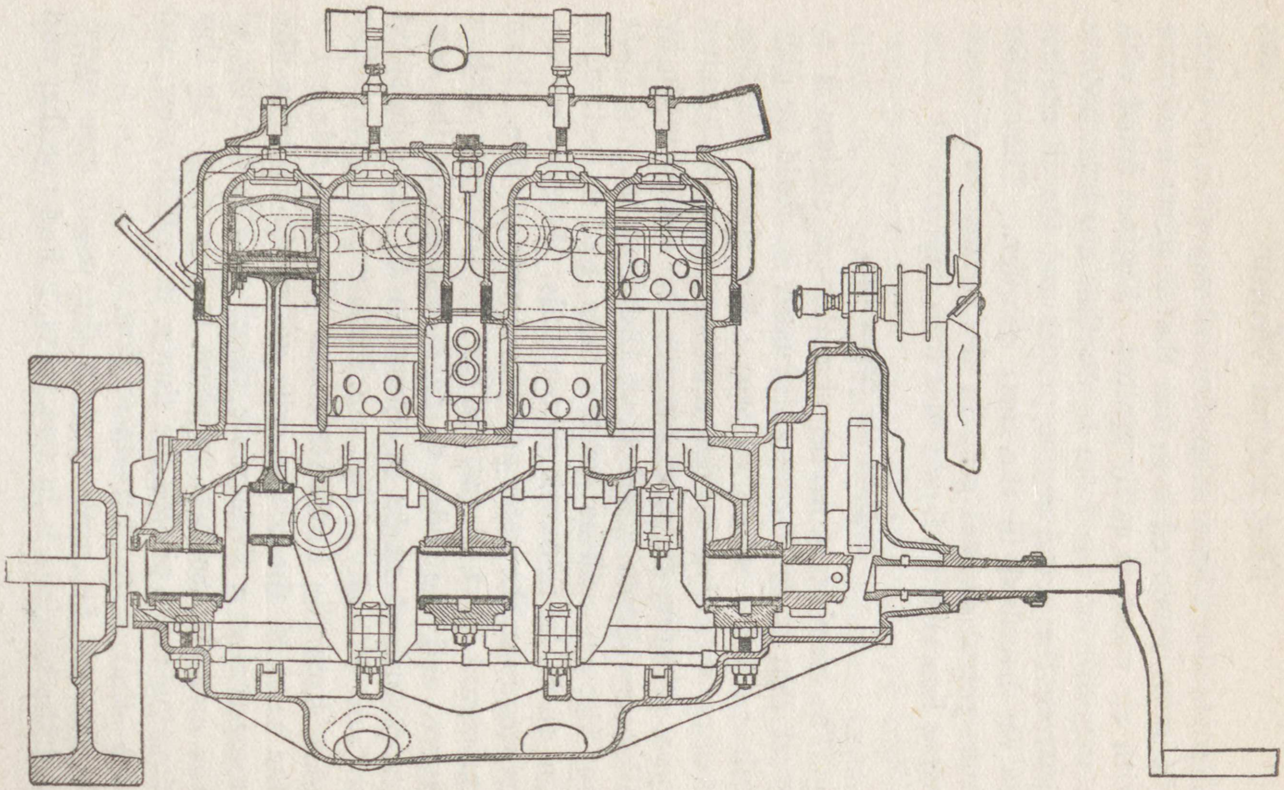


Fig. 123.—Longitudinal section of a 16-20 horse-power engine

provided with a well in the lower portion in which the lubricating oil collects, and whence it is pumped to other parts of the engine. Below each crank is an oil trough. A small dipper on the connecting rod end enters this oil when the crank is at its lowest point and lubricates the pistons by "splashing." No lubricating oil should be allowed to enter the cylinder itself if it can be avoided. Under the high temperature of the explosion it would char, leaving a deposit of soot on the ends of the pistons and the inside of the cylinders, and if a particle of this remained red hot from a previous explosion it would cause pre-ignition. Almost invariably a small amount creeps

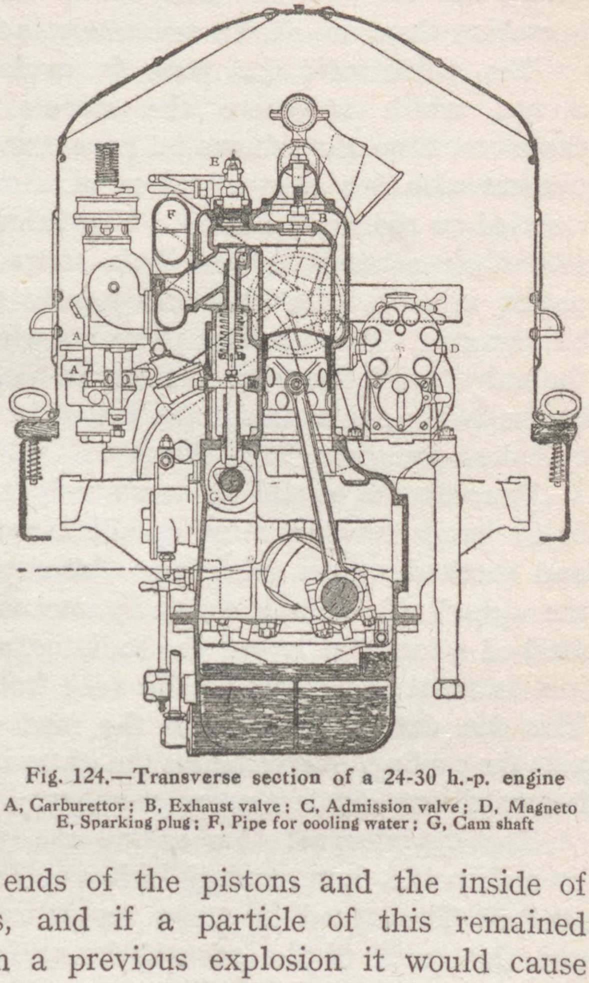


Fig. 124.—Transverse section of a 24-30 h.-p. engine
A, Carburettor; B, Exhaust valve; C, Admission valve; D, Magneto E, Sparking plug; F, Pipe for cooling water; G, Cam shaft

past the piston rings, and the interior has to be cleaned out by an oxy-acetylene blow-pipe flame.

The valves work in a small combustion chamber on the far side of the drawing, and not, therefore, shown in the figures. They and the method of operating them are shown separately in Fig. 124.

The adjustment for wear is made by turning a nut, which lengthens the spindle, and differs, therefore, from that shown on page 210. The valve plunger also has a small piece of compressed fibre inserted to reduce the noise. The valves are ground into their seats with jeweller's rouge in order to obtain a perfect fit, and occasionally they need to be reground. The sparking plugs are fixed just above the valves, and the order of firing in the four-cylinder engine is 1, 3, 4, 2, this being the order in which the cylinders compress their charges.

The water is caused to circulate by a small centrifugal pump on the same spindle as the magneto, and marked 19 on Plate 19. After passing round the cylinder jackets it flows by means of the pipe marked 9 into the top of the radiator, which is fixed just in front of the fan at the very front of the car. This fan draws air through the nest of tubes and aids the cooling. Nevertheless the water in the radiator becomes very hot in warm weather.

The cylinders of this engine are $3\frac{9}{16}$ inches or 90 millimetres bore, and $4\frac{3}{4}$ inches or 121 millimetres stroke. The speed is 1,200 revolutions a minute, and the speed of the car can be varied from 7 to 28 miles per hour. For higher powers six cylinders rather larger in size are necessary. The power is communicated to the rear axle by various mechanisms which it would be out of place to describe here, but which are, nevertheless, of first-rate importance in considering the car as a whole. It is in this sphere, perhaps, that the greatest difference between a good and a bad car is to be found. So far as engines are concerned, the chief variations occur in the general arrangement. Thus the cylinders may be cast singly or in pairs or in fours. The valves may be in the ends of the cylinders or in combustion chambers at the side. In the Lanchester engine, for example, they are operated by flat "leaf" springs which press upon the ends of the valve spindles just as one might do with the end of the finger; and this engine also has a wick carburettor in which the petrol vapour is drawn through wicks dipping into a reservoir. In some cases the water circulates naturally, and in others it is driven round by a pump. Where extreme lightness is required the crank case may be made of aluminium alloy, and the pistons, instead of being made of cast iron, may be of steel, or even of aluminium alloy. Apart from excellence of material, accuracy of workmanship, and perfect fit, the most essential condition of satisfactory working—and this is true of any kind of high-speed engine—is that all rubbing surfaces should be flooded with oil. It must never be forgotten that in a space of, say 2 feet by 2 feet by 1 foot, energy is being liberated at the rate of 20 horse-power—that is to say, work is being done at the rate of 660,000 ft.-lb. per minute.

And if, in this confined space, something goes wrong, so that this energy is not exerted through its proper channels, serious damage will be done.

The Motor-cycle Engine

The motor-cycle engine differs in no important respect from those which have been described save that water cooling is unnecessary. The cylinder is provided with fins, and is exposed freely to the air. The rapid motion of the machine has the same effect as a strong current of air blowing over the surface and carrying away heat as fast as it is produced. Not only is the cylinder lighter than one provided with water jackets, but tank, radiator, and a not inconsiderable amount of piping are rendered unnecessary, reducing both weight and cost of the machine.

The more powerful machines are provided with double-cylinder engines, and these are arranged either opposite to one another or in the form of a V. The latter form is more economical of space and is the most frequently adopted. Two-stroke engines are very popular because of their simplicity, and the reduction of weight which results from the absence of admission and exhaust valves, tappets, and cam shaft.

All single-cylinder engines have a crank consisting of a crankpin fixed between two solid flywheels, this, again, economising weight and space. The tank for fuel and lubricating oil is carried under the top bar, so that both can flow to the engine by the action of gravity. The carburettor is fixed in such a position that the supply of oil to the jet is not affected by the inclination of the jet when going up hill, but it does not differ in construction or principle from those used on other types of petrol engine. Similarly the explosive mixture is fired by a spark from either a coil or a magneto, the latter being, perhaps, more frequently fitted.

Figs. 125 and 126 on Plate 21 show a $3\frac{1}{2}$-horse-power Humber and a 6-horse-power V-type A.J.S. engine.

Engines for Motor-boats

The earliest internal combustion engines used on boats were simply motor-car engines—extremely light, quick-running engines which gave wonderful speeds and led to a great development of racing. For most purposes, however, a heavier, slow-speed engine is to be preferred, and during the last fifteen years engines have been specially designed for the purpose. As these were less economical, there has also been a tendency to use paraffin instead of petrol. The typical motor-boat engine of to-day is, therefore, a small marine engine, using paraffin as fuel, strongly built, and running at a moderate speed. Generally, the cylinders are in a row, because this arrangement takes up the least space transversely, and if the V form is adopted the angle between each cylinder of a pair is, for the same reason, a very small one.

The chief disadvantage that attends the use of an internal combustion engine on a boat is its non-reversibility. It is very important to be able to go ahead or astern at will when manœuvring in a crowded waterway, and in the ordinary sense the four-stroke engine is non-reversible. On a motor-car there is a complicated system of gearing for which room is provided underneath the car, but in a boat this takes up floor space which cannot well be spared. One method of avoiding it is to use a reversible propeller. In this ingenious device, by merely pulling a lever, the blades of the propeller are twisted round so that, while it still rotates in the same direction, it will propel the boat either ahead or astern as desired. Failing this, the gear box is essential for all four-stroke engines. A two-stroke engine will run

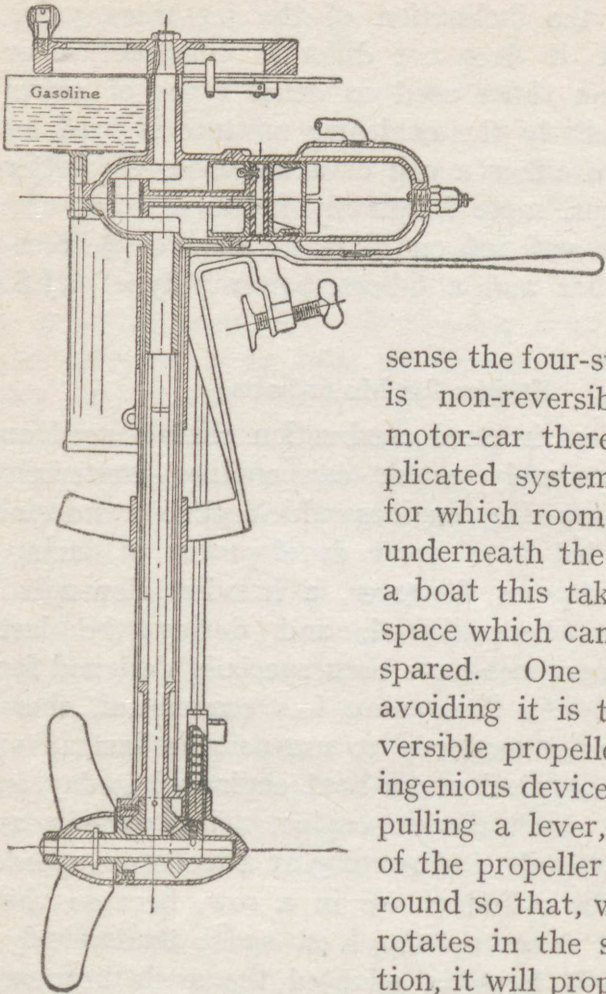


Fig. 127.—Evinrude out-board motor

equally well in either direction, and to reverse it is only necessary so to advance the spark that a back fire occurs. Generally, this sets the engine running in the opposite direction, but it is not absolutely certain, and, in any case, it entails rather rough usage.

For very small boats there are several very ingenious arrangements whereby a small motor is fixed to the stern, and a screw propeller driven from it by means of a vertical shaft and bevel wheels. The cylinder is fixed horizontally with a flywheel above and the shaft projecting below. They work on the two-stroke principle because the absence of valves and valve gear simplifies the engine, enables them to be produced at a low cost, and facilitates reversing. Lubrication is effected generally by mixing lubricating oil with the petrol in the proportion of 1 to 20.

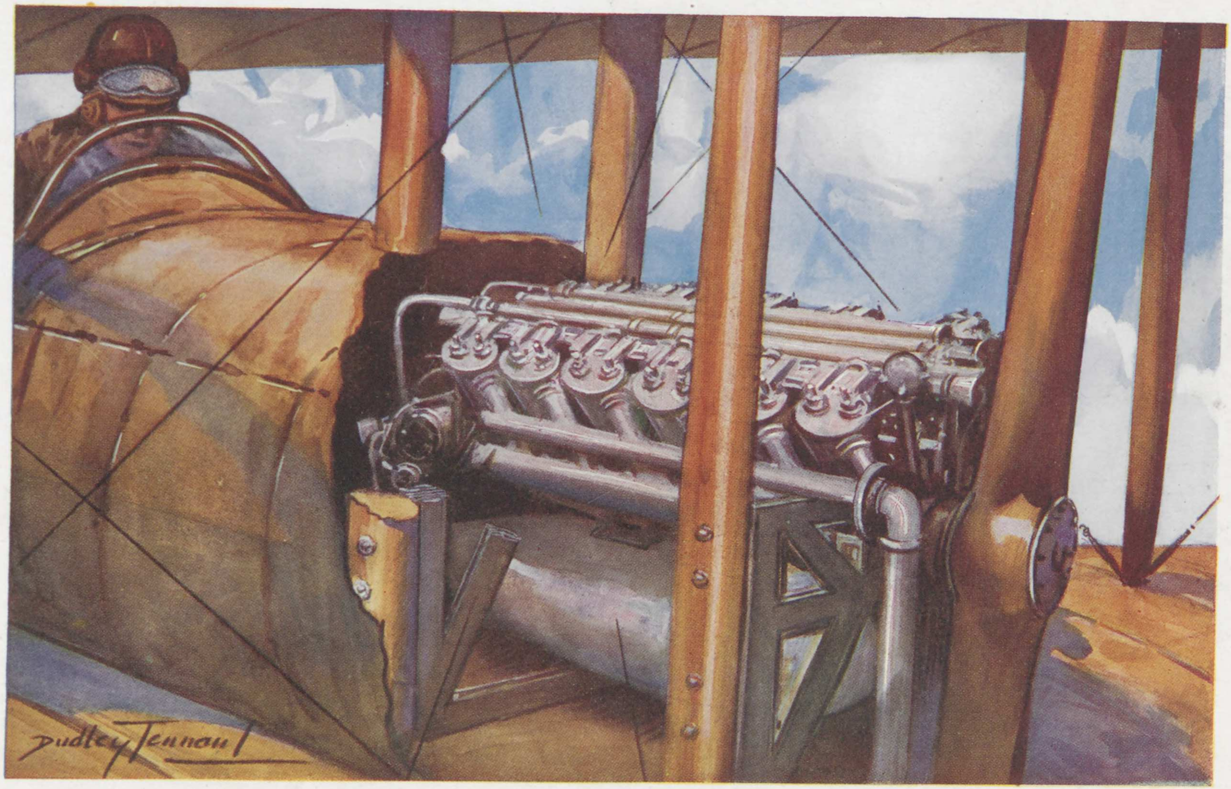
One of the best-known "outboard" motors is the Evinrude motor, illustrated in Fig. 127. With a single cylinder this can be made to give from $1\frac{1}{2}$ to 4 horse-power. No rudder is required, the boat being steered by turning the engine about the vertical shaft by means of a short tiller. When the engine is running this gives a very powerful effect; but, of course, it has no influence when the engine is at rest.

Another method which has been developed for the propulsion of barges, and of small boats required to navigate very shallow or weed-choked waters, is the use of an aerial propeller. That is to say, the boat is propelled by a screw working in the air and driven usually by a two-cylinder two-stroke engine. As the air flung back by the propeller passes over the engine the cylinders do not need to be water-jacketed, but they are provided with fins to increase the cooling surface.

Engines for Aeroplanes

The aeroplane engine is nothing more or less than a motor-car engine in which the highest quality of material and workmanship is combined with the lightest possible construction. When Professor S. P. Langley, of the Smithsonian Institution, Washington, made his memorable experiment on mechanical flight in 1896, the lightest steam engine he could construct contained sufficient fuel and water for a journey of one and a half minutes. At the end of that period the model aeroplane sank slowly on the waters of the Potomac, where the experiment was tried. In 1897 Ader, a Frenchman, succeeded in flying about 300 yards, but this remained unnoticed until flying became almost an everyday matter. The brothers Wright flew 200 yards in 1903 and from eleven to thirty miles in 1906. From that year flying on machines heavier than air passed out of the region of occasional experiments into that of regular practice, though apart from the achievements of the Wrights the distances were never more than a few hundred yards.

In these early days, as now, nearly everything depended upon the motor. The Wrights made their own, and so did Glenn Curtiss, who won the speed



From a drawing by Dudley Tennant

PICTORIAL DIAGRAM OF AN AEROPLANE ENGINE: A 12-CYLINDER GREEN TYPE

competition at the Aviation Meeting at Reims in 1909. In that year Lathom failed to cross the Channel owing to a defect in the motor, while Blériot was successful because the Anzani engine was reliable. None of these early motors were of more than 25 horse-power. They had three or four cylinders

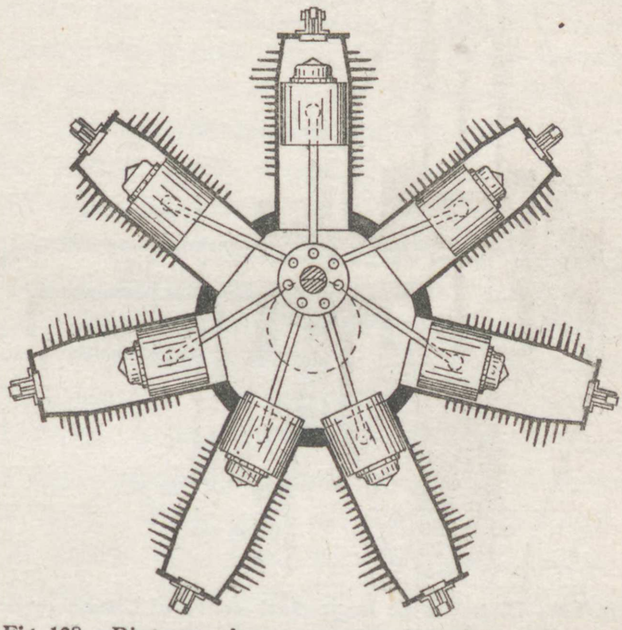


Fig. 128.—Diagrammatic transverse section of Gnome engine

arranged to work on one crank, and in many cases more time was spent in getting the engine to work than in actual flying.

In 1910 a great impetus was given to flying by the invention of the Gnome engine, which was not only more reliable, but also more powerful than any which had been used before. The smallest size was of 50 horse-power, and had seven cylinders driving one crank. The cylinders were bolted to a ring fitting over the main shaft, which was *fixed*, and as the cylinders themselves rotated round the shaft the

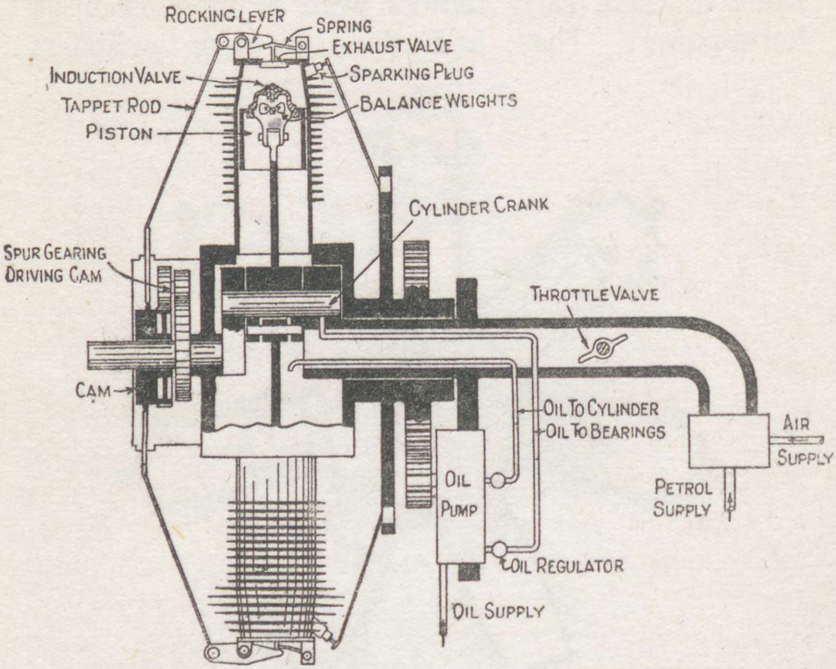


Fig. 129.—Diagrammatic longitudinal section of Gnome engine

pistons moved in and out. Remembering that the crank is fixed and that the cylinders alone can move, fix the attention on any one cylinder with its piston and connecting rod as the cylinders rotate. Obviously the piston will move up and down in the cylinder, and if a charge of petrol and air is introduced at the proper moment and exploded the motion will be kept up.

The mode of operation was as follows: The crank case was enclosed and supplied with air and petrol from the carburettor. As each piston (by the motion of the cylinders) was withdrawn, the air and petrol passed through a valve in the head of the piston into the cylinder. On the return of the piston (again by the motion of the cylinders) the mixture was compressed, and since more room for the expanding gases could only be provided by the rotation of the cylinders, that motion was encouraged. As the piston again approached the closed end of the cylinder the exhaust valve in that end opened and the waste gases were swept out. The cycle was, therefore, a four-stroke one.

The chief advantage of this engine was its extreme lightness—a little over 2 lb. per horse-power. In fact, the weight of a 100 horse-power engine was only 220 lb. The cylinders were not water-jacketed, as the rapid motion through the air kept them sufficiently cool. They were of steel, turned and bored out of solid cylinders so that the sides were only ⅛ inch in thickness, with "fins" on the outer surface, to increase the cooling effect. The rotating cylinders themselves served as a flywheel, giving a remarkably steady effect. It occupied a very small space, the 80 horse-power seven-cylinder type being only about 2 feet 6 inches in diameter and less than 1 foot from back to front at the thickest part.

Against these advantages there were certain objections. The lubricating oil in the crank chamber was flung outwards by centrifugal force, and passed through the valve in the piston with the air and petrol. Some of it was flung out through the exhaust valve while that which remained was liable to be charred by the temperature of explosion. This caused premature ignition, interfered with regular sparking by depositing soot on the sparking plug, and choked up the exhaust valve. In spite of these defects it was by far the most popular aeroplane engine in 1912, when the makers introduced several important improvements. The valve in the piston was abolished, ports were provided in the cylinder at a point where they were covered and uncovered by the piston. The exhaust valve remains open for a short time after the waste gases have been expelled, and a certain amount of air enters the cylinder. The valve then closes, the ports in the cylinder are uncovered, and a rich mixture of petrol and air is forced in by a pump. With these alterations the speed can be varied by means of a throttle valve from 1,000 to 200 revolutions a minute, and though powerful rivals have arisen the engine is still used on aeroplanes to-day.

At the military trials in England in 1912 the prize for speed was won by S. F. Cody on a biplane of his own construction, driven by a 120 horse-power Austro-Daimler motor. The following year, in the War Office reliability trials of aeroplane engines, only one succeeded in passing the test—a continuous run of twenty-four hours—and that was the Green engine, All the wonderful progress made during the war was under the stress of military necessity, and the details were known only to those immediately concerned in their production and use. It may be said, however, that in addition to the Gnome and the Green engines, and the R.A.F. designed at the Royal Aircraft Factory, nearly every well-known type of motor-car engine has been adapted for aeroplanes. The Rolls-Royce is popular on account of its reliability; the

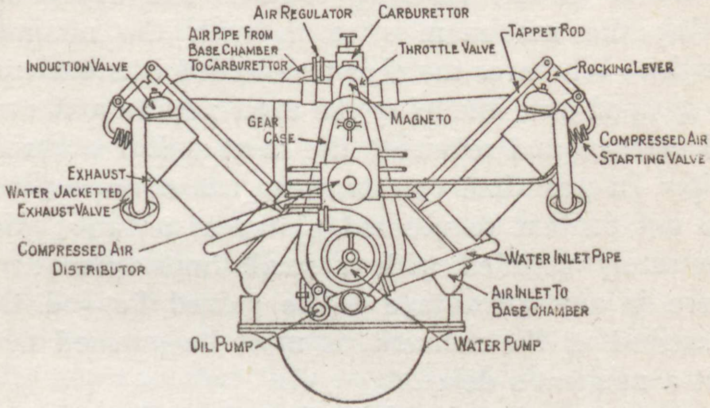


Fig. 130.—Diagram of V type of aeroplane engine

improved form of the Austro-Daimler, known as the Beardmore, is being made in large numbers; the Sunbeam, and several others are also used.

The Gnome remains the only radial, the only rotary, and the only air-cooled motor. So long as the number of cylinders does not exceed six, the ordinary vertical type is preferred; but for any number beyond cylinders are so arranged that each pair forms a V and works on the same cranks as in Fig. 130.

In most of them the valves are situated in the tops of the cylinder, rendering a combustion chamber unnecessary and economising weight and space. They are opened by rocking levers operated from a cam shaft in the usual way. Every possible device is employed to reduce weight. The crank cases are of aluminium alloy, and so are the pistons. The water jackets are of thin copper or aluminium. The connecting rods are of steel, "drop-forged" in the shape of an H girder, tapering towards the upper end, giving the maximum strength with the minimum weight. Wherever metal is not needed it is cut away or scooped out, involving the most minute and exact calculations and requiring the most skilful workmanship. In war time cost is of no consequence; men are not content to proceed a step at a time; they are rarely satisfied with a small improvement; if there is any advantage to be gained beyond that possessed at the moment, it must be pursued without a moment's delay.

What wonderful things these aeroplane engines are! Here is one with six cylinders, which two men can lift, capable of giving 120 horse-power! There is another, V-pattern, with twelve cylinders arranged in six pairs, not beyond the capacity of four men to lift, and yet capable of being coaxed up to 300 horse-power, or of performing work at the rate of 9,900,000 ft.-lb. per minute! The crank shaft rotates 1,000 times a minute. Six times in every revolution does an explosion speed the shaft on its way. There are, therefore, 6,000 explosions every minute, every one timed exactly, so that they occur at equal intervals and with a regularity which is astounding.

CHAPTER IX

The Oil Engine

THROUGHOUT the whole history of discovery and invention there are scores of cases in which men have struggled for generations to solve a problem, and when once it has been solved they pass from success to success so rapidly that the mind can hardly follow the changes as they occur. For a hundred years the internal combustion engine had been a veritable will-o'-the-wisp to men of a mechanical turn of mind. Often they felt that they were about to succeed, and always some unexpected difficulty arose so that they seemed as far away as ever from the goal of their ambition. But when the Otto gas engine was invented events moved rapidly—rapidly, that is to say, when one looks at the thousands of years during which man has been mastering natural forces, and rapidly even if only the period during which this particular object had been sought is passed in review. For the gas engine was introduced, as we have seen, in 1876, the petrol motor in 1884, and Priestman, of Hull, invented an oil engine in 1889.

What, now, is an oil engine? The answer to this question is that it is an internal combustion engine using as its fuel paraffin or petroleum, such as is used in lamps to produce light. This oil is heavier than petrol, and requires a higher temperature to convert it into vapour. When once it is converted into vapour and the vapour is mixed with air, the mixture is highly explosive, and just as useful as the lighter and more volatile petrol for producing mechanical power. Moreover, and this is all-important, it is cheaper. So the oil engine is similar to the petrol engine, but works on a cheaper fuel. It is, therefore, more suitable for larger powers, and in construction it resembles a gas engine rather than the dainty little motor which is used in the car, the boat, and the aeroplane.

In the Priestman engine the oil was vaporised in a chamber heated by a lamp before it entered the cylinder, and the explosion was caused by an electric spark. Before it had been in use more than three or four years a new form arose. The Hornsby-Ackroyd engine embodied a totally new principle, which can be most easily explained by reference to Fig. 131 on Plate 23. At the back of the cylinder is a space called a combustion chamber which, before the engine is to be started, is heated by a blow lamp, and into which the oil intended for combustion is sprayed, together with the requisite quantity of air. This takes place on the outward stroke of the piston. The oil is immediately converted into vapour, and the explosive mixture of this vapour with air, which has expanded into the cylinder, is compressed in the combustion chamber by the returning piston. Now, it will be remembered that

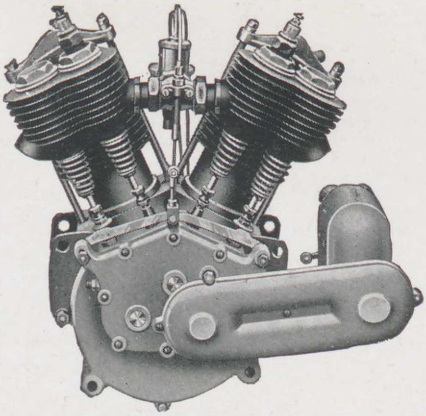


Photo by permission of A. J. Stevens (1894), *Ltd.*

Fig. 125.—A Typical V-shaped Motor-Cycle Engine, 6-h.p.

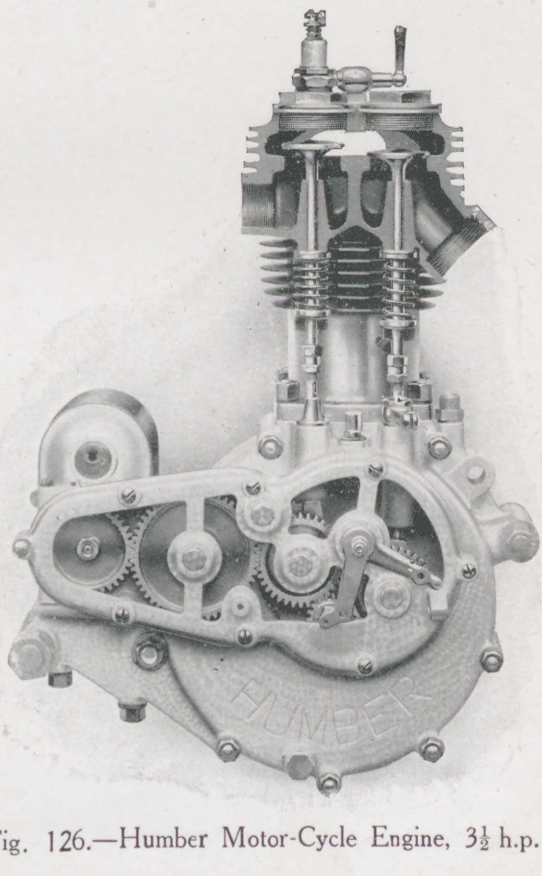


Fig. 126.—Humber Motor-Cycle Engine, $3\frac{1}{2}$ h.p.

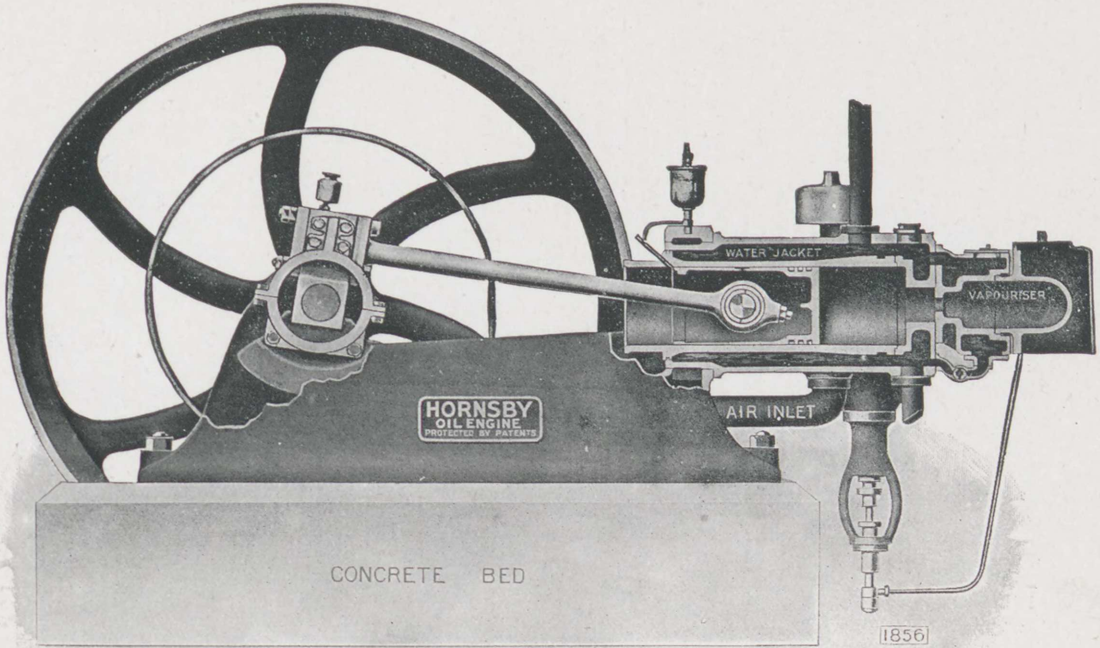


Fig. 131.—Section of Hornsby-Ackroyd Oil Engine

in a gas engine the compression must not be too high lest the heat produced should cause a premature explosion. In the Hornsby-Ackroyd engine this was actually allowed to occur—not prematurely, but at the right moment. The heat of the chamber, added to the heat produced by compressing the mixture, was sufficient to cause explosion, so that when once the engine had fairly started the lamp could be removed. Successive explosions afterwards kept the combustion chamber sufficiently hot. No further heating was required. There was no hot tube, no delicate and complicated coil or magneto to get out of order, no accumulators to run down just when they were wanted, no sparking plugs to get clogged up: just the combustion chamber, alternately warmed up by the explosion and cooled down by the spray of oil. Surely one of the simplest and most beautiful applications of a scientific principle to a practical purpose that was ever made!

The oil was delivered by a pump which, driven at half the speed of the engine, delivered at each stroke exactly the quantity required for one charge. The only valve, therefore, was that for the exhaust, and it was operated by a cam and rocking lever exactly as in the gas engine. Apart from the combustion chamber or the end of the cylinder and the single valve, there is nothing to distinguish this engine from a gas engine in appearance or construction. For small powers they are in competition to-day, and but for the increase in price of oil which has taken place in recent years, the competition would extend higher up the scale. Its place has been taken, however, by

The Diesel Engine,

which embodies another new principle in its mode of working. Engineers who experimented with gas engines had discovered that the efficiency increased as the compression rose; but the compression could not be increased beyond a certain point lest the mixture should be prematurely ignited. In the early nineties it occurred to Dr. Rudolph Diesel that if the fuel could be kept out of the cylinder until the air within had been fully compressed—that is, until after the piston had reached the end of the compression stroke—the advantages of high compression might be secured and all risk of premature explosion avoided. Moreover, it might be possible to use a cheaper variety of oil which is less easily converted into vapour, since it would be burnt immediately it entered the cylinder instead of having to wait while the engine made from one to two strokes before ignition occurred.

Dr. Diesel's experiments were carried out first in France and then in Germany, where, with the financial aid of the powerful Krupp firm, he constructed an engine according to the plan he had conceived, and took out a patent in 1895. But it was not all plain sailing. The compression was higher than had hitherto been employed—reaching 500 lb. on the square inch—and there were many difficulties of construction to be overcome. Engines of fifty and a hundred horse-power were built and gave great satisfaction, but it was ten years before one of 500 horse-power was made, and in the meantime thousands of pounds were spent in experiments.

All these efforts were not inspired by the desire to perfect a novelty. Success carried with it two very real advantages. The great demand for petrol for motor-cars had led to the production of large quantities of petroleum residue for which there was only a moderate sale; and the engine promised to use the cheapest form of liquid fuel on the market. Again, the new engine converted over 38 per cent. of the heat obtainable from the fuel into useful work, using only ½ pint of crude oil per horse-power per hour. And a further advantage for both land and marine work lay in the fact that this heavy oil was difficult to ignite and far less dangerous on this account than the highly inflammable petrol. On submarines, for example, petrol has been responsible for several serious explosions with loss of life. And so men spent time and money in overcoming apparently insuperable difficulties.

The first Diesel engine built in Great Britain was constructed by Mirrlees, Watson and Co., of Glasgow, in 1896, and in 1908 new works, under the management of Mirrlees, Bickerton and Day, were erected near Stockport, solely for the purpose of making Diesel engines. Meanwhile, many other firms also began their manufacture. We shall describe the Mirrlees Diesel in some detail because it is the one with which the writer is most fully acquainted, and

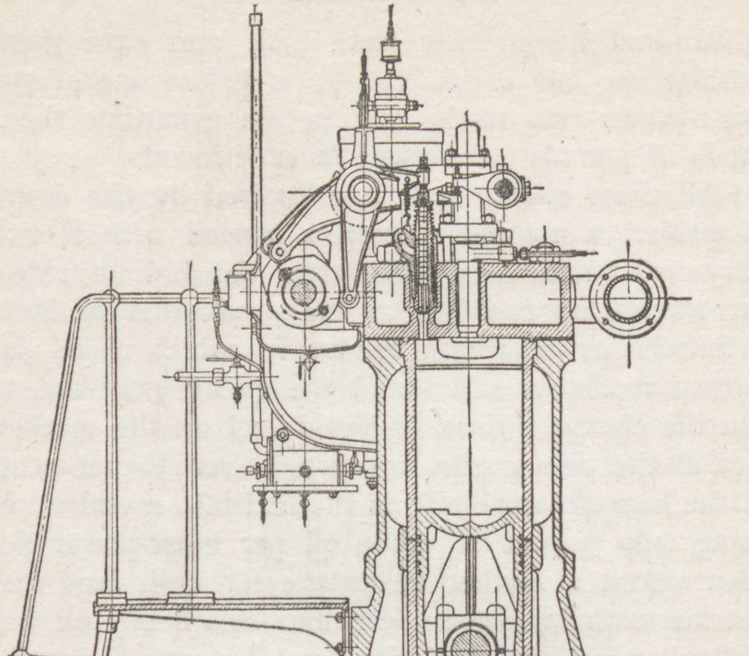


Fig. 132.—Transverse section of Diesel engine

then pass to the various purposes for which Diesel engines are used. The general arrangement will be understood from Figs. 132 and 133.

In the first place, Diesel engines are generally made vertical, because all the reasons which can be advanced in favour of vertical steam engines and some others are at least equally applicable to Diesel engines. Secondly, the type most usually met with is a four-stroke engine, in which the piston receives one impulse in every two revolutions of the flywheel. The first outward stroke of

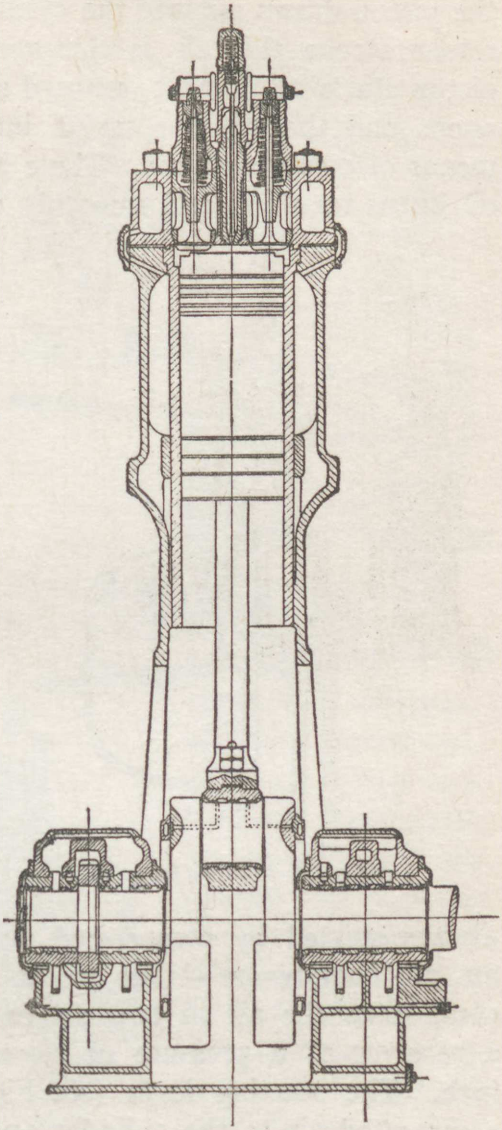


Fig. 133.—Longitudinal section of Diesel engine

the piston draws air into the cylinder, and during the return stroke this air is compressed. Then, as the piston starts on its next outward stroke the fuel valve opens and the oil is sprayed into the cylinder, by means of compressed air. There is no explosion; the oil burns regularly and smoothly as fast as it enters. The supply only lasts for about a tenth of the stroke, and the pressure on the piston is kept up by the hot expanding gases which result from the combustion of the oil in the compressed air. Finally, in its return stroke the piston sweeps out the waste gases through the exhaust valve.

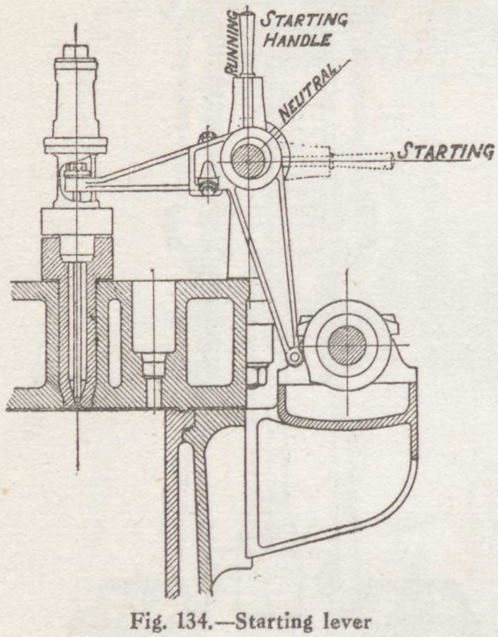


Fig. 134.—Starting lever

The engine is always started by compressed air. On the shaft is an air compressor — that is, an air pump — which compresses the air in two stages and delivers it to a receiver at a pressure of 1,000 lb. on the square inch. The starting lever (see Fig. 134) admits this compressed air to the cylinder and at the same time it locks the fuel valve so that no premature explosion is possible. After a few turns of the crank the starting lever is pulled back again, the compressed air is cut off, and the fuel valve is opened. The engine then starts running on fuel in the ordinary way.

The air and exhaust valves are of the mushroom type, which have already been described in connection with gas, oil, and petrol engines. They are held on their seats by springs and are opened by tappets or levers operated from a cam shaft. In the Mirrlees engine the exhaust valve levers are hinged, so that the removal of a bolt enables that

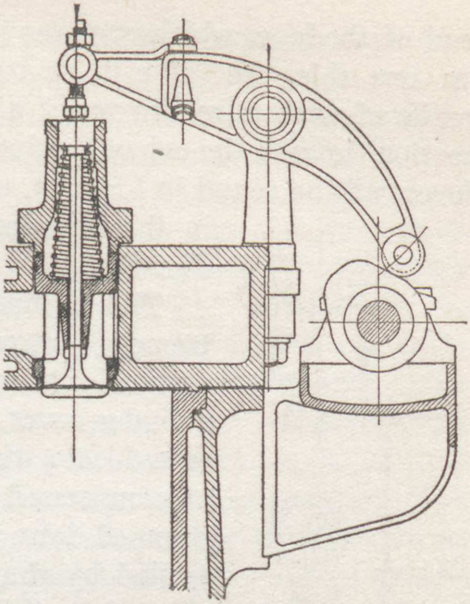


Fig. 135.—Section through valve showing jointed lever

Fig. 136.—Section through cylinder cover

end of the lever which operates the valve to be swung on one side, the valve to be inspected, reground, or replaced with a minimum of time and trouble. A section through the exhaust valve, showing the jointed lever, will be found in Fig. 135, while the three valves in the cylinder cover are shown in Fig. 136.

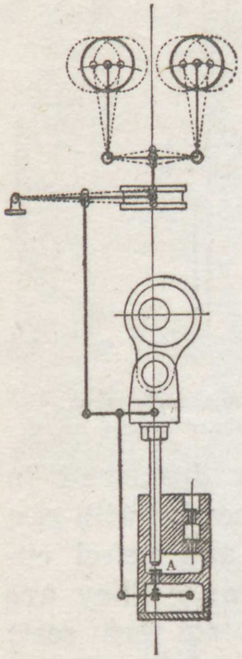


Fig. 137.—Method governing Mirrlees Diesel engine

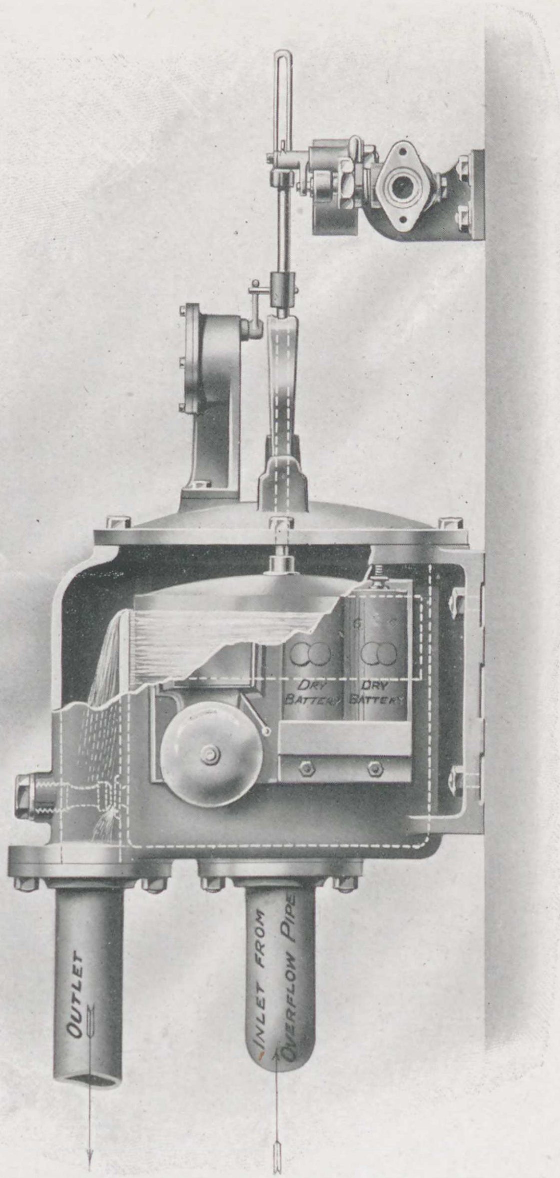
The method of governing is extremely interesting. The fuel is pumped into a small chamber on the cylinder cover, from which it is injected into the cylinder by means of compressed air, and the amount pumped into this chamber is controlled by the governor. Fig. 137 shows how this is done. The pump is driven by an eccentric, and the plunger enters a chamber A which is filled with oil. Suppose the volume of the plunger which enters this chamber on every downward stroke is 1 cubic inch. Then, provided the suction valve just below the plunger end closes at the commencement of the stroke, the amount of oil delivered to the chamber on the cylinder cover for the engine is 1 cubic inch. But if the suction valve remains open for a time after the stroke has commenced the delivery is less. And this is just what happens. When the engine is running too fast the governor balls fly outwards and the suction valve is held open for a longer or shorter part of the stroke through the linkages shown in the diagrams.

Diesel engines are constructed with trunk pistons or with cross heads and connecting rods. In the latter case they are usually enclosed, high-speed engines with forced lubrication. As the system of forced lubrication has been described in connection with steam engines in Chapter VI., it need not be referred to again. But there are interesting facts about the construction which deserve record. The pistons are made in two parts—the head and the skirt. The former has to resist rapid changes of temperature and the latter has to resist wear. The head is made of a special iron, low in phosphorus, which will stand temperature changes without cracking, and the latter is made of a hard, close-grained cast iron of good wearing qualities. Further, a cavity in the head is filled with asbestos, which prevents some of the heat from reaching the pin upon which the upper end of the connecting rod turns.

Now while the presence of lubricating oil above the piston is not attended with the risk of premature explosion, as in gas and petrol engines, it is nevertheless objectionable, because it may permit overheating to occur. And it is extremely difficult to prevent oil creeping past the cylinder rings—that is to say, more oil than is needed to lubricate the rubbed surfaces. The lower ring does not scrape off the excess of oil splashed up from the oil bath, because it cannot push before it a thin film of oil of considerable area. But in the Mirrlees Diesel piston there is a groove just below the ring into which the oil can be pushed, and from which it escapes to the inside of the piston through a number of small holes. This simple expedient adds much to the internal cleanliness of the engine.

One of the most interesting accessories is a piece of apparatus which prevents accidents through failure of the water supply to the cylinder jackets and valve chambers. From Fig. 138, Plate 23, it will be observed that the cooling water passes into a piece of apparatus like a small gasometer with a leak in the side. With a full supply of water, however, the hood or float is lifted and water pours over the edge. If the supply fails the vessel is emptied through the side hole, the float falls, the fuel supply is cut off, and an electric bell calls the attention of the attendant to what has happened. By another device the amount of compressed air driving fuel into the cylinder is made to correspond with the quantity of fuel. Again, the pump supplying oil to the bearings, etc., can be worked by hand for a minute or two before the engine starts, so that the oil which drains away when the engine is resting is replaced and all rubbed surfaces are thoroughly lubricated before the first stroke of the piston.

When it is remembered that there are no boilers, no vaporisers, carburettors, or sparking arrangements to be looked after, it will easily be seen that the amount of attention required is very much less than that for steam, gas, or petrol engines; while since oil fuel occupies a much smaller space than



By permission of Messrs. Mirrlees, Bickerton & Day, Ltd.

Fig. 138.—Water Alarm for Diesel Engine

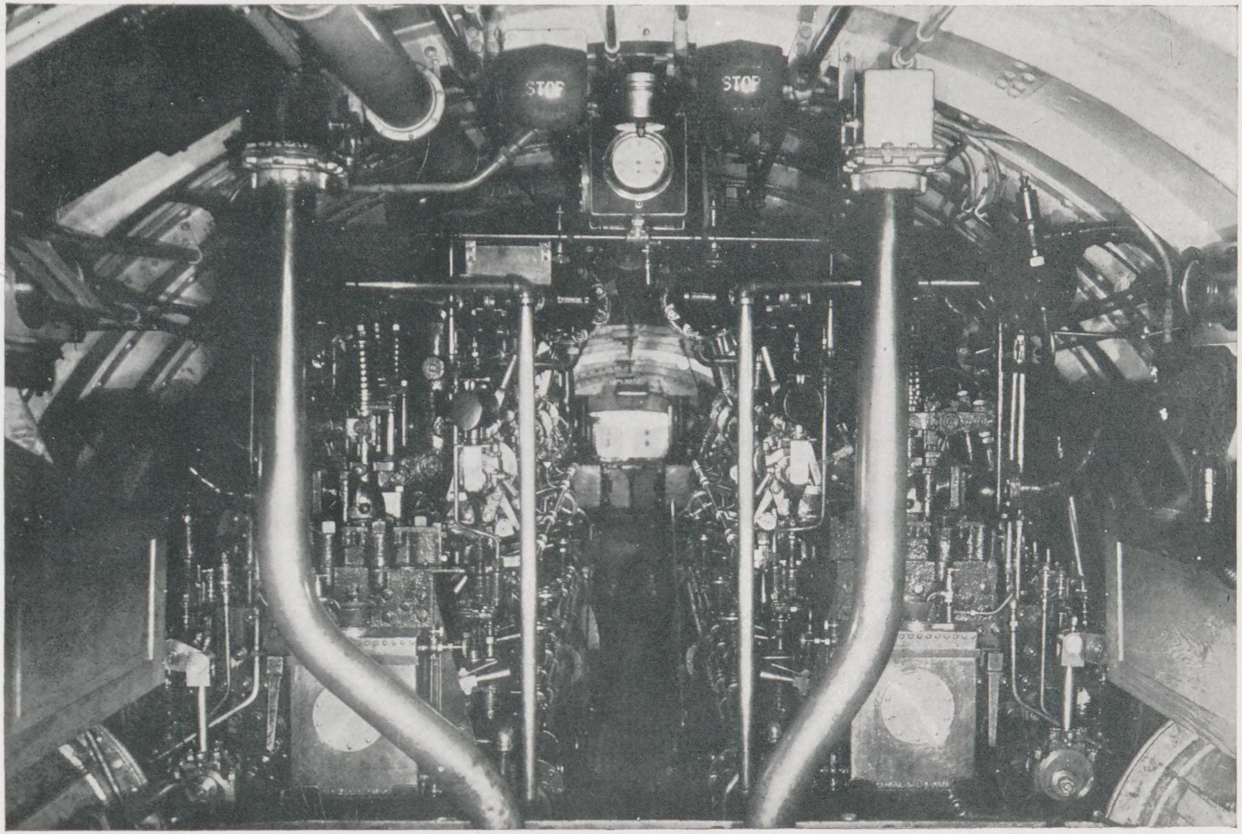


Photo by permission of The Electric Boat Co.

Fig. 139.—The Engine Room (looking aft) of a Holland Submarine

any form of solid fuel, there are obviously advantages apart from the economy of the engine. The amount of attention is, indeed, reduced to a minimum. But it must not be assumed, as we have already had occasion to point out, that any less intelligence is desirable in its management. The attendant is relieved of a good deal of manual labour, and the strain of continuous watching oil, air, and water supply is transferred to automatic devices. It is still necessary, however, for him to see that these devices are acting properly, and to know how to make adjustments when necessary. The man must, in fact, not only understand his engine, but he must also understand the little accessories which control its motion. He does not have to act so frequently, but when he does act it must be with wider knowledge and deeper understanding than before.

In addition to the single-acting, four-stroke engine that has been described, two-stroke and double-acting engines have been made. The two-stroke engine acts on the same principle as the two-stroke gas and petrol engines explained in previous chapters. Near the end of the explosion stroke the piston uncovers a number of openings in the walls of the cylinder through which issues a stream of compressed air. This air acts as a scavenging charge, sweeping out the waste gases, and leaving in sufficient air for the compression stroke. In this way the piston receives an impulse every revolution. The cam shaft, which operates the valves, must now rotate at the same rate as the crank shaft in order that the exhaust valve shall be open every second stroke of the piston. The double-acting engine acts in the same way, but fuel is admitted at each end of the cylinder in turn. A trunk piston is here inadmissible, and there must be a front cover to the cylinder.

The principal difficulty of making two-stroke and double-acting Diesel engines arises from the tendency to overheating, and consequent jamming of the pistons. With one "combustion" occurring every two revolutions the cold water in the cylinder jackets keeps the pistons cool enough, but with combustions occurring twice or four times as frequently the piston itself must have hollow spaces through which water is constantly circulating. This necessitates jointed tubes leading from the engine frame to the cross head and then up into the piston.

The Mirrlees Diesel engine is made with single cylinders of 50, 80, and 125 horse-power, and from these sixteen different engines from 50 to 750 horse-power can be built. It is also made as a high-speed engine in nine sizes between those limits. It is used for driving machinery in factories, for pumping, and for driving dynamos, and it has also been applied to a rolling mill—a very severe test for any engine on account of the great variations of load. For factories in which steam is not required for other purposes than power the engine has been found very suitable, and even in textile mills where steam is required to charge the atmosphere with moisture it has been employed.

Diesel engines are used for pumping by the Mersey Docks and Harbour Board, which has a 5,000 horse-power pumping engine at work; by the Manchester Ship Canal Co., and at numerous waterworks. It is especially useful for intermittent work, because it can be started within a couple of minutes, whereas a steam engine can only be started quickly and at short notice when steam is kept up in the boilers. Its value in electric light stations depends partly upon this fact and partly upon the fact that there is less difference in the efficiency of large and small Diesel engines than in the efficiency of large and small steam engines.

The problem in electricity generating stations is how to deal with the "peak load." In the day time current is required only for the trams and power; at night it is only required for light. But there are short periods, especially in winter, when it is required for power, light, and a heavy tramway traffic all at the same time, and the resources of the station are severely taxed. The difficulty has been met by installing a Diesel engine to meet the extra demand when it occurs. And if the station is supplied entirely with Diesel engines, there may be several of small size, and just so many employed at once as are needed to meet the demand.

When the Diesel engine was first introduced there were great hopes of its application to the propulsion of ships. In no case is space so limited and so valuable, and the prospect of reducing by 30 per cent. the space for fuel, and of running the engines with a fraction of the number of men required to manage steam machinery proved an enormous attraction. Thus a writer in the Special Oil Power Number of *Cassier's Magazine* in 1911 examined the result of producing the 70,000 horse-power required by the *Mauretania* in Diesel engines. The space occupied would be only one-third of that now occupied by the steam engines and boilers. And since there would be no need for stokers and coal trimmers, 192 stokers and 120 trimmers might be discharged, with a saving in wages of £40,000 a year! Only a quarter of the weight of fuel would enable the vessel to travel the same distance without renewal.

This, however, is the vision of an enthusiast. It may be possible in the future, but it is not practicable at present. In the first place, it would require engines giving 1,500 horse-power per cylinder. Cylinders giving this power have been constructed, and cylinders giving 1,000 horse-power each are working quite satisfactorily; but they must be double acting and are difficult to make and keep cool. The main obstacles, however, are two in number: the Diesel engine is adapted for running always in the same direction, and it is not very good for slow speeds.

Let us amplify these points.

Firstly, the engine *will* run in either direction, but complicated apparatus is necessary for re-timing the valves, and reversal is more usually accomplished through toothed wheels. These have been so greatly improved in recent years, as we shall note in the chapter on Engines for Ships, that the plan is far more satisfactory than a complicated valve gear.

Secondly, the Diesel engine has a good range of speed when it has once started; the best way to start it is to get up speed on compressed air. But in a narrow or crowded waterway a ship can only be manœuvred safely with engines that are fully under control and capable of speeds which fall to the barest perceptible movement.

Nevertheless, the marine Diesel engine is growing in favour, and is being installed especially on oil tank steamers, both because it is safer and because the vessel trades only between ports where oil fuel can be readily obtained. Attempts are being made to overcome the difficulty of reversal by using the engine to drive a dynamo, and using the electric current thus produced to drive a motor. The motor can then be reversed by altering the direction of the current. This arrangement also allows the speed to be varied, and permits of that delicate manœuvring which is necessary in narrow or crowded waters.

But the greatest marine success has been in submarines. In these vessels space is restricted to the last limit, as will be seen from the illustration of the engine room of the Holland submarine, Fig. 139, Plate 24. Ten years ago these vessels were 10 feet in diameter at the largest section, or little more. To-day they are over 20. As the size increases, however, so also does the power required to drive them. Moreover, the surface speed has increased in the same time from 12 to 20 knots, or perhaps even more than this, for over the details of the latest types is drawn the impenetrable veil of official secrecy.

The first practicable submarine vessel became possible towards the close of last century by the invention of the petrol motor. But petrol, producing a highly inflammable vapour, was an extremely dangerous substance to be kept in such a limited space, and there was more than one terrible explosion, accompanied by loss of life. Steam engines with special soda boilers were tried in France, but without much success; and though it is possible that some submarines to-day are fitted with steam engines and oil-fired boilers, the majority are equipped with twelve-cylinder Diesel engines for surface cruising and electric power for propulsion when submerged.

For some purpose or another, then, the Diesel engine has come to stay. It will be used to a greatly increasing extent in those parts of the world where petroleum is found, and where the heavy oils remaining after distillation are plentiful and cheap. But the extent to which it is used in districts remote from the oilfields depends upon the way in which we and other countries dependent upon coal decide to use that fuel. If we decide to burn less of it in ordinary boiler grates and open fireplaces, and to make and consume more gas, then in the tar oils produced by gas manufacture we shall find an excellent fuel for Diesel engines, which may become almost as familiar as the ubiquitous gas engine is to-day.

The Semi-Diesel Engine

The Diesel engine was an advance on the ordinary oil engine in two respects: it used a very much cheaper fuel, and it converted a greater proportion of the heat produced by combustion into useful work. The second result was achieved, as we have seen, by high compression. In earlier internal combustion engines the compression had been limited by the fact that the fuel was admitted at the beginning

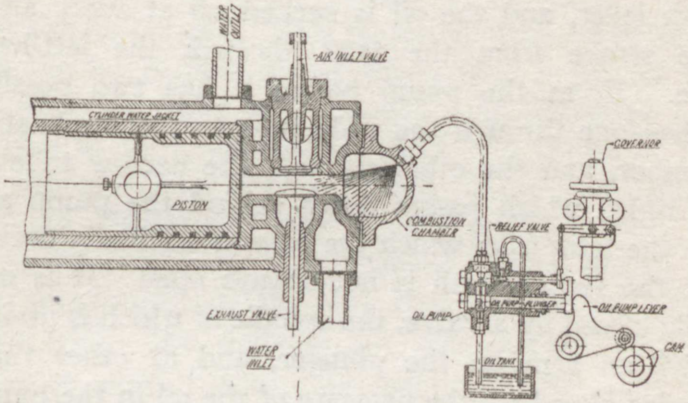


Fig. 140.—Section of Crossley semi-Diesel cylinder, vaporiser and oil pump

of the compression stroke, and the heat produced would have caused premature explosion. As soon as it was realised that the fuel could be injected at the end of compression, engineers began to make a new type of engine, known as the semi-Diesel engine, which was similar to the Diesel in every respect except the pressures employed. In this way they produced engines which were more efficient than ordinary oil engines, and less expensive to run because they used cheaper fuel.

The semi-Diesel engine has a compression which may vary in different makes from 120 lb. to 350 lb. on the square inch. In construction they are more like the ordinary oil engine, having a combustion chamber at the end of the cylinder. Perhaps the most interesting feature is the way in which the fuel supply is controlled by the governor. The pump plunger is operated by a cam acting through a bell-crank lever, and the oil is sucked up at every alternate stroke from the tank through the left-hand tube. From the pump barrel it has two possible paths—one through the wide tube to the combustion chamber, and the other through the narrow tube on the right, which passes down behind the pump and into the tank from which the oil was originally drawn. But the second path is not always open. It is normally closed by a valve, the spindle of which is pushed in by an arm on the plunger, and at other times remains closed by the pressure of the oil in the pump. Between the arm and the valve spindle is a wedge which hangs from a lever operated by the governor. As the speed increases, this wedge is raised, the thicker portion is interposed, the upper plunger is pushed in, and the overflow valve, as it is called, is opened. Some oil then flows back into the tank instead of passing to the engine. Generally speaking, for small powers the ordinary oil engine is used, for moderate powers the semi-Diesel, and for large powers the Diesel engine.

CHAPTER X

The Locomotive

IF the steam engine had only been employed to supply power for mines and factories the progress which has been recorded would never have been made. Goods have not merely to be made; they have also to be sold. Raw materials must be brought from the far distant places where they occur, to the centres where they are wrought and fashioned and changed as by a magician's wand into things of use and beauty. And if these things of use and beauty could be distributed only in the pedlar's pack, on the back of a horse, in a wheeled vehicle drawn by some quadruped, by the slow barge or the uncertain sailing ship, the demand for the factory product would be small indeed. To people remote from the centres of manufacture they would be rare and costly luxuries, like many of the wares displayed at fairs in the Middle Ages. But the railway and the steamship, by facilitating their distribution, have made these things plentiful and cheap, so that even the poorest may share in the products of the world's genius.

But quite apart from the encouragement of trade and commerce, there is another aspect in which steam locomotion on railways has revolutionised habits and customs and modes of thought. It has destroyed the isolation of town and village and created a new and stronger sense of national unity. Before the advent of the steel road few men travelled ; now all men travel. Each town or village was formerly in the main self-supporting, owing little to the men in other places and receiving little from them. But the spread of the railway has created mutual dependence and mutual responsibility. Every man is now interested in matters affecting the country as a whole, because he *can* be interested in it. The railway has thrown upon every man the duty of exercising his intelligence in the government of the country to which he belongs, for he can no longer plead ignorance of national affairs. The steam engine prints the newspaper and the book, and the steam locomotive brings these to his very door, so that from being merely an inhabitant of a village he becomes a citizen of the world.

The enormous results of improved means of transport and communication stirred the imaginations of many men while the steam engine was as yet in the stage of promise rather than performance. Probably as many men tried to use steam for this particular purpose as tried to make a really satisfactory steam engine—content if it would work at all. Even the great Sir Isaac Newton, early in the eighteenth century, designed a steam carriage. The brilliant Erasmus Darwin—poet, philosopher, physician—was a vigorous and constant advocate of the application of steam to locomotion from the time of

Watt's invention. But the first practical steam carriage was constructed by W. J. Cugnot, a Frenchman, in 1769, for the purpose of transporting artillery. (Fig. 141, Plate 25.)

The cylinders of this engine were 13 inches in diameter, and the wheels were turned by a ratchet and pawl. Watt himself had ideas on the subject, and with the aid of Murdoch he made a model in 1784. But the demand for engines for driving mills and factories was so great that he had no time to devote to the subject. Indeed, he appears to have lost interest in it.

It was Richard Trevithick, a Cornishman, who made the most persistent efforts and came nearest to success. In 1804 he built a locomotive to run on the Penydarren tramway in South Wales, and four years later he constructed a circular railway in London and ran an engine upon it at 12 to 15 miles an hour. For the first time it became generally understood that an engine would draw a load on smooth rails, and that so long as the line was fairly level, no toothed wheels and rack were required. Trevithick in England and Evans in America were the first men to use high-pressure steam. And Trevithick is really the inventor of the locomotive.

The real father of the railway, however, was George Stephenson, who, like nearly all the inventors of the eighteenth and early nineteenth centuries, started life without any advantages of education or worldly wealth. Born on June 9th, 1781, at Wylam, near Newcastle-on-Tyne, where his father was engine-man at a colliery, he started while he was still a child to look after cows on a neighbouring farm. Even then most of his spare time was occupied in constructing models with the aid of a pocket-knife; and when he started to work at the pit the engine was a perpetual source of interest to him. He felt keenly his need of education, and attended a night school when opportunity occurred. In such circumstances the man whose name was to become known throughout the world as the founder of the world's railways learnt, at nineteen years of age, to write his own name.

Always working, spending his evenings and week ends in studying or in adding to his scanty income by mending boots and repairing watches, he secured steady promotion until, in 1812, he was appointed engine-wright at Killingworth Colliery at £100 a year. In this position he had great opportunities for improving the machinery in his care, and he used them to the utmost. During the previous forty years the practice had arisen of laying first wooden and then iron plates upon the ground to carry the wheels of trucks of coal drawn by horses, and at Killingworth Colliery there was a track of this kind, several miles in length, leading to the quay side. He had already constructed a self-acting incline in the pit by which the loaded wagons running downhill drew the empty wagons uphill, and in this way reduced the number of horses required from 100 to 16; and he became possessed of the idea that a steam engine would be more effective than horse haulage on the surface. He went to see experiments of this kind at Wylam and at Leeds, and then succeeded in persuading Lord Ravensworth, the owner of the Killingworth pit, to advance money for the attempt.

His first engine was completed in 1814 and succeeded in drawing a load of 30 tons on a rising gradient of 10 feet a mile, at a speed of four miles per hour ; but he found that it was no cheaper than using horses. A second engine, containing several improvements, was built in the following year. It had vertical cylinders fixed in the top of the boiler, and the cranks were operated by long connecting rods on each side. The front and rear axles were connected by a chain working on sprockets or toothed wheels, which fitted the links. The most curious contrivance was the use of pistons working in cylinders in the lower part of the boiler to support the axle boxes and to serve the purpose of springs. But the main improvements lay in the jet through which exhaust steam escaped into the chimney, thus increasing the draught and doubling the power of the engine.

The engines built in 1816 were still more effective, and some of them remained in use for many years. About the same time better methods of tracklaying and of jointing the rails were introduced. The amount of success gained was an incentive to further study, and Stephenson began to make experiments on the relation between the weight of the train and the force required to draw it—the draw-bar pull, so called because a spring balance is introduced between the engine and the train. He found that a force of about 10 lb. per ton weight was required, and as a gradient of 1 in 100 decreased the weight capable of being hauled by about 50 per cent., he became convinced of the necessity of making the track as level as possible.

Before Stephenson's time interest had been centred mainly upon the use of steam for propelling carriages upon ordinary roads, but when the importance of smoothness and level had been so clearly demonstrated the importance of the latter was overshadowed for many years. It is not, however, within the scope and purpose of this book to deal with the development of the railway, and we must now examine in greater detail the development of the locomotive as a steam engine.

Stephenson further established his reputation in 1822 by using locomotives on the level portion of the Hetton Colliery track, near Sunderland; and in 1823 he built the Stockton and Darlington Railway and ran upon it the "Locomotion," an engine of his own construction. This engine was quite successful, but after the opening ceremony horses were employed for passenger traffic. (See Fig. 142 on Plate 25.)

Appointed engineer to the Liverpool and Manchester Railway, he succeeded in persuading the directors to give the steam locomotive a trial, and a prize of £500 was offered for the best engine. There were four entries—the "Novelty," the "Sanspareil," the "Perseverance," and Stephenson's "Rocket,"

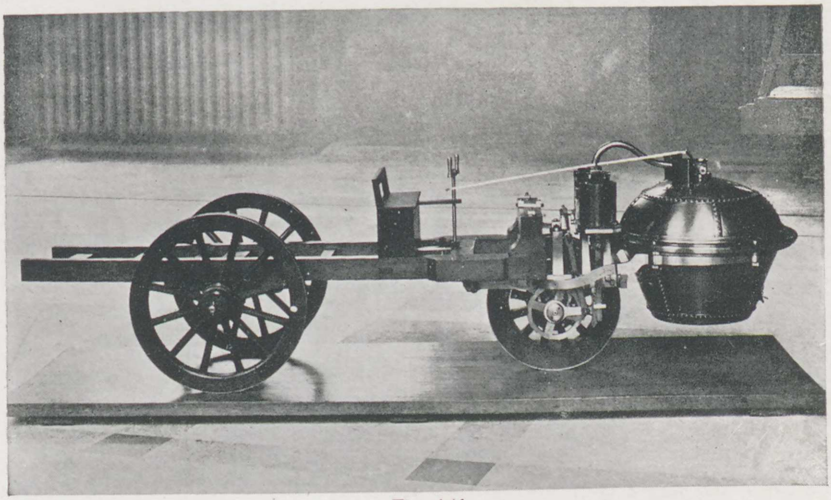


Fig. 141

Fig. 143

Fig. 141.—Cugnot's Steam Carriage

Fig. 142.—The Locomotion

Fig. 143.—The Rocket

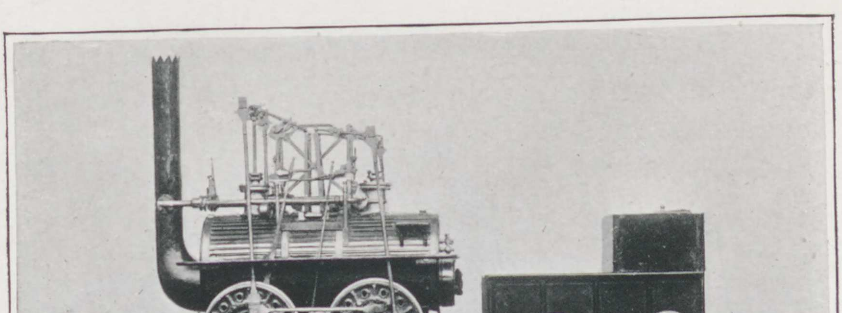
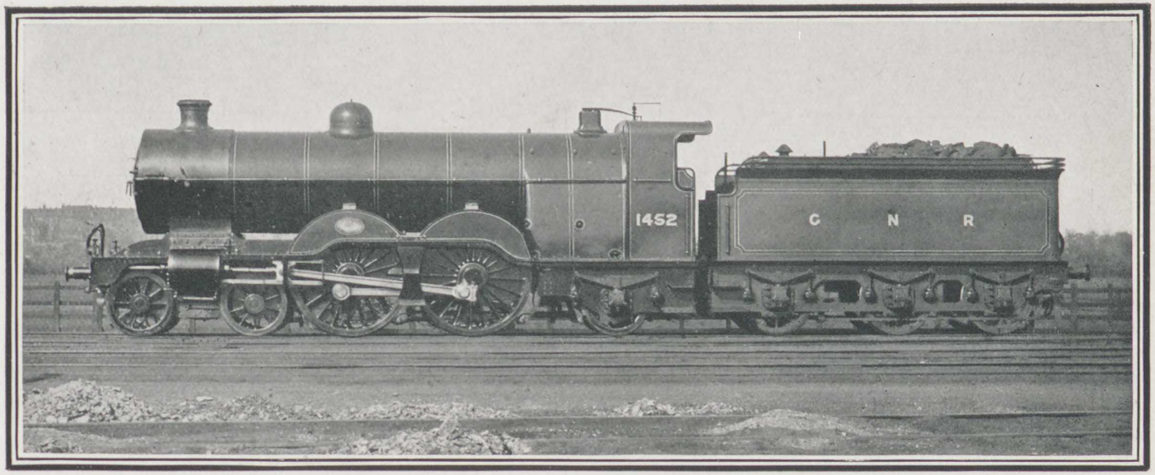


Fig. 142

(a)



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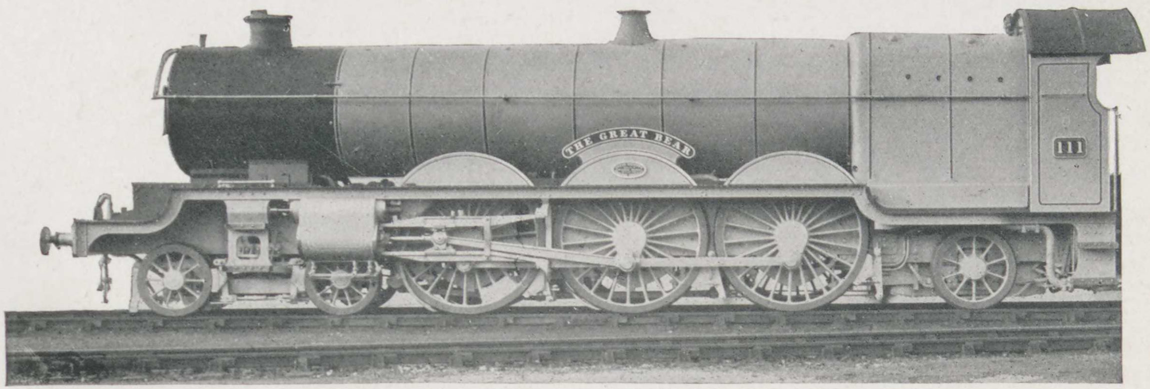


Photos by permission of the Great Northern Railway and the Great Western Railway

Fig. 155.—(*a*) A Great Northern Atlantic type of Locomotive (4—4—2). Weight, with tender, 112·5 tons
(*b*) The Great Bear (Great Western) (4—6—2). Weight, 94 tons

and the "Rocket" won. It weighed only $4\frac{1}{2}$ tons, while the modern engine weighs 100 tons. The boiler was 6 ft. long, 40 inches in diameter, and contained twenty-five 3-inch tubes giving a large heating surface, and enabling steam to be made rapidly. The cylinders were inclined, and the wheels were connected by a coupling-rod so as to increase the grip on the rails. (See Fig. 143, Plate 25.)

By the time that the line was opened several engines were ready, but the joy of success was marred by a terrible tragedy. Mr. Huskisson, M.P., a famous statesman, was knocked down and so badly injured that he died the same day. In conveying him to a place where he could receive attention, the "Northumbrian," with Stephenson on the footplate, covered a fifteen-minute journey at the rate of thirty-six miles an hour. The sad event secured great publicity for the locomotive, and led perhaps to a greater interest in it than would have been obtained if there had been no mishap.

During the next three years improvements were made, and the locomotive rapidly assumed the general form which is so familiar to-day. The cylinders were placed in front, underneath or on each side of the smokebox, and were horizontal or only slightly inclined. The boiler was supplied with a steam dome, in which was placed the valve admitting steam to the cylinders. The greater height of this valve above the surface of the water enabled drier steam to be obtained and thus reduced priming. Apart from these features, there was one outstanding invention due to Stephenson, or rather to one of Stephenson's workmen named Howe, which deserves a separate paragraph for its description. This is the link motion or reversing gear to enable the engine to run forwards or backwards.

The arrangement shown in Fig. 144 consists of a slotted link attached by pins to a pair of eccentrics

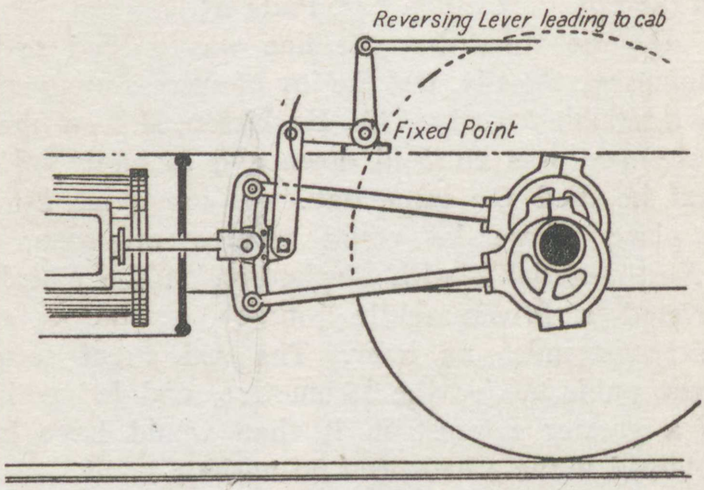


Fig. 144.—Stephenson's link motion

so placed on the shaft that when the latter rotated one would move the slide valve forwards while the other would move it backwards. The end of the valve rod is pinned to a block which is capable of sliding up and down in the link—or rather permits the link to rise and fall without putting any strain on the rod. When this link is raised or lowered by means of a lever in the cab, one or the other eccentric may be brought into operation, or by keeping the link in mid-position neither eccentric is operative. In intermediate positions of the link the valve is moved, but has a shorter stroke ; cut-off and release are therefore earlier ; the engine uses less steam but produces less power.

The Modern Locomotive

Nothing illustrates so strikingly the increase in size of the locomotive as the accompanying Fig. 145

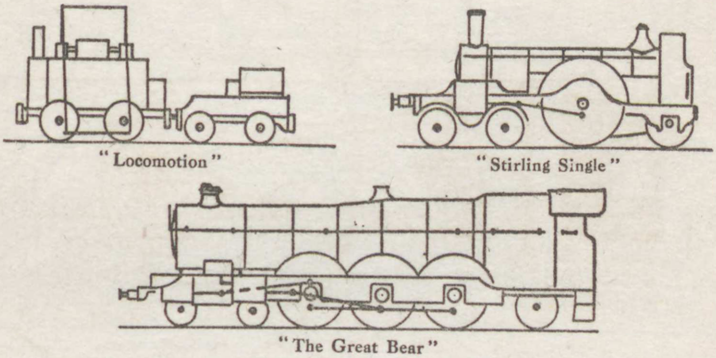
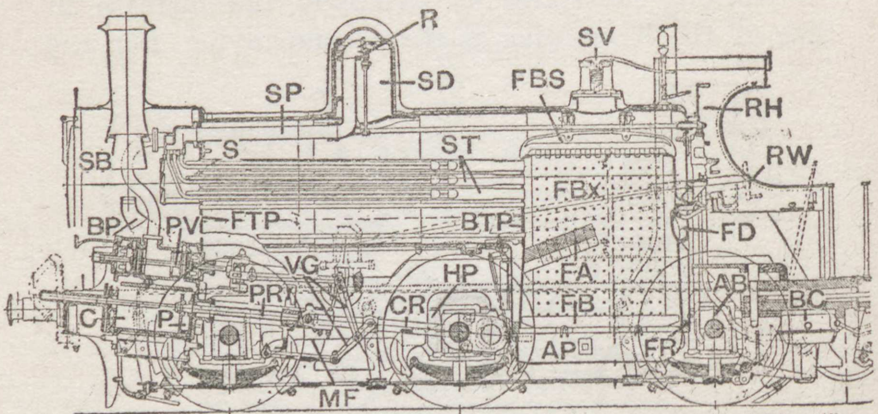


Fig. 145.—Stephenson's "Locomotion," a "Stirling Single," and "The Great Bear" to the same scale

copied from Mr. C. Edgar Allen's book on "The Modern Locomotive." Here we have, drawn to the same scale, the "Locomotion" of 1825, a Stirling's "Single" of 1870, and the G.W.R. "Great Bear" of 1905. The first named had cylinders of 10 inches bore, and not much smaller than the 15-inch by 26-inch cylinders of the "Great Bear." But whereas the steam pressure used in the former engine was only 25 lb. on the square inch, in the latter it was 225 lb. Moreover, the "Locomotion" had only two cylinders, and the "Great Bear" had four. Then, consider the relative weights of the engines—for it is this which gives rise to the friction between rails and wheels, and enables the engine to draw heavy loads. So that when we find that the weights on the driving wheels of the "Locomotion" was only $6\frac{1}{2}$ tons, while that on the driving wheels of the



From "The Modern Locomotive," by C. Edgar Allen

Fig. 146.—General arrangement of a modern locomotive

AB	Axle box	FA	Fire arch	HP	Horn plate	S	Super heater
AP	Ash pan	FB	Fire bars	MF	Main frame	SB	Smokebox
BC	Break cylinder	FBS	Firebox girder stay	P	Piston	SD	Steam dome
BP	Blast pipe			PR	Piston rod	SP	Steam pipe
BTP	Back tube plate	FBX	Inner firebox	PV	Piston valve	ST	Smoke tubes
C	Cylinder	FD	Fire-door	R	Regulator	SV	Safety valve
CR	Connecting-rod	FR	Foundation ring	RH	Regulator handle	VG	Valve gear
		FTP	Front tube plate	RW	Reversing wheel		

"Great Bear" was 60 tons, there is no wonder that the draw bar pull of 1,000 lb. of the earlier engine looks small compared with the pull of 26,000 lb. of the later one.

The general arrangement of a modern locomotive is shown in Fig. 146, and though the drawing is necessarily full of detail, the accompanying index to parts will render it intelligible.

The aim of the designer is, of course, to produce the largest quantity of steam at the required pressure in the smallest time. He is limited, however, by the gauge. The Great Western alone of the pioneer lines had the rails 7 feet apart. Stephenson chose 4 feet 8½ inches, and as all other railway builders in this country, except Brunel, followed his plan, the necessity for interchanging traffic forced the G.W.R. ultimately to alter their gauge. Thus, while the driving wheels are only 4 ft. 8½ in. apart, the boiler must be less than that. Moreover, tunnels and bridges in Great Britain had all been built to accommodate the pioneer engines of sixty years ago. The modern locomotive must therefore be built to pass through holes of limited size. It must not be more than a certain breadth, nor more than a certain height, and its rigid wheel-base must not be more than a certain length or it would not go round curves. It is like a giant in chains, always struggling to grow larger in order to draw heavier burdens, and always prevented.

When the limit in size has been reached, more power can only be obtained by producing steam more quickly. To produce a greater quantity of steam in a given time two methods may be used. One is to improve the circulation, and the other is to increase the grate area. A large improvement in the circulation could only be obtained by altering the type of boiler, and using water tubes instead of, or as well as, fire tubes; and though experiments in this direction have been made they have not yet been adopted on such a scale as to justify their inclusion in this book. Mr. G. J. Churchward, of the G.W.R., secured an increase in the size of the boiler by making it slightly conical, with the smaller end towards the front (see Fig. 145).

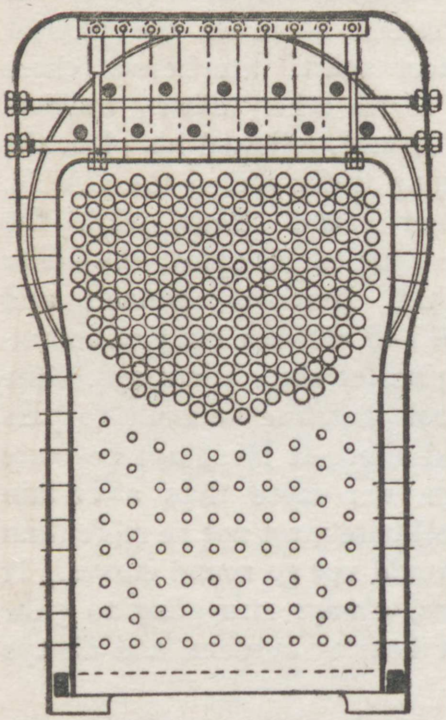


Fig. 147.—Belpaire firebox

This form has several advantages. In the first place, the greater volume of water is at the hottest end, and as a large firebox can be used, the heating surface is also increased. The steam dome is done away with, and there is less priming. Moreover, the surging backwards and forwards, when the engine slows down or increases its speed, is to some extent prevented, and there is less danger, therefore, of the crown of the firebox being uncovered.

In this engine, and also in the engines of the Midland, London and North Western, Great Central, Great Eastern, Lancashire and Yorkshire, and North

British Railway Companies a firebox (Fig. 147), invented by the Belgian engineer, Belpaire, is adopted. The outer casing has a flat top, and the crown of the firebox is parallel to and connected with it by stays similar to those used at the sides. In the diagram most of the stays are indicated only by their centre lines. Another form, tried to some extent in Great Britain, but much more frequently used in the United States, is the Wootten firebox, shown in Fig. 148, in which the side stays are shown only by centre lines and only a few of the tubes have been drawn. It is very wide at the base—sometimes more than 7 feet—and the frame of the engine must be so designed as to enable the firebox to fall well behind the rear driving wheels. The original object was to permit inferior fuel to be used. Generally, American and Canadian engines are larger and more powerful than British, and have exceptionally large fireboxes.

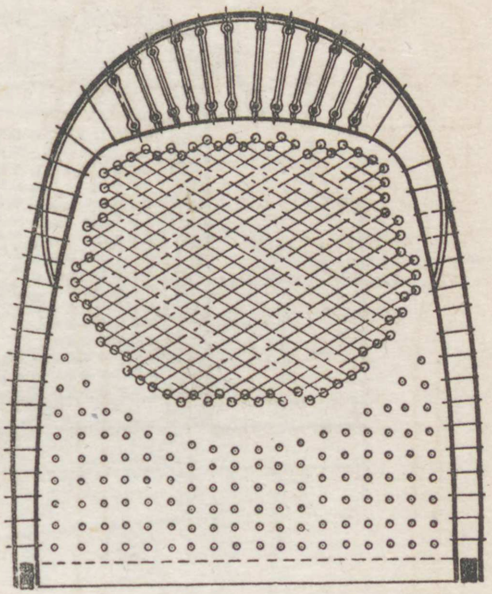


Fig. 148.—Wootten firebox

A typical English form is shown in Fig. 149, which also contains, to a larger scale, some of the details contained in Fig. 146. Here will be seen

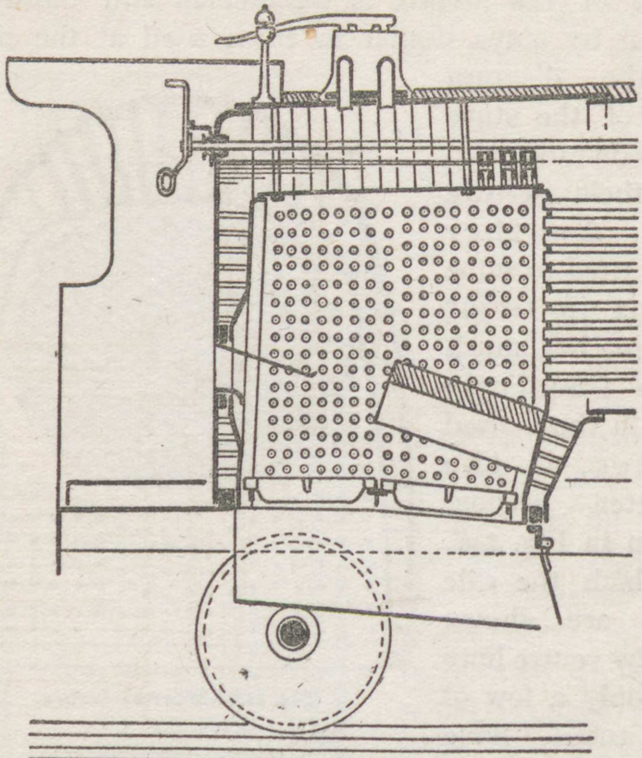


Fig. 149.—Typical firebox of British locomotive

the arrangement of the firebrick arch and the deflecting plate over the furnace door. From the footplate, in the cab of the engine, every lever and cock necessary in working is within reach. The furnace door, safety valve, injector, whistle, starting valve, reversing lever, and damper lever are close to hand.

The damper lever serves to regulate that portion of the draught which is due to the entry of air at the lower front end of the firebox, another part being created by the exhaust steam. The draught through the furnace of a locomotive when it is running at full power is so great that 25 per cent. of the fuel is thrown out of the chimney in the form of smoke and fine cinders.

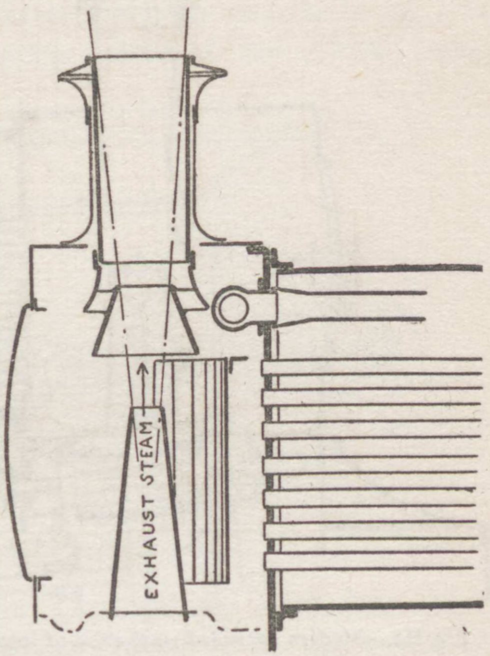


Fig. 150.—Short smokebox

Looking now at the other end of the boiler, we shall observe the smokebox. In the older engines, and still in many of those built to-day, the smokebox was comparatively short, as in Fig. 150. The exhaust steam passes up through the blast pipe and sweeps through the chimneys, creating, like all fluid jets, a reduction of pressure in its neighbourhood. The spark arrester is simply a flat plate placed in front of the draught tubes in order to intercept small cinders. Deprived of their velocity in this way, they fall to the bottom of the smokebox. The wide tube near the top, leading from the interior of the boiler, is the main steam pipe.

Fig. 151 shows in section the modern long smokebox, first introduced in America. It has the advantage that the draught through the tubes is stronger and steadier. An arrangement is indicated whereby the blast can be varied. In continuation of the main steam pipe just after it has emerged from the boiler is placed the superheater. This consists of a number of tubes bent in the shape of long U's and lying in wide flues in the upper portion of the boiler.[1] Through these the steam passes on its way to the cylinders, yielding more power than if steam at ordinary boiler temperature was used. Superheating was tried on locomotives many years ago, but experiments were not very successful.

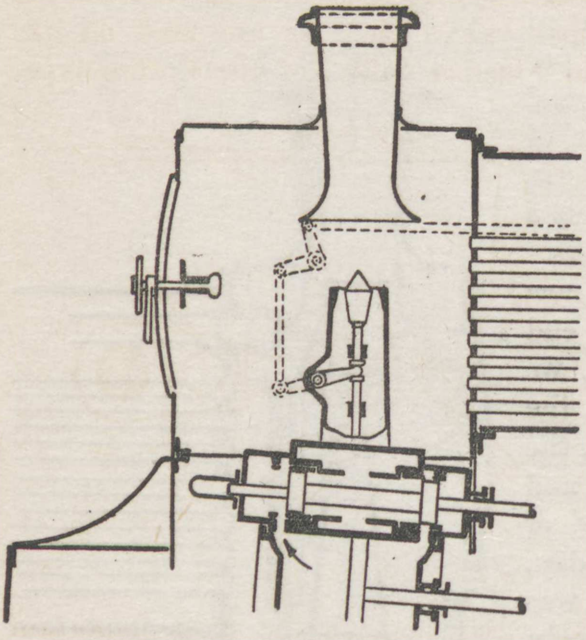


Fig. 151.—Modern extended smokebox of locomotive

[1] The superheater flues are not shown in Fig. 151.

Since 1900, however, it has become general, and there are now over 30,000 engines using superheated steam.

The cylinder valves on British locomotives are either " short D " slide valves or piston valves, which have already been described in Chapter V. On the Continent poppet valves, such as are used on gas engines, and in America valves of the Corliss type,

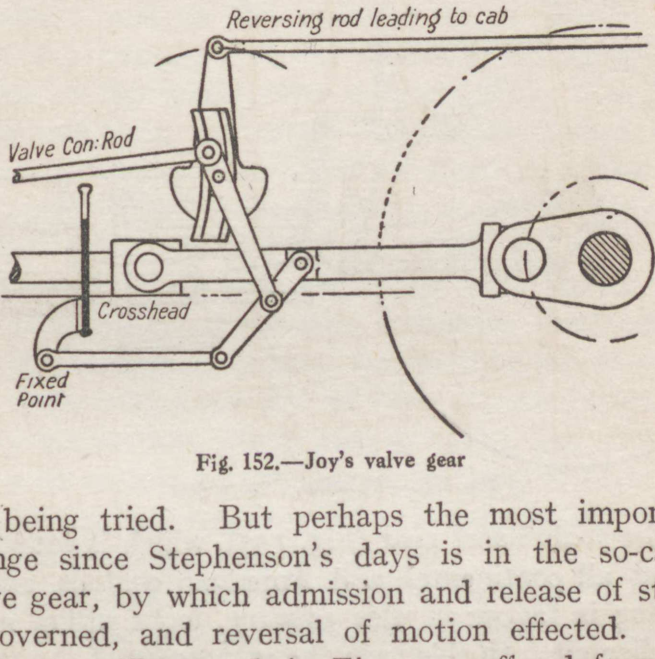


Fig. 152.—Joy's valve gear

are being tried. But perhaps the most important change since Stephenson's days is in the so-called valve gear, by which admission and release of steam is governed, and reversal of motion effected. The mechanism illustrated in Fig. 144 suffered from the disadvantage that the " lead " was altered when the link was moved.[1] The gear frequently met with in

[1] As, however, the gear can be arranged to give an increasing lead as it is " notched up," the variable lead is regarded as an advantage by some engineers on account of the fact that at high speeds the engine generally runs on short cut-offs, and an increased lead tends to reduce " wire drawing," which is explained in Chapter XII.

Great Britain is the Joy, shown in Fig. 152. The motion of the valve rod is effected through a system of levers driven from the connecting rod, and no eccentric is used. The best way to understand this and all other gears is to cut out models in thin cardboard and to study the position of the valve for every position of the crank, both on the forward and backward strokes.

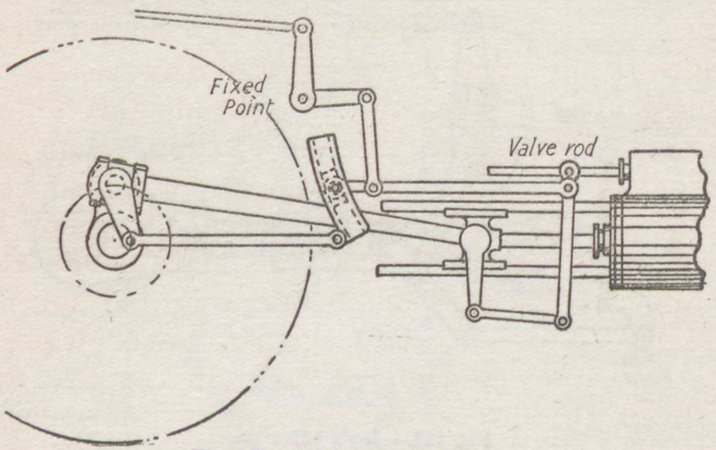


Fig. 153.—Walschaert valve gear

The Walschaert gear (Fig. 153), which is found on almost all continental and American engines, and is growing in favour in this country, looks rather more complicated. In this case the movement of the valve is effected partly by an eccentric, or, on outside cylinder engines, by a return crank. and partly by a lever pivoted to the cross head. The eccentric acting alone gives a valve movement in which there is no lead, and the cross-head motion supplies lead.

British engines have usually two cylinders of the same size, each taking steam directly from the boiler; but a few of the most powerful types have four cylinders. Compound engines, which are popular on the Continent and in the United States, have been tried in this country and discarded. One disadvantage lies in the fact that steam enters the cylinders in succession, so that when starting from rest the whole of the duty falls upon the high-pressure cylinder; and as this cylinder has a smaller bore than the cylinders of an ordinary double-cylinder engine of the same power a heavy train is only set in motion with difficulty. To obviate this a "by-pass" is arranged so that, on starting, steam may be admitted to both cylinders at once, and compound working reverted to when the train has acquired a fair speed. But this adds to the complication of the mechanism, increasing the first cost and the expense of up-keep, and must be set off against the gain from economy of fuel. In countries such as Great Britain, where coal is cheap, the saving in the cost of fuel by compound working is said to be insufficient to compensate for the increased cost of construction and maintenance.

Let us now consider the different types of engines and see how they are distinguished from one another. The terms "express," "goods," etc., do not convey much information, and a more exact classification is based upon the arrangement of the wheels. Thus if the connecting rod acts upon only one pair of wheels—that is, if there are no coupling rods—the engine is called a "single"; if two pairs of wheels are "coupled," it is known as a "four-coupled"; and if three pairs are connected it is termed a "six-coupled" engine. All these are "driving wheels" because the power is applied to them, and their "grip" on the rails determines the motion of the train.

In some of the smaller engines there is a single pair of wheels in front, but generally the weight of this end is supported on a "bogie" truck with two pairs of wheels. The truck is pivoted to the engine frame so that it can turn slightly when the engine goes round a curve. Usually, but not always, there is a pair of trailing wheels or a bogie truck at the back.

The chief types are shown in Fig. 154, which will indicate the meaning of the terms "2-2-2," "4-6-4," etc., used in describing them. The names are those of the first engine of the type constructed, and they serve to describe the class to which this and all similar engines belong. A great many passenger express engines are of the 4-4-2 and 4-6-0 types, which, for this purpose, have displaced the types 2-4-0 and 4-4-0. On the G.W.R. the 2-6-0 type is used, but the "Great Bear" is a 4-6-2 engine. Heavy goods engines are often 0-6-0 and 0-8-0, which gives a large grip on the rails, but owing to the absence of leading and trailing bogies are not good for taking curves at high speeds. Heavy shunting engines, which need a good grip on the rails and have to negotiate points, are often of the 4-8-0 and 0-8-4 types. The "Decapod," 2-10-0, and "Santa Fé," 2-10-2, are types of American engines for very heavy trains over steep gradients.

English railways were, from the beginning, built in a substantial manner, with small gradients and curves of large radius; for they were laid for the most part through thickly populated country dotted with the factories and workshops which had grown

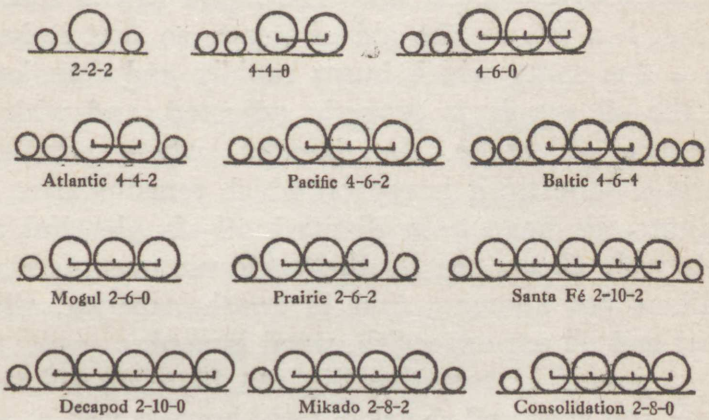


Fig. 154.—Wheel arrangements

up under the Industrial Revolution. But in North America and the Colonies the railway was the pioneer agent in opening up the country, and until the land was settled very little return on the outlay was possible. In recent years the Canadian Pacific Railway Company, for example, has spent millions in easing the gradients and smoothing out the curves.

The trouble from curves can be overcome to some extent by articulated locomotives—that is, locomotives with joints in them. In America the Mallett articulated locomotive is very largely used, and in Western Australia the Garrett is used. The latter is really two engines on separate trucks with a boiler between.

Again, while coal is the usual fuel, many engines are constructed to use oil or tar. The only English company which adopts this plan is the North Eastern, which uses tar or tar oil. The liquid fuel is sprayed through a jet, by the aid of steam, so that it issues in a fine spray which burns rapidly and completely if the oil supply is properly adjusted, and with an absence of smoke. In America, where petroleum residue—the thick heavy oil which remains after the lighter oils have been distilled off—is plentiful and relatively cheap, the South Pacific use over 3,000,000 gallons per annum. And in South America, where coal and oil are expensive, wood is used.

A powerful locomotive (Fig. 155, Plate 26) will weigh over 100 tons and develop 1,500 horse-power, so that in the ninety-nine years which have elapsed since the "Rocket" achieved success the locomotive has grown considerably. Heavier and more powerful than this it is not likely to be on British railways, because of the limitations imposed by gauge, tunnel, and bridge; but it may well become more economical. Every year our railways consume 13,000,000 tons of coal, and though we were endowed with a wonderful stock of this fuel it will not last for ever. That is why locomotive engineers have adopted superheating, and it will probably lead to feed water heating, which has already been tried on the L. & S.W.R.

CHAPTER XI

Engines for Ships

JUST as the railway facilitated intercourse between town and town, so the steamship brought nations separated by wide seas into close and intimate relation. In olden times great civilisations grew and flourished along the shores of the Mediterranean, and ships laden with merchandise ploughed the waters of the tideless sea. Of the remote interiors of Europe, Asia, and Africa little was known, while what lay westwards, across the vast unexplored ocean, was still more a matter of speculation and a field for fancy. When ships sailed southwards or eastwards from Aden, or ventured past the frowning rock of Gibraltar, they hugged the coastline, and the sailors told tales wonderful and terrible of those who were supposed to have ventured into the unknown.

The great oceans began to yield up their secrets at the end of the fifteenth century, when Vasco da Gama and other navigators made longer voyages than any which had been attempted before. Gradually, as the centuries passed, Portuguese, Dutch, French, and British seamen acquired greater confidence and skill. An oceanic voyage, though fraught with peril and discomfort, no longer called for the reckless daring of pioneers and adventurers; but the ships were at the mercy of wind and tide, and until the giant steam could be harnessed in the mariner's service speed and regularity were alike unattainable.

From the time that the latent power of steam first attracted attention men sought to apply it to the propulsion of ships. Neither the early inventors of the steam carriage nor the pioneers of steam navigation waited for the steam engine to be perfected as an engine before they attempted to apply it to their cherished purposes, and the early history of the factory steam engine, the locomotive, and the marine engine belongs to the same period as the early history of the steam engine itself. But there was no satisfactory solution until James Watt had discovered the conditions under which power could be economically obtained.

Watt patented his rotary engine in 1782, and five years later Fitch constructed a steamboat with paddles at the sides which drove the vessel along very much in the way that an Indian propels a canoe. Again, in 1801, Lord Dundas and an engineer named Symmington launched the *Charlotte Dundas*, which showed by its performance that the idea was not impracticable.

The first passenger vessel built in Europe was the *Comet*, constructed by Henry Bell in 1812. She was 40 feet long, 10½ feet beam, and had two paddles on each side, driven by a 3 horse-power engine. For a number of years she made three return journeys per week between Greenock and Glasgow, a distance of twenty-four miles.

Bell, however, was anticipated by Robert Fulton, an American, who about 1793 forsook art for engineering. From the beginning he went about his work in a scientific spirit, making numerous experiments to ascertain the resistance of various forms when towed through the water. His first vessel was launched on the Seine in 1803 and broke up—an accident which not infrequently happened in those days. In the following year he ordered a Boulton and Watt engine, which he conveyed to America in 1806. The *Clermont* was launched on the Hudson in the spring of 1807, and before the end of the year had astonished the world with its performance. It was 133 feet long, 18½ feet beam, and 9 feet deep. With Watt's engine and a pair of paddles it made the journey from New York to Albany, a distance of 150 miles, in about thirty hours. Dry pine wood was used for fuel, so that smoke, sparks, and flame issued from the funnel, and as it sped along the river in the darkness there were not a few timorous people who thought that the end of the world had arrived.

Fulton also built the first steamship of war, the *Fulton the First*, in 1814. It had two hulls, side by side, with a space between them for a single paddle wheel 16 feet in diameter. The sides were 4 feet 10 inches in thickness, and the armament consisted of thirty 32-pounder guns for throwing red-hot shot. A copper boiler, 22 feet long, 12 feet wide, and 8 feet high, provided steam for the engine, which had a cylinder 48 inches in diameter with a stroke of 5 feet. A curious contrast, surely, to the warships of to-day!

The successes of Fulton and Bell naturally led to an enormous development. In 1814 there were only five steamers in Great Britain, in 1820 there were 34, and in 1840 there were 1,325. By that time the Atlantic had been crossed by vessels depending entirely upon steam, and the first regular transatlantic service had been established. The ships were still of wood, and were provided with paddle-wheels. Iron ships came in about 1850, and the screw propeller began to displace paddle wheels about ten years later. In the eighties large vessels were fitted with twin screws, and with the dawn of the twentieth century the largest vessels were propelled by triple screws.

One of the marvels of the nineteenth century was the *Great Eastern*, built by the brilliant but, in some respects, unfortunate engineer Brunel, and launched in 1858. This huge vessel was 692 feet long, 83 feet beam, 60 feet deep, and displaced 24,000 tons. She was propelled by both a screw and paddle wheels. The latter were 56 feet in diameter, and the screw was 24 feet. Four engines were required for each. The cylinders were 6 feet 2 inches in diameter, and steam was supplied by ten boilers with seventy-two furnaces. The horse-power was 8,000.

In size these engines compare very favourably with those of modern ships, but they are far inferior to them in power. Thus the *Olympic* has not ten, but twenty-nine boilers, each weighing not 50, but 105, tons; and while the *Great Eastern* consumed only about 300 tons of coal per twenty-four hours the

Mauretania requires 1,000 tons. But before considering modern marine engines, let us glance at the changes which have taken place in their form since the *Clermont* and the *Comet* clove the waters of the Hudson and the Clyde.

The Evolution of the Marine Engine

The first satisfactory engine, it will be remembered, was a pump, in which the pump shaft was operated by a beam. When Watt adapted his engine for rotary motion he still retained the beam, and the early builders of marine engines followed his example. But as the beam took up a lot of room they soon began to fix it low down at the side. Long connecting rods from the cross head were pinned to one end of the beams, and the other end operated the cranks on the paddle-wheel shaft through short connecting rods. This side-beam engine persisted for a considerable time.

Another type peculiarly adapted for paddle boats was the oscillating cylinder, invented by Murdoch. This in its single-acting form will be familiar to every boy who has received a cheap model engine as a birthday or Christmas gift. The cylinder is pivoted to a block through which two holes are bored. One of these holes is connected with the boiler through the steam pipe, and the other leads to the air or to a condenser. As the crank shaft turns, the cylinder swings about the pivot, and a hole leading into the upper end of it is brought alternately opposite to the steam and exhaust ports in the block. Steam is therefore alternately admitted to and released from the cylinder.

In the double-acting oscillating engine the cylinder is pivoted at its centre, and there are ports leading to each end. The block, to which the cylinder is pivoted, has one steam and two exhaust ports, and steam is admitted and released by the swinging of the cylinder about the pivots as the crank turns. The advantage of oscillating engines lies in the fact that no connecting rod is used, and that space is, therefore, saved. Even to-day they are to be seen on many paddle steamers plying on lakes and rivers, but for efficiency they cannot be compared with modern engines.

The cramped space on board ship led to inclined engines, built on sloping bedplates, being used for paddle steamers, and on screw steamers engines with a return connecting rod were employed. The vertical form, with the cylinders over the shaft, was slow to be adopted, because the A-shaped standards had to be very heavy castings in order to withstand the vibration. But with improved materials and workshop processes this form gradually replaced every other, because it took up less space and the parts were more readily accessible.

Ever since they were introduced by John Elder in 1850, compound engines have always been employed on ships. The shipowner wants to carry as little coal as possible in order to provide the largest space for profitable cargo, so he demands engines which will give the greatest amount of power for the smallest consumption of fuel. Moreover, since boilers produce steam more economically at high than at low pressures the boiler pressure has risen to 200 or 225 lb. on the square inch, and with these high pressures two cylinders are insufficient, so that triple- and quadruple-expansion engines are employed, though the latter are less common.

It must be remembered that a four-cylinder engine is not necessarily a quadruple-expansion engine. Thus, if the boiler pressure is high the low-pressure cylinder tends to become unduly large, and frequently two low-pressure cylinders are used. In this case the best balancing is not obtained by having the cranks at right angles, but at such angles as to suit the arrangement of the cylinders, and to balance most effectively the rotating parts, The two low-pressure cylinders are generally placed at the ends, with the high-pressure and intermediate cylinders between them. This is the plan adopted on the White Star liner *Olympic*.

The Modern Marine Engine

Let us now consider the modern marine engine of the reciprocating type—the kind of engine which was universal from about 1860 to 1890, and which is still employed for ships of moderate speed.

First (see Fig. 156), there is a strong, heavy bedplate carrying the bearings and provided with "wells" into which the cranks are able to dip. On the bedplate are bolted firmly the A standards which support the cylinders and provide the guides for the cross head.

Small engines for launches, etc., frequently have only a half standard, the front of the cylinders being held up by a steel rod, a plan which reduces weight and renders the moving parts more accessible. The shafts

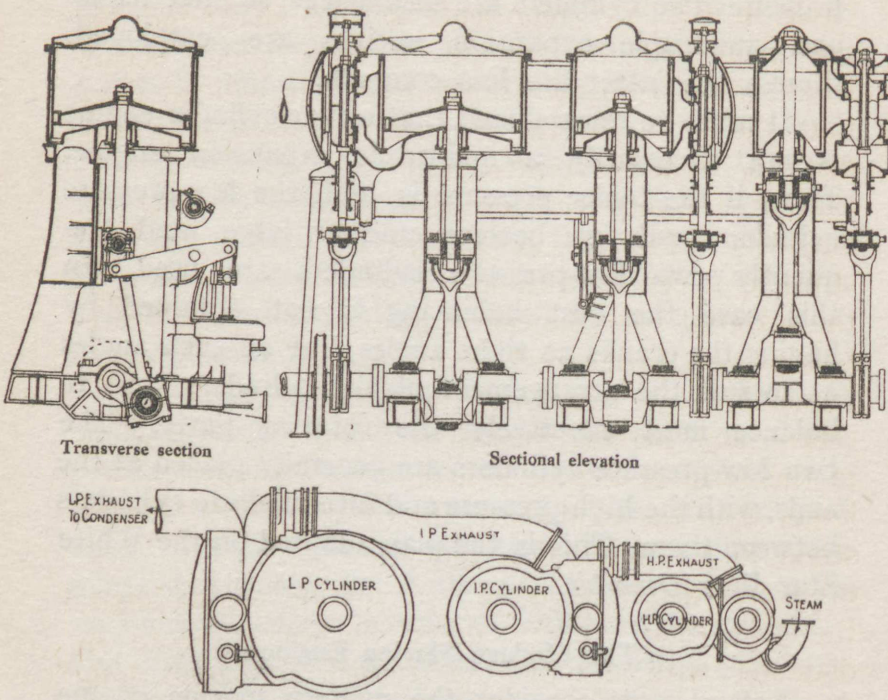


Fig. 156.—Three views of a triple expansion marine engine

of marine engines are generally made hollow, and though larger in diameter than a solid shaft of equal strength, they are lighter. The elementary scientific fact involved here is worth a short explanation.

In a marine engine the power is applied at one end of a long shaft and given out at the other. As a rule, the shaft must be long, because the engine room cannot be placed in the rapidly narrowing portion of the ship near the stern, and a blunt stern reduces the speed. The transmission of power through a long shaft in this way causes twisting. Suppose the circle in Fig. 157 represents a solid shaft and the two diameters the amount of twist which occurs when power is being transmitted. It will be clear that the strain in the material increases with the distance from the centre, and that if the material on the outside is bearing as much stress as it can do with safety, the material near the centre is bearing very little stress. Consequently by removing the centre and making the shaft in the form of a tube a little larger than the solid shaft, the stress in the material is more even and weight is saved. A marine engine shaft, therefore, may be 12 to 24 inches or more in diameter with a 6-inch or 10-inch or larger hole through its entire length. It is made in sections, bolted together by means of flanges.

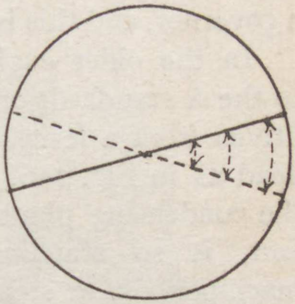


Fig. 157.—Diagram to illustrate torsion of a shaft

The high-pressure cylinder of a marine engine is invariably fitted with a piston valve, because with this form there is the smallest friction and a most perfect balance under high pressure of steam. The intermediate and low-pressure cylinders have long double-ported D slide valves. In order to secure lightness the pistons are of cast or pressed steel, conical in form, as shown in Fig. 156, and the cylinder covers are designed to match as nearly as possible the upper and lower surfaces of the pistons in order to reduce the amount of "clearance."

Since the vessel is required to move both ahead and astern the engines must be fitted with reversing motion, and Stephenson's gear is generally employed. Further, as the engine tends to race when, in rough weather, the screw rises out of the water, there must be a governor, and this is usually fixed on the crank shaft.[1]

In the older engines the condenser was attached to the A standards on one side while the air pump was driven from a lever pinned to the low-pressure crosshead as in Fig. 156. But the modern plan is to have the condensing plant entirely separate. Nothing, in fact, is so startling as the amount of auxiliary machinery on a steamship, and the consideration of air pumps and condensers, circulating pumps, evaporators, ash extractors, etc., connected with the main engines, together with the steering engines, winches, and what not, deserve a book all to themselves.

For the present let us concern ourselves with the main engines, tracing the steam from the boiler to the condenser and beyond. Steam is, of course, raised more quickly if water tube boilers are installed, but these are to be found only in the highest class

[1] A centrifugal governor is not really sensitive enough to deal with the large alterations of speed which occur when a rough sea is running. The best arrangement is one in which the admission of steam is controlled by the pressure of water in the neighbourhood of the propeller. When the stern sinks the pressure increases, and this, acting on a piston, causes the throttle valve to open. Similarly, when the stern rises the reduction of pressure closes the valve.

of liner and in ships of war. All cargo vessels and tramp steamers—and, indeed, many liners—are fitted with the single or double-ended marine boiler. There is one interesting device for improving the circulation, when steam is being got up in the main boilers, which

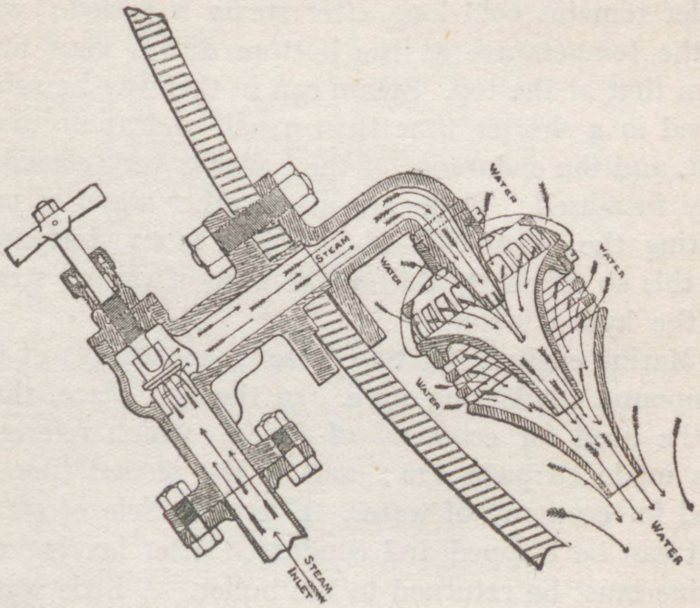


Fig. 158.—Weir's Hydrokineter

is worth describing. This is Weir's Hydrokineter shown in Fig. 158. It consists of an injector, fitted just inside the casing of each of the main boilers, and supplied with steam at a pressure of about 30 lb. on the square inch from a donkey boiler—that is, a small separate boiler used to supply a "donkey" or "general utility" pump. Condensed steam alone issues from the first nozzle, but in the case of the second and third nozzles, water is drawn in through the slots in the upper portions, and the jet from the first is reinforced. In his "Manual of Marine Engineering" Mr. A. E. Seaton says:

"Without this instrument the bottom of a large boiler remains cold long after steam is raised; with it the temperature at the bottom differs very little from that at the top. Steam can in this way be safely raised in a shorter time than usual, and at no extra cost, and the endurance of the boiler is very considerably increased. There are many other ways of promoting the circulation when steam is up, but none do this so efficiently during the time of raising steam as the hydrokineter."

Marine engines, for two reasons, are always of the compound condensing type. In the first place, there is the need for economy of fuel to which reference was made on page 272; and in the second there is need for economy of water. Every particle of steam that can be trapped and condensed after leaving the engine must be returned to the boiler. A little waste is unavoidable, and this has to be made up by the evaporation from sea water, because space is far too valuable for cargo to be used in carrying fresh water to supply the boilers. The air pumps and condensers must be highly efficient, therefore, not only to extract the last unit of energy from the steam, but also in order to retain as much as possible of that steam for returning to the boilers. Moreover, if reciprocating engines are used the steam must be passed through filters to remove oil, to avoid trouble in the boilers.

As the only cooling water available is salt, jet condensers are inadmissible, and surface condensers are used. The surface condensers do not differ greatly from those used on land except that as space

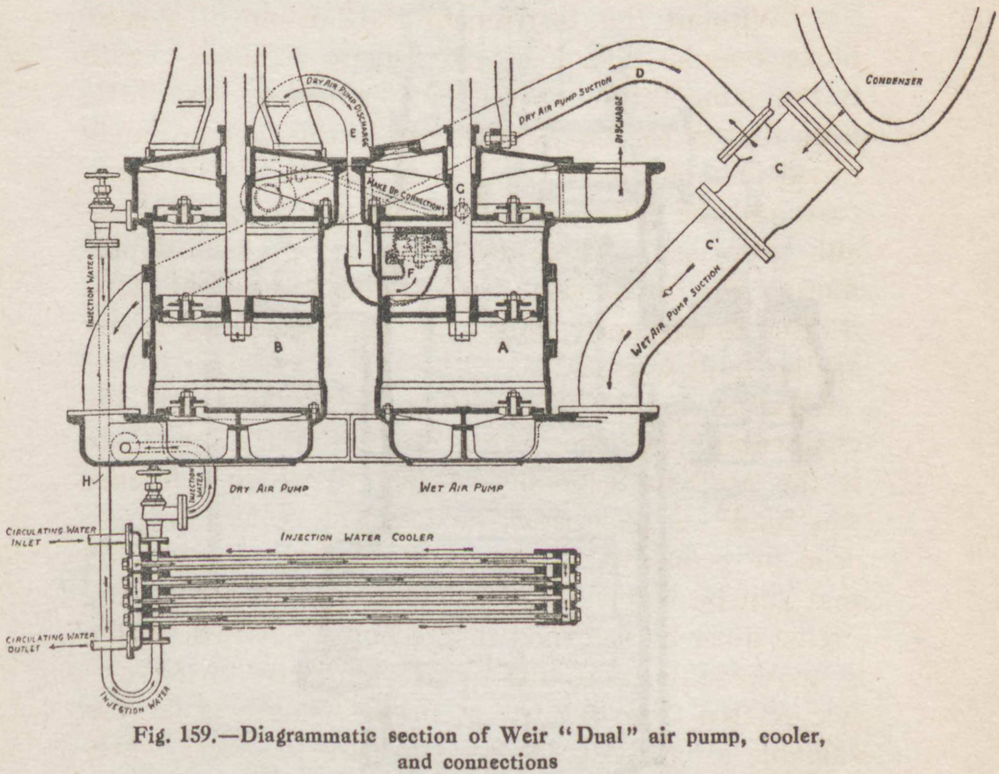


Fig. 159.—Diagrammatic section of Weir "Dual" air pump, cooler, and connections

is valuable the smallest and most efficient form must be adopted. The air pump, again, need differ in no important respect from that employed in land stations, and it may be driven by means of levers from the main engines or have its own separate steam cylinder. For the highest possible vacua Messrs. Weir and Co., of Glasgow, recommend two pumps, as in Fig. 159, arranged so that one removes only dry air from the

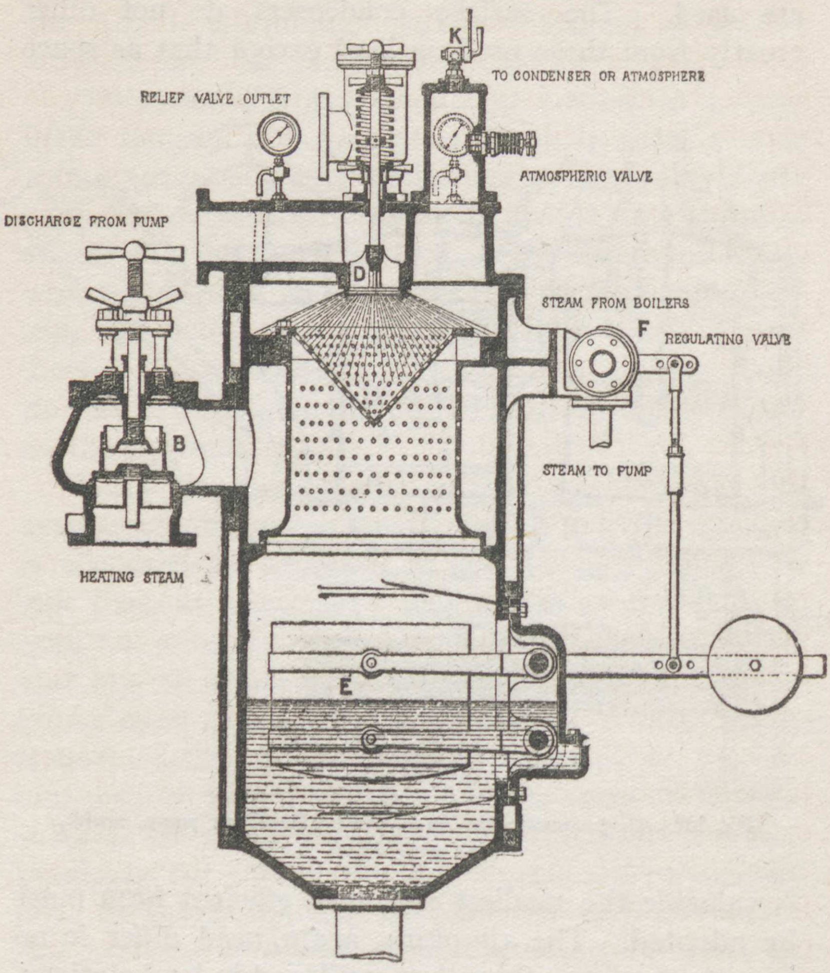


Fig. 160.—Weir's direct contact feed water heater

condenser and the other the condensed steam. The efficiency of the dry air pump depends upon its working at the lowest possible temperature so as to remove the greatest possible quantity of air per stroke. The efficiency of the wet air pump, on the other hand, depends upon the removal of the condensed steam at the highest possible temperature, so that it will require the smallest amount of heating before it goes back to the boiler. The temperature in the dry air pump is kept down by means of an injection of cold water.

Another device of Messrs. Weir, who have made a speciality of auxiliary machinery, not only of ships but also of land stations, is the direct contact feed water heater shown in Fig. 160. The steam for heating is drawn from the low-pressure receiver of the main engine and the exhaust of such auxiliary engines as pumps, electric light, and fan engines, etc., and it is led into the heater through the non-return valve B. From thence it passes through the perforated cylinder and mixes with feed water delivered through the spring-loaded valve D and the conical spray piece in the form of a fine spray. Any air contained in the water is liberated and escapes into the condenser or into the atmosphere through the cock K. The level of the water in the heater is kept constant by an ingenious self-regulating device. The float E is a pan, suspended on levers so that the levers are horizontal when the pan is full of water and immersed to half its depth. The position of this float regulates the amount of steam supplied to the feed pump through the regulating valve F.

Probably the most popular pump for marine

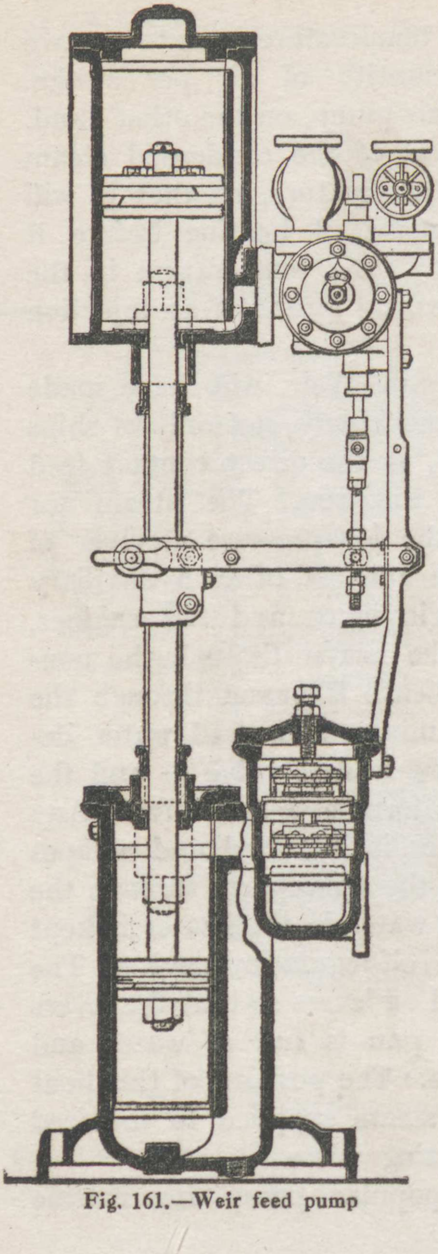


Fig. 161.—Weir feed pump

engine work is that made by Messrs. Weir—in fact, it is also used very extensively for land installations. Unfortunately, it is a very difficult pump to describe, and the reader who desires to understand how the admission and release of steam is controlled will have to follow the accompanying diagrams very closely. The whole pump, except the steam chest, is shown in section in Fig. 161. Fig. 162 shows the ports C, H, and D by which steam enters or leaves the cylinder. Fig. 163 shows a horizontal section, and Fig. 164 a vertical section through the valves of which there are two. Referring to Figs. 163 and 164, A is the main valve, which is operated by steam and the purpose of which is to distribute steam to the pump cylinder, and B is the auxiliary valve, the main purpose of which is to distribute steam to work the main

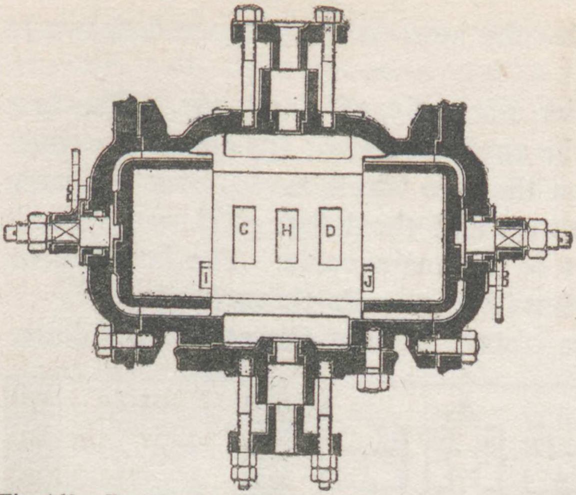


Fig. 162.—Ports through which steam enters or leaves cylinder of Weir pump

valve. Both valves have a simple sliding motion; but in Fig. 163 the main valve, which is a cylinder, moves backwards and forwards from right

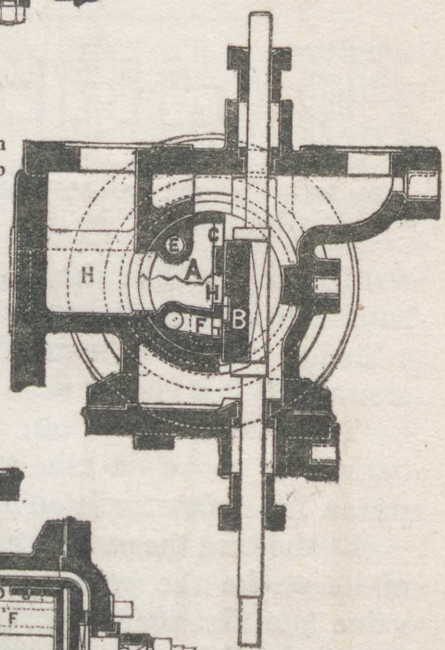


Fig. 164.—Vertical section through valves of Weir pump

to left, and the auxiliary valve is pushed

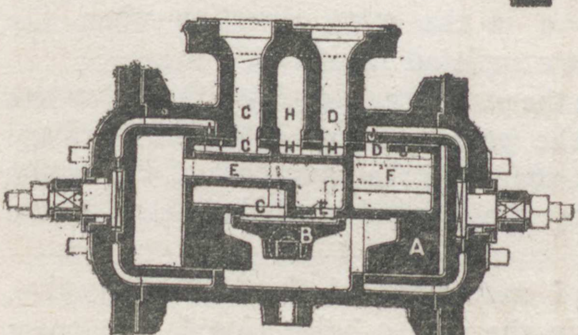


Fig. 163.—Horizontal section through valves of Weir pump

up and down by the nuts on the pump rod shown in Fig. 161.

Now examine Figs. 165, 166, and 167. The first named shows the auxiliary valve; the dotted lines indicate a recess on the face which moves over the main valve. The second and third figures show the front and back faces of the main valve. The lettering on the different views corresponds throughout.

Suppose the piston to be at the end of the down-

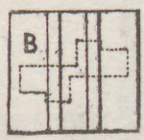


Fig. 165.—Auxiliary valve

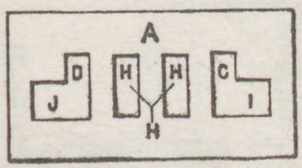


Fig. 166.—Main valve face

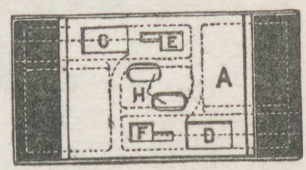


Fig. 167.—Main valve back-face for auxiliary valve

ward stroke. Then the main valve is in the right-hand position, as shown in Fig. 163, and the port C leading to the bottom of the cylinder is open to steam. This is clearer from Fig. 164.

The piston now rises, and the auxiliary valve begins to move in the same direction when the piston has half completed its stroke,

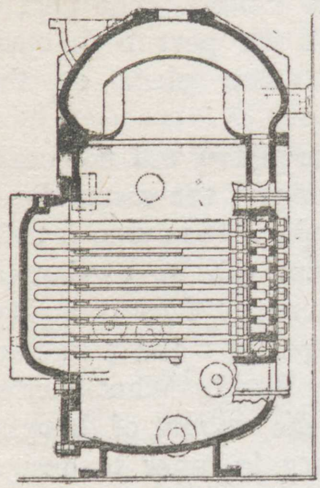
By the time the piston has completed three-quarters of its stroke the port C is closed by the auxiliary valve (see Fig. 164), and the remainder of the stroke is completed by the expansion of the steam in the cylinder.

The upward movement of the auxiliary valve, which results in the port C being closed, also opens to exhaust the port E, leading to the left-hand end of the main valve. At the same time, it admits steam through F to the right-hand end of the main valve, causing it to be forced to the left against the cushion formed by the exhaust steam. The port C is now open to exhaust, and the port D is open to steam. The same action takes place on the down stroke.

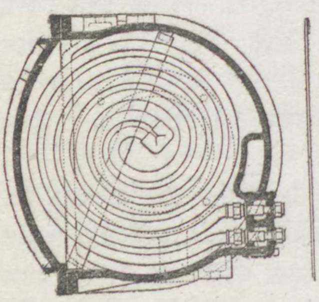
Under certain conditions the piston will not complete its stroke by the expansion of the steam from three-quarter stroke—for example, if the pump is cold on starting, much of the steam will be condensed and the piston will come to rest. This difficulty is provided against by the by-passes I and J in Fig. 162, which can be operated by hand. What excites admiration about this pump is the amount of thought which must have been necessary in order to design the valves and ports by which the distribution of the steam is so delicately controlled. The sea-going engineer, however, would say that what he admired most was its efficiency and reliability. He is less interested in pretty devices than in results. And, after all, this is the main test.

Although the steam used by the main engines and auxiliary apparatus is condensed and returned to the boilers, there is a small loss of from 4 per cent. to 8 per cent. daily, which has to be made up; and to carry this amount of fresh water would be impossible. For suppose a 10,000 horse-power vessel to evaporate 12 lb. of water per horse-power per hour, the total evaporation per hour will be 120,000 lb., and for twenty-four hours it will be 2,880,000 lb.

Five per cent. of this will be 144,000 lb., or more than 64 tons, and for a voyage of only ten days' duration more than 640 tons of fresh water would have to be carried to supply the boilers alone, to say nothing of the requirements of the passengers.



Vertical section



Horizontal section

Figs. 168, 169.—Weir's Lunette evaporator

It follows, therefore, that every ship must carry evaporators by means of which fresh water can be prepared from sea water. An evaporator is really a boiler, charged with sea water, which is heated by means of coiled pipes supplied with steam. Horizontal and vertical sections of one of Weir's Lunette type evaporators are given in Figs. 168 and 169. It will be seen that there are a number of copper coils placed one above another in the lower part of the evaporator, which has a door in the side so that they can easily be removed and cleaned. The steam is usually taken from the main boilers. The older plan was to take it from the intermediate cylinder valve chest, but the higher temperature of the steam in the boilers enables smaller evaporators

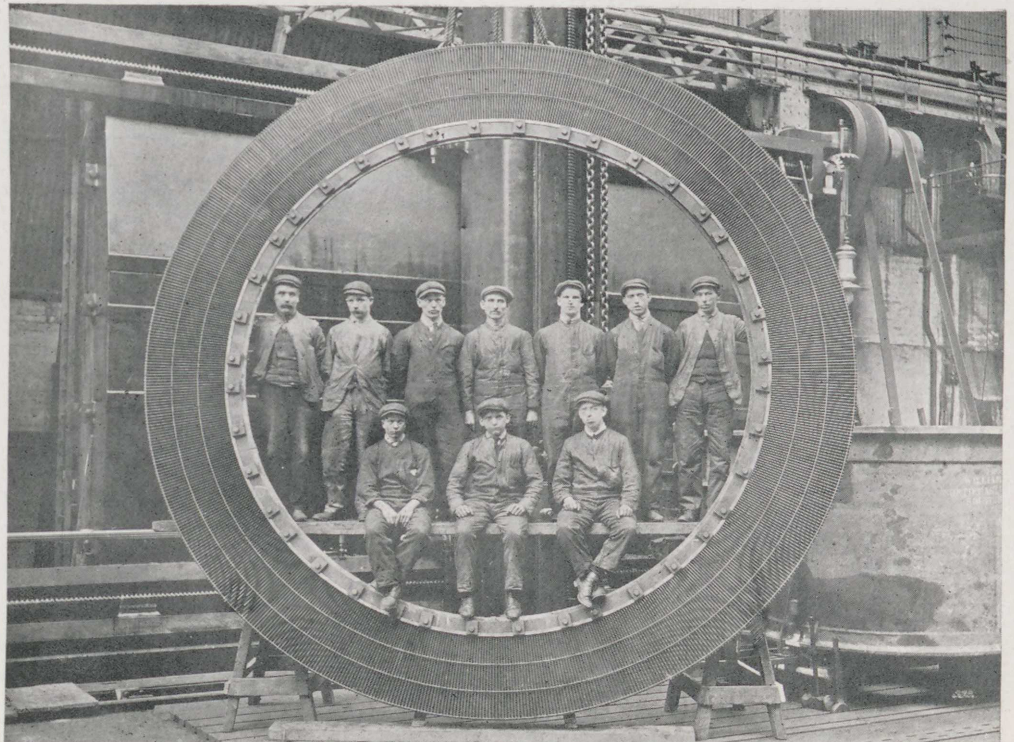


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Fig. 171.—Turbine Blading of the *Mauretania*

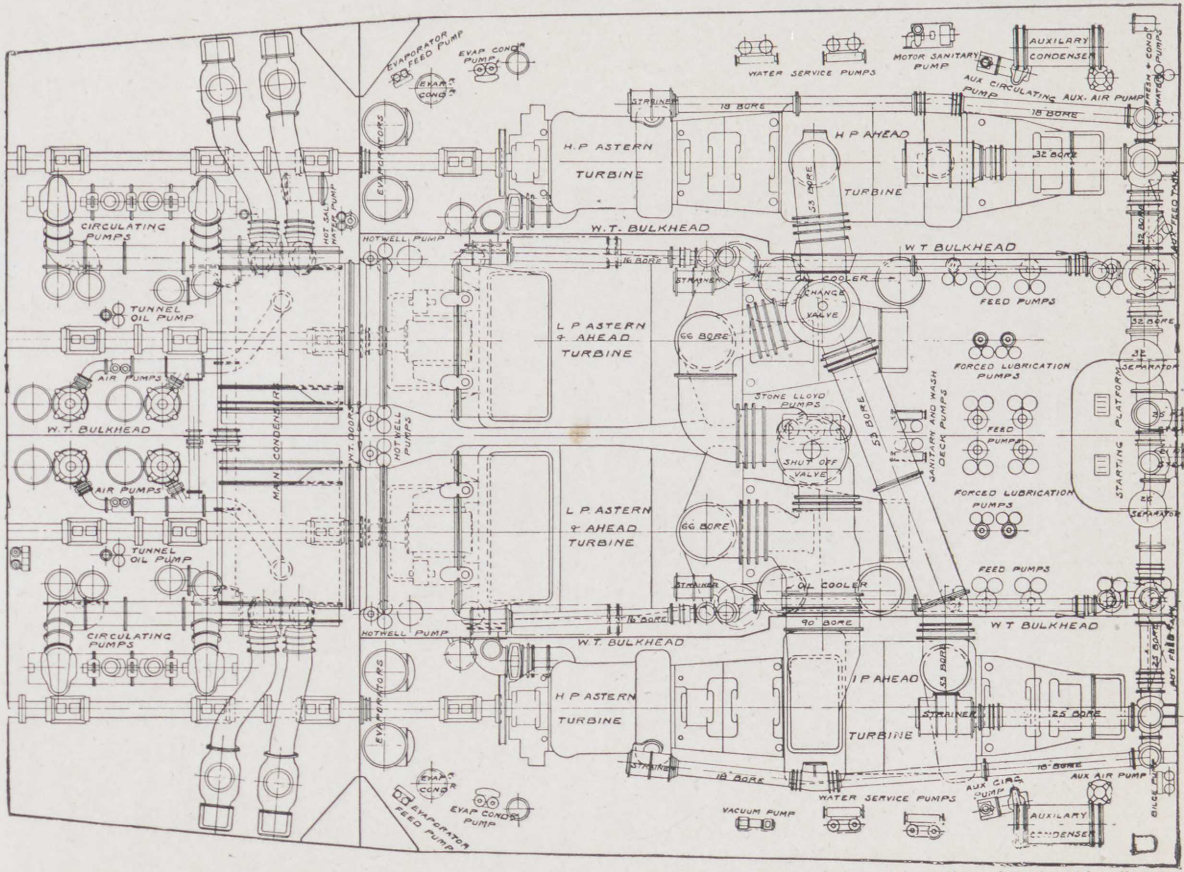

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Fig. 173.—Plan of Engine Room of the *Aquitania*

to be used. The one illustrated is made in sizes to produce from 20 to 80 tons of distilled water per day; the largest is 9 ft. 8 in. high and occupies a floor space of 5 ft. 6 in. by 4 ft. 3 in. But that is only a small fraction of the space which would be required for the water.

The Machinery of Great Ships

The steam turbine was first used for marine propulsion about twenty years ago, when a small vessel, the *Turbinia,* which was about 100 feet long, accomplished a speed of 32 knots, beating by 8 knots the fastest vessel then afloat. After this experiments were made on both war ships and fast passenger vessels leading to a considerable increase of speed as well as economy. The greatest triumph of all, perhaps, was secured by the sister ships *Mauretania* and *Lusitania,* of the Cunard Line. Since they were launched in 1907 these vessels have been surpassed by other vessels of the mercantile marine in size, but never in speed, and the *Mauretania's* 26 knots still remains a record for a merchant ship.

This wonderful vessel has twenty-five boilers, twenty-three double-ended, the other two being single-ended as in Fig. 35.

The former have eight and the latter four furnaces each, so that there are 192 furnaces altogether, and these require 192 stokers and 120 trimmers, working in shifts to keep them fired. This duty is not left to the men to do or not as they think fit. On many ships the orders for firing are sent from the engine room, because the engineer in charge has the responsibility of keeping up steam. This plan is followed on all big ships. Each of the *Mauretania's* double-ended boilers is 22 feet long, 17 feet 3 inches in diameter, and weighs about 100 tons. Every twenty-four hours they consume 1,000 tons of coal, and the quantity required for a return voyage between Liverpool and New York is equivalent to twenty-two train loads, each train consisting of thirty 10-ton trucks.

To carry off the waste gases are four funnels, oval in shape, about 100 feet high, with a long diameter of 23 feet 7 inches and a short one of 16 feet 7 inches. The ashes are removed by means of See's ash ejectors. They are shovelled into receptacles, swept upwards through an inclined tube and over the side by a jet of water. This is shown on the left-hand side of Fig. 170.

Propulsion is effected by four screws, two driven by high-pressure and two by low-pressure turbines, and two high-pressure turbines on the inner shafts for going astern. The high-pressure "ahead" rotors are 8 feet in diameter, mounted on hollow shafts 3 feet in diameter, with blades from 2½ to 12 inches in length (see Fig. 171 on Plate 27).

The rotor and shaft weigh 72 tons. The low-pressure drums are 11 feet 8 inches in diameter on shafts 4 feet 4 inches in diameter, with blades from 8 to 22 inches, and weigh 126 tons each. The length of the casing for the high-pressure is 45 feet 8 inches, for the low-pressure 48 feet 2 inches, and for the "astern" turbines 30 feet $1\frac{1}{4}$ inches. Individually these are smaller and less powerful than the great turbine described in Chapter VI., but they repre-

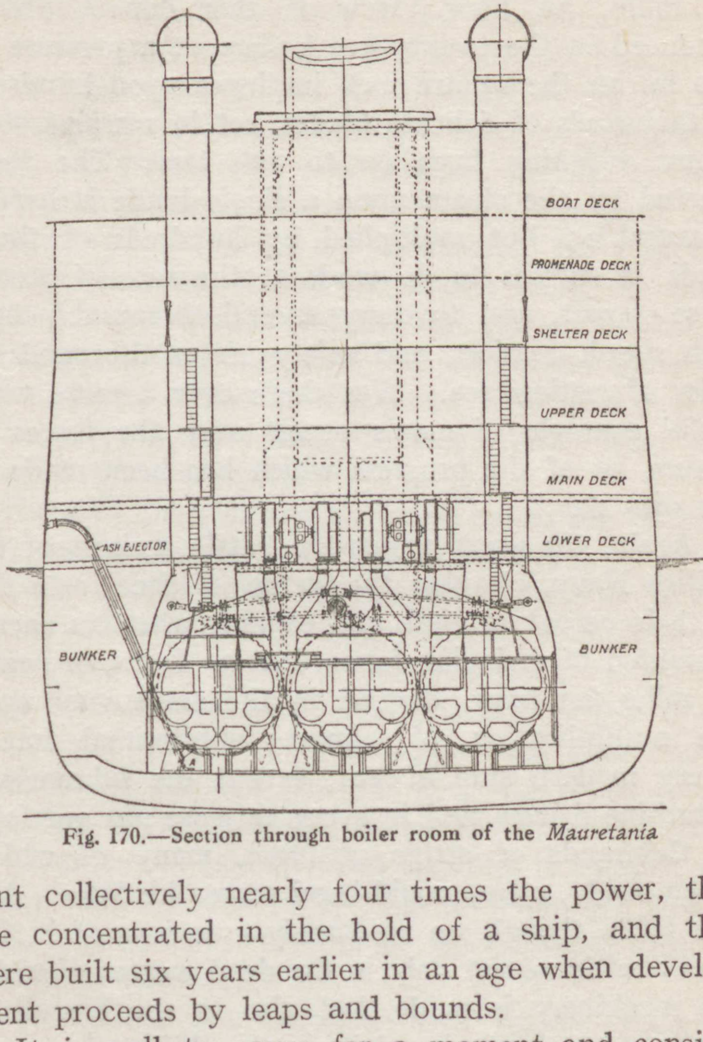


Fig. 170.—Section through boiler room of the *Mauretania*

sent collectively nearly four times the power, they are concentrated in the hold of a ship, and they were built six years earlier in an age when development proceeds by leaps and bounds.

It is well to pause for a moment and consider what is involved in the facts pressed into the foregoing paragraphs. Here is a great ship of 33,000 tons propelled through the water at a speed of 26 knots, or 30 miles, an hour. How is this done? Steam produced in the twenty-five boilers at a pressure of 200 lb. on the square inch impinges upon hundreds of thousands of delicate blades, set in massive steel drums weighing from 60 to 126 tons. The force exerted by the steam upon a single blade is hardly measurable; but multiplied by hundreds of thousands it suffices to do work at the rate of 70,000 horse-power, and to carry several thousand people with speed, comfort, and safety across thousands of miles of restless sea. Was there ever a more wonderful example of man's power over the forces of Nature, or of the progress which has been made in our own day?

Again, the great 30,000-ton battle cruisers of the British Navy, cleaving the waters of the North Sea in their perpetual vigil, and capable when an enemy is sighted of springing forward at 30 knots, or nearly 35 miles, an hour, depend in the same way upon the multiplication of almost infinitesimal forces. Every modern ship of war, except the submarines, is turbine driven, and in every case we pin our faith to thousands of strips of brass, many of which, taken singly, a boy could bend across his knee. And this faith, though we are barely conscious of it, implies confidence not only in the dead matter of which the machinery is made, but also in the knowledge of the man who designed it, in the skill and honesty of every man who helped to shape the parts and put them together.

A larger, more recent, and slightly less speedy vessel than the *Mauretania* is the *Aquitania*, belonging to the same company. She is 901 feet long over all, 97 feet beam, and 64 feet 6 inches in depth, displacing 53,000 tons, and having a speed of $23\frac{1}{2}$ knots. There are twenty-one double-ended boilers, 17 feet 8 inches in diameter and 22 feet long, with eight furnaces in each. Though not constructed for a higher pressure than 195 lb. on the square inch, the shell plates are $1\frac{19}{32}$ inches and the end plates $1\frac{5}{32}$ inches in thickness, and the latter are supported by solid steel stays $2\frac{7}{8}$ inches in diameter. The total length of the tubes is more than fifty-four miles! They are arranged three abreast.

Three of the *Aquitania's* boiler rooms are 78 feet long, each containing six boilers; the fourth is 42 feet long and contains the remaining three boilers.

One of the most interesting devices is the Stone's under-water ash expeller, one of which is to be found in each stokehold. Below a grid in the floor is a hopper connected with a pipe, and when ashes are shovelled through the grid they are swept away by a flow of water which varies automatically with the quantity of ashes. Each expeller is capable of dealing with 15 tons to 18 tons of ashes per hour, which is more than three times the quantity that is likely to be produced.

The boilers are supplied with forced draught directly to the ashpits of the furnaces by means of twenty-eight fans. Fresh air reaches the stokeholds through the ventilators on the upper deck, and as it gets warmed and vitiated it is forced by the fans through tubes which are heated by waste gases, so that the furnaces are fed with hot air. Something like 700 h.-p. is needed to drive the fans.

The steam pipes for each boiler are about 8 inches in diameter, but as they collect the steam from all the boilers they gradually increase in size up to 21 inches and 25 inches in diameter. The main steam pipes in the boiler and turbine rooms vary from 16 inches to 32 inches in diameter. The valves admitting steam to the various turbines are operated by seven engines of a special type which is made by Messrs. Brown Bros., of Edinburgh. They are a combination of steam and hydraulic, and the largest, which works the 53-inch change-over valve, has a cylinder 16 inches bore and 15½ inches stroke!

The turbines are arranged for triple expansion when going ahead, the outer screws being driven by high and intermediate pressure, and the two inner screws by low-pressure turbines; but valves are provided which enable them to be used in almost any combination. The sizes of the turbines are given in the table on the following page.

The only way to realise what these figures mean is to measure up some of the sizes and then attempt to form a mental picture of the thing itself by the aid of what you have read in Chapter VI.

The general arrangement will be understood from

	H.P. *Ahead*	H.P. *Astern*	I.P. *Ahead*	L.P. *Ahead and Astern*	
Length of spindle from after coupling to forward end . . .	39 ft. 5 in.	22 ft. 11 in.	40 ft. 9½ in.	53 ft. 5¾ in.	
Length between centres of main bearings .	25 ft. 4½ in.	17 ft. 7½ in.	26 ft. 0½ in.	35 ft. 1⅛ in.	
Total weight . .	240 tons	120 tons	283 tons	445 tons	
Diameter of rotor spindle at drum ends .	2 ft. 11 in.	2 ft. 3 in.	2 ft. 11 in.	3 ft. 2 in.	
Weight of rotor drum completed . .	80 tons	40 tons	90 tons	140 tons	
				Ahead	*Astern*
Length of rotor drums	14 ft. 9½ in.	7 ft. 11½ in.	14 ft. 3¼ in.	15 ft. 3 $\frac{1}{16}$ in.	8 ft. 4$\frac{3}{16}$ in.
Diameter of rotor drums	9 ft. 2 in.	7 ft. 10 in.	10 ft. 4 in.	12 ft.	10 ft.
Length of blades .	3⅜–7 in.	1½–3 in.	6¾–14 in.	7–20 in.	5–7 in.

Fig. 172, which is a cross section through the turbine room looking aft, and Fig. 173 on Plate 28, which is a

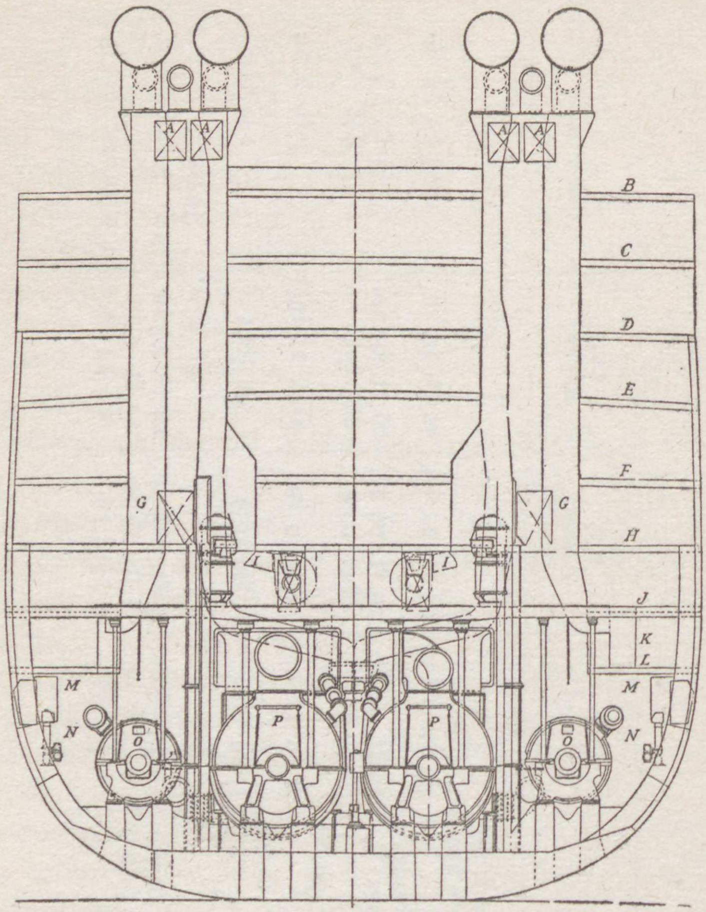


Fig. 172.—Section through turbine rooms of the *Aquitania*, looking aft

A, Hinged doors in ventilating shafts; B, C, D, E, F, H, J, and L are decks; G, Empty reserve oil tanks; I, Gravitation tanks; K, Engineer's store; M, Reserve oil tanks; N, Water service pumps; O, High-pressure astern turbines; P, Low-pressure turbines

plan of the engine room. One of the two main condensers is shown in Fig. 174, Plate 29. Contrast it with the size of the man standing in the foreground. It is 18 feet 8 inches high, and the 9,353 brass tubes, 12 feet 6½ inches long, give a cooling surface of 23,000 square feet. The main circulating pumps are capable of supplying to each condenser 18,500 gallons of cooling water per minute. They are of the centrifugal type, made by W. H. Allen, of Bedford. Weir Dual air pumps are used to maintain a vacuum of 28½ inches when the barometer stands at 29 inches.

No fewer than twenty-six fans are employed to ventilate the engine room, for which 700,000 cubic feet of fresh air per minute is provided.

New Systems of Ship Propulsion

While the turbine has no rival as a means of propulsion for the fastest passenger ships and ships of war, there are objections to it for the slower cargo boats under less highly skilled control. Unless the turbine is made excessively large the speed must be very high, and the screw propeller is most efficient at moderate speeds. For the sake of economy and of space boilers must produce high-pressure steam, and turbine speeds must be as low as possible. Those of the *Mauretania* run at 700 revolutions a minute as compared with the 160 or thereabouts of even a respectable cargo boat driven by reciprocating engines. The turbine, again, is not very convenient for manœuvring in a restricted space, and owing to its high speed reversal cannot be very rapidly effected. For these and other reasons, engineers have been casting about for methods of utilising the manifest advantages of the turbine, and avoiding its disadvantages. So far, four of these have been devised.

The first is the use of reciprocating engines and exhaust steam turbine. It will be recollected that the reasons for the high efficiency of the turbine with low pressure steam were given in Chapter VI., and seven or eight years ago experiment showed that the combination on a ship resulted in a reduction of coal consumption of from 12 to 15 per cent. The cruiser *Bristol* was equipped in this way, but the most famous example is the White Star liner *Olympic*. This 50,000 ton vessel has three screws, the outer ones driven by reciprocating engines, and the central one driven by the turbine. The former are triple expansion, having one H.P., one I.P., and two L.P. cylinders of 54-inch, 84-inch, 97-inch bore and 75-inch stroke. Each set develops about 15,000 horse-power at 75 revolutions per minute. Each engine bedplate weighs 195 tons, and each pair of columns supporting the cylinders 21 tons. Each L.P. cylinder, with its liner, weighs 50 tons. Between these is a low-pressure turbine of the Parsons type, receiving steam at 9 lb. and exhausting it at 1 lb. per square inch. The rotor is 13 feet 8 inches long, 12 feet in diameter, and weighs 130 tons. It is fitted with blades varying from 18 inches to 25½ inches in length. The whole turbine weighs 420 tons, and develops 16,000 horse-power at 165 revolutions per minute. When going astern or manœuvring it is put out of action, and the steam passes directly from the reciprocating engines to the condensers. The inside of this turbine contains as much space as the room of many a cottage, and if a dining-table were placed down the middle a dozen persons could sit down to a meal without feeling cramped!

The second of the newer methods of propulsion is to use steam turbines and to transmit the motion to the propeller shaft by means of gearing. Ordinary toothed wheels are very noisy, and the more noisy they are the worse they wear. Even with the most accurate gearing for large powers and high speeds, as ordinarily made, there are inaccuracies of sufficient magnitude to cause knocking and grinding.

But Sir Charles Parsons showed that these inaccuracies were due mainly to inaccuracies in the machine in which the teeth were cut, that they occurred at regular intervals, and that by an alteration in the design of the machine they could be spread out all round the wheel—spread so thinly, in fact, that they became practically indistinguishable. The gearing then ran silently and with so little friction that it transmitted 98½ per cent. of the power from one shaft to the other. Moreover, it enables a turbine to run at high speed with the highest efficiency, and the propeller to run at low speed with the highest efficiency.

The geared turbine, as the above arrangement is called, has received a great impetus by the invention of the Mitchel Thrust Block. When the screw rotates it pushes the water backwards from the ship's stern, while the reaction tends to force the propeller shaft into the ship. In fact, the whole force tending to propel the ship through the water is transmitted through the propeller shaft, and the thrust used to be taken up by a "thrust block." This was, and for reciprocating engines still is, composed of a number of flanges on the shaft, fitting in recesses in a long bearing. Such a block takes up a large amount of space, and when large powers are transmitted the oil is liable to be squeezed out by the great pressure on the flanges. In the turbine driving a propeller directly this is not serious, because the action of the steam on the blades was opposed to the thrust, but in the case of the geared turbine the thrust is not applied to the turbine shaft at all, but to that carrying the propeller and one of the toothed wheels.

In the Mitchel Thrust Block the propeller shaft carries a single flange, which bears upon the face of a flat ring through a hole in the centre of which the shaft passes. On the face of this ring are recesses into which bearing blocks are fitted. These are flat on the face, where they rest against the face of the flange, but rounded on the back so that they can rock a little. Owing to this freedom of movement of the blocks the spaces between their front faces and the face of the flange is always wedge-shaped, and it is practically impossible for oil to be squeezed out. And so long as the oil is not squeezed out the bearing will take the thrust without overheating. There are many engineers who believe that the geared turbine and the Mitchel Thrust Block form the best method of ship propulsion, which will quickly overhaul its competitors.

The third method is to use steam turbines to drive dynamos and to use the electricity thus produced to drive motors coupled to the propeller shaft. The rapidity with which an electric current can be switched on or off, and the ease with which it can be regulated are much in favour of this plan, but the electrical machinery adds greatly to the weight. It was strongly advocated by the late Mr. H. A. Mavor, of Glasgow, and has been tried on several ships; but there are no signs yet of its becoming popular. In any case it is less efficient than the geared turbine, and there is an increased number of appliances in which a breakdown may occur.

The fourth and last method was proposed by a German named Fottinger, and was tried in 1913 with a vessel of 10,000 horse-power. In this case a turbine drives a centrifugal pump, and the water from the pump drives a water turbine on the propeller shaft. The idea is very simple, and the same water circulates round and round through the pump and turbine. But both in this and the preceding method 15 per cent. of the power is lost in the extra machinery, and at present neither of them is a serious rival to the geared turbine.

The machinery of a modern ship is not confined to the main engine room, but to deal with all the engines, winches, pumps, and so on would take up more space than can be afforded here. For example, the refrigerating plant of the *Aquitania*, by means of which food is preserved in cold chambers, is capable of making 30 tons of ice every twenty-four hours. Of course, only a little ice is made, the chambers being cooled by brine circulating in pipes. These are placed near the roof—not, like hot water pipes, near the floor—because cold air sinks. Again, the *Olympic* has 10,000 electric lamps, and a central generating station producing as much power as is consumed by many towns of 100,000 inhabitants. There are 520 electric radiators throughout the ship and 150 motors, varying in horse-power from ½ to 40. Then the steering of the same ship is effected by means of a steam engine with three cylinders, each 17 inches in diameter and 18-inch stroke, taking steam at 100 lb. on the square inch.

In respect of its machinery the warship is far more fully equipped than the passenger or cargo vessel. For though there is less provision for comfort, there is all the power for working the guns and hoisting the ammunition to be supplied. It is, in fact, one vast power station, employing not only steam engines, but engines which use sources of power far more dangerous than steam. But sufficient will have been said to show that a modern ship presents, perhaps, more than anything else in the world, the greatest variety and the most wonderful examples of the power of steam.

CHAPTER XII

Power and Its Measurement

WE read in Chapter III. that James Watt's success was due largely to his discovery that the steam engine was a heat engine, and that the steam was used merely to convey the heat from the boiler to the engine. It will be clear that before we can hope to understand the methods that are used to increase the efficiency of an engine—that is, to increase the amount of work done per pound of fuel—we must know how work is measured, how heat is measured, and how many units of heat correspond to a unit of work.

Though this may sound rather terrifying, it is not so in reality. When a man goes into a shop and puts down five pennies for a pound of sugar he knows what he is going to get for his money. If the engineer puts a pound of fuel into the furnace he wants to know what work the engine will do for it, and he is no more willing to accept short weight in work than the other man is willing to accept short weight in sugar.

Now, as we have previously explained, it a weight of 1 lb. is lifted through a height of 1 foot, 1 ft.-lb. of work is done. If a weight of 2 lb. is lifted through a height of 1 foot, or a weight of 1 lb. through a height of 2 feet, then 2 ft.-lb. of work is done. Similarly, 10 lb. lifted through 25 feet will involve 10 ×

25 = 250 ft.-lb. of work. The work done in lifting is always equal to the product of the weight lifted in pounds, and the height through which it is raised in feet.

This is true not only of lifting, but in all cases where a force applied to a body succeeds in moving it. If a force of 10 lb. applied to heavy table is sufficient to move it steadily across a room, then 15 ft.-lb. of work will be done when it has moved $1\frac{1}{2}$ feet. 30 ft.-lb. when it has moved 3 feet, 70 ft.-lb. when moved 7 ft., and so on.

Again, if a force is applied to the handle of a grindstone the same rule will apply. Suppose the arm on which the handle is fixed is 1 foot long, and the weight required to keep the grindstone moving steadily is 7 lb., then, since the diameter of the circle round which the force moves is 2 feet, the distance which the force moves in one revolution is

$$2 \times 3\frac{1}{7} = 2 \times \frac{22}{7} = \frac{44}{7} \text{ feet,}$$

and the work done in one revolution is

$$7 \text{ lb.} \times \frac{44}{7} \text{ ft.} = 44 \text{ ft.-lb.}$$

For twenty revolutions $44 \times 20 = 880$ ft.-lb. will be required.

It will be evident that work can be stored up in a body which is lifted or set in motion. If a weight of 14 lb. is lifted 5 feet it will have 70 ft.-lb. stored up in it by reason of its position. And if in falling back to its lower position it drags a rope after it this rope may be made to lift another weight. But it would not lift 14 lb. through 5 feet because the pulley or lever which would have to be used would not be without friction, and some work would be required to overcome that. Similarly, if you put work into a wheel by setting it in motion, the wheel will do work after the force has been removed, until it comes to rest. But it will not give out the work that has been put into it, because of the friction of the axle, and the resistance of the air. Stored up work is called *energy*, and energy due to position, as in the case of the weight, is called *potential energy*, while energy due to motion, as in the case of the grindstone, is called *kinetic* energy.

In Watt's days, though something was known about energy from the discoveries of Sir Isaac Newton, very little was known about heat—in fact, a good deal of what was thought to be known was erroneous. And while it is evident that Watt realised the connection, he never stated it in such a way as to carry conviction. A clear demonstration was given by Benjamin Thomson, an American, who held the Austrian title of Count Rumford and who, in 1799, noticed the great amount of heat produced by boring cannon. Surrounding the portion which was being bored with a vessel of water, he showed that very shortly the water began to boil. From this it followed that mechanical energy was being converted into heat. Whenever friction occurs a very small part of the energy required to overcome it is used in removing a small quantity of material, and the main part is converted into heat. Soon after Count Rumford's experiments Sir Humphry Davy caused two blocks of ice to melt by rubbing them together; and probably every boy knows that if a brass button be rubbed vigorously on a board it soon becomes too hot to hold in the hand.

Before the exact relation between heat and work can be considered, the unit of heat must be defined. This is the amount of heat which is necessary to raise the temperature of 1 lb. of water through one degree Fahrenheit, and as this quantity is not quite the same at all temperatures it has been measured at a temperature of 39° Fahr., although it is sufficiently accurate for most engineering purposes to assume that one unit of heat will raise the temperature of 1 lb. of water one degree at any temperature. It is called a British Thermal unit or B.T.U. Since the freezing point on Fahrenheit's thermometer is 32°, and the boiling point is 212°, 180 units are required to raise a pound of water at the melting point of ice to the boiling point. But to convert 1 lb. of water at 212° Fahr. into steam at the same temperature requires 967 units of heat. This quantity, therefore, is necessary to change the state from liquid to vapour. It cannot be detected by a thermometer, so it is said to be not *sensible* heat, but *latent* heat, and the total heat of the steam is obtained by adding together the sensible and latent heats, or

$$H = h + L.$$

Measured from water at 32° Fahr. the total heat of steam at 212° Fahr. is, therefore,

$$180 + 967 = 1{,}147 \text{ B.T.U.s.}$$

The number 967 only expresses the latent heat of steam at 212° Fahr.—that is, the number of B.T.U.s required to convert 1 lb. of water at that temperature into steam at that temperature. To find it for any other temperature the engineer uses a formula or refers to "Steam Tables," which give the figures for all temperatures likely to occur in practice.

If the temperatures are measured in degrees Centigrade, the unit of heat is called the *pound-calorie*, and the latent heat of steam at 100° C. is 537 *pound-calories*. The total heat of steam at 100° C., starting from water at 0° C., is then 100 + 537 or 637 *pound-calories*.

No accurate measurement of the relation between heat and work was made until 1849, when James Prescot Joule, after six years of the most careful experiment, came to the conclusion that one B.T.U. was capable of being converted into 772 ft.-lb. of mechanical work. That is, it would be capable of raising 772 lb. 1 foot high, or 1 lb. 772 feet high, or 386 lb. 2 feet high, or any other product of pounds and feet which comes to the magic number 772. Later experiments by Professor H. A. Rowland and others give 778 and 774, but they are all so near together that for practical purposes it does not matter much which is used. The corresponding value in Centigrade units is 1,400.

Now 1 lb. of fairly good coal produces, when burnt, 14,000 B.T.U.'s, so that the energy stored up in it is 10,892,000 ft.-lb. Since there are 2,240 lb. in 1 ton, this means that by burning 1 lb. of coal enough energy would be produced to raise a weight of 4,862 tons 1 foot from the ground.

Take a piece of coal in your hand and try to realise the hidden power that this black mass contains. It will soil your hands, but that does not matter. You are in the presence of a power so stupendous that it staggers the imagination. There is no need to wonder now that the habits and customs of the civilised world have been altered since James Watt showed how to use the steam engine effectively. For steam is merely the agent which conveys the energy of the coal to the cylinder of the engine, where it drives the piston to and fro, and produces the motion which is used on the railway, in the factory, in the steamship, and the mine.

The piston and cylinder, or the turbine, are merely convenient devices for abstracting from the steam the heat which it has absorbed from the furnace. We speak of an engine taking in steam at a certain pressure and exhausting it at another lower pressure, but it is really taking in steam at a high temperature and exhausting it at a lower one. The temperature of exhaust in the case of steam cannot be lower than 32° Fahr. or 0° C., because at that temperature water changes into solid ice. The higher temperature is only limited by the ability of the parts of the engine to remain steam tight, by the impossibility of lubricating very highly heated surfaces, and by the difficulty of avoiding loss of heat to surrounding objects, for the loss of heat in this way is roughly proportional to the difference of temperature. Moreover, as all gases and vapours expand on heating and exert force by reason of the heat they contain, all gases and vapours can be used to convert heat into mechanical work. Liquids are useless, because the alteration of volume with change of temperature is so very small. And of all vapours that of water is for many reasons the most convenient, as it is the most widely distributed and plentiful in the world.

Let us glance now at that much-abused word "power." In one sense it merely denotes general ability or strength, as in speaking of a powerful man. But in reference to engines it signifies "rate of doing work." A thousand foot-pounds may be done in an hour, or it may be done in a minute, and the one is sixty times greater than the other. To measure the rate at which work is done we must have a unit, and that chosen is 33,000 ft.-lb. per minute. It is called a horse-power, though it would require a pretty strong horse to raise 33,000 lb. 1 ft. from the ground, or 1 lb. 33,000 feet from the ground in sixty seconds! A given amount of work can be done slowly or it can be done quickly, but it is done all the same. But if the time in which it is to be done is specified, then what we have in mind is not so much the work to be done as the rate of doing it. We are thinking of power, and the units of measurement are not foot-pounds, but foot-pounds per minute. Dividing this quantity by 33,000 gives the result in horse-power.

How is the horse-power of an engine measured? Consider the piston in the cylinder with the steam pressing on it. The pressure in pounds per square inch multiplied by the number of square inches of piston upon which it acts, will give the total force driving the piston along. In one stroke the number of foot-pounds of work done will be given by the product of this force with the distance through which it acts, or the length of the stroke in feet. And if this result is multiplied by the number of strokes per minute the result will be the number of foot-pounds of work done per minute. Calling the pressure P, the area A, the length of the stroke L, and the number of strokes per minute N, the work done per minute will be $P \times A \times L \times N$, or, to put it in a form that is easily remembered, P.L.A.N. Lastly since 1 horse-power is 33,000 ft.-lb. per minute, the horse-power of the engine is:

$$\frac{\text{P.L.A.N.}}{33{,}000}$$

Apply this now to an actual engine. The area of the piston and the length of the stroke can be measured, and the number of strokes per minute can be counted. But the pressure varies from the point of cut-off to the end of the stroke. What this pressure ought to be can be calculated from the known properties of steam. It is, however, impossible to look into the cylinder and to ascertain whether steam is admitted at exactly the right moment; if it passes freely through the ports without being throttled or "wire-drawn," and if it expands with loss of pressure by condensing in contact with the cold walls of the cylinder and the passages leading to it. We must, in fact, have some means of measuring the pressure of the steam behind the piston

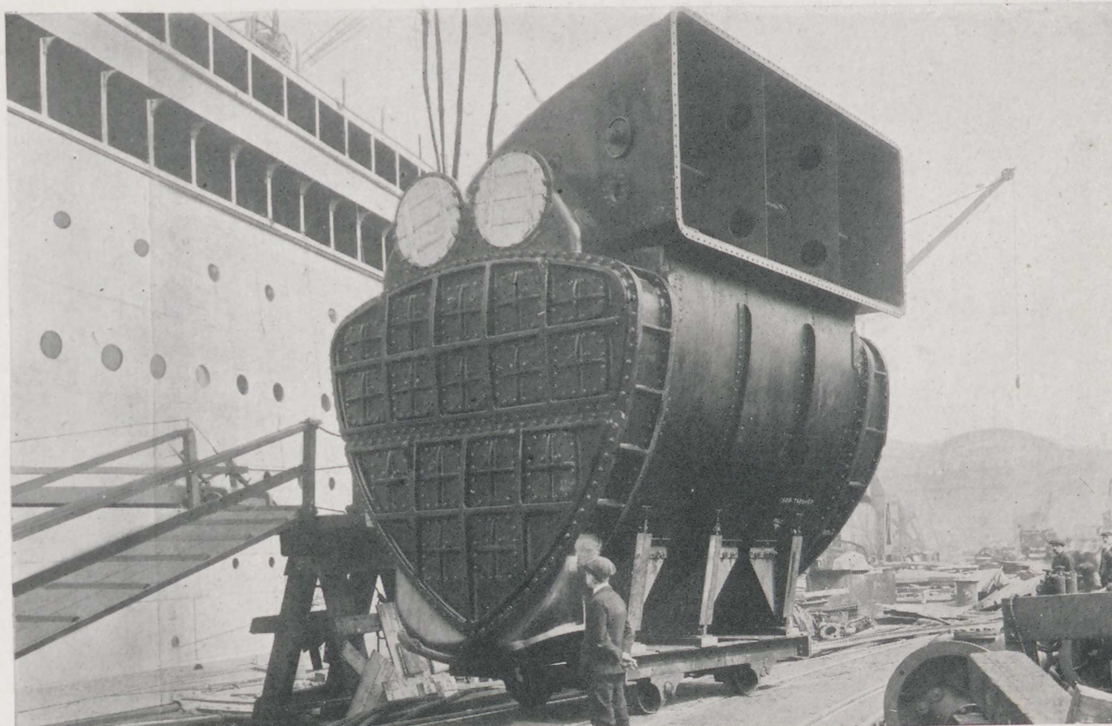


Photo by permission of the Editor of "The Shipbuilder"

Fig. 174.—One of the *Aquitania's* Condensers

PLATE 30

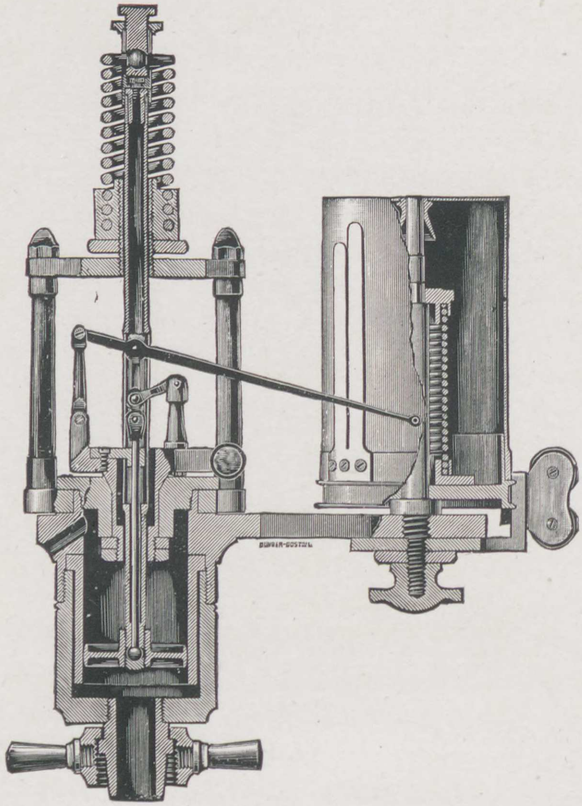


Fig. 176.—Crosby Steam Engine Indicator

throughout the whole of the stroke, and this means is provided by the steam engine indicator.

Suppose we have a piston fitted in a small chamber connected by means of a pipe with the interior of the cylinder, as in Fig. 175, and held down by a spring. Then as the pressure in the cylinder varies, the piston will rise and fall in unison with it. A pencil, therefore, attached to the little piston rod will make a straight line up and down on a piece of paper pressed against the point. If now this paper is caused to move in a direction at right angles to that in which the pencil is pointing, a more or less curved line, indicating the fall of pressure, will be produced. Moreover, if, at the end of the stroke, the paper moves in the opposite direction, the line drawn upon it will represent the pressure during exhaust. The vertical distance between these two lines will represent the effective pressure upon the piston, assuming that it does not matter in which end of the cylinder the pressures are measured.

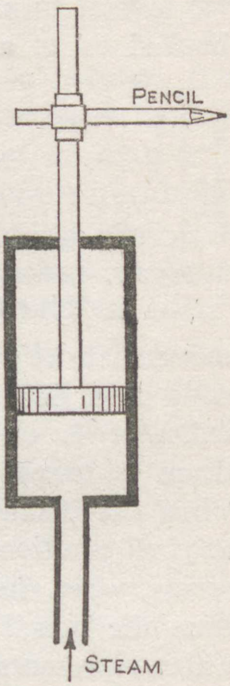


Fig. 175.—To illustrate principle of indicator

In the actual steam engine indicator, a good type of which is shown in Fig. 176 on Plate 30, there is a small piston in a vessel which is connected to the inside of the cylinder by means of a pipe, and the piston is held down by a spring which will be seen at the top of the illustration. Any movement of this piston operates a lever which carries on its right-hand end a small pencil or pen. The paper is mounted on a drum which has a spring inside. On a pulley near the lower edge of the drum a cord is fixed and wound round for several turns. The other end of the cord can be hooked on to a lever that is moved backwards and forwards by the cross-head, or, in the case of a gas or oil engine, by the piston. This lever has arms of such lengths that a complete stroke of the engine causes a movement of the paper of, say, 3 inches. This ratio is a definite one. If the tap connecting the indicator is closed and the engine is working, the drum is turned a definite portion of a revolution when the piston moves forward, and returns to its original position, under the influence of the internal spring, when the piston moves back again ; and each time the pencil draws on the paper a straight line which represents the length of the stroke to a definite scale. Similarly, if the drum is disconnected and the tap is opened, the movement up and down of the pencil represents to scale the variations of pressure within the cylinder. When the drum is connected and the tap opened for two strokes of the engine, both vertical and horizontal movements take place at once, and we get a closed diagram like that in Fig. 177, which shows exactly to scale the variations of the

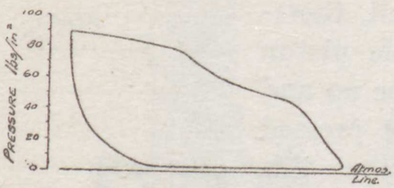


Fig. 177.—Indicator diagram of steam engine

pressure throughout one complete revolution of the engine.

The effective pressure at any point of the stroke is represented by the vertical distance between the upper and lower lines in the diagram, and the mean effective pressure, which is P in the formula $\frac{P.L.A.N.}{33,000}$, is represented by the mean distance between those lines. To ascertain this, divide the whole diagram into a number of vertical strips, say 10, draw a line down the middle of each strip, measure the lengths of these "mid-ordinates," add them up, and divide by 10 to obtain the average. The pressure represented by one inch in height of the diagram depends, of course, upon the strength of the spring, and the value furnished by the makers for the spring employed.

But the horse-power of the engine—the indicated horse-power—can be found directly from the diagram itself. The width of the diagram represents to scale a force, and the length represents also to scale the distance over which that force acts, so that their product represents the work done by the force. And, as the average width multiplied by the length gives the area of the figure, this area represents to scale the work done in one revolution of the engine. The engineer does not trouble to measure and calculate the average width, but uses a planimeter, an instrument which, when applied to the diagram, enables him to read off the area directly. Since this area represents to scale the work done in one revolution of the engine, he has only to multiply this work by the number of revolutions per minute to find the work done by the engine per minute ; and that, divided by 33,000, gives the *indicated* horse-power of the engine. We shall return to this term: meantime there are other points of interest in the diagram.

Let us follow the pencil all the way round, from the left hand near the bottom corner, up this side, along the top, round the toe, and back again along the lower line. Firstly, then, the line forming the top left-hand boundary should rise abruptly. If it does not we know that steam is admitted late. The valve is slow in opening, and if it be late ever so little the piston will have moved some distance upon its stroke before the steam exercises its full pressure. This is clearly of the greatest importance in high-speed engines.

Secondly, the horizontal portion at the top represents the period during which the steam exercises its full pressure, and it should be quite horizontal. If it falls, there is evidence that the steam is strangled, as it were, in the ports, and is unable to follow up the rapidly moving piston. This is called *wire-drawing*, because wire is made by drawing a thin rod through conical holes in a steel plate or die.

Thirdly, the end of this horizontal line is the point of cut-off, usually more or less rounded, owing to wire-drawing and slowness of the valve in closing, and the curved sloping portion indicates the fall of pressure during expansion. At the end of this curve is the point of exhaust. If this exhaust port is opened too early the pressure will fall very rapidly ; if too late the toe will almost point upwards.

Fourthly, the bottom line represents the pressure of the steam during exhaust. It should be fairly straight, and in a non-condensing engine it will be at or above atmospheric pressure. In a condensing engine it will, of course, be below this. The exhaust port is closed just before the end of the stroke and cushioning occurs. This causes a rise of pressure, and is represented by the upward curve at the left-hand bottom corner. It is always more pronounced in high-speed than in slow-speed engines, because of the great necessity there is of bringing the reciprocating parts of the engine to rest smoothly, and avoiding all jerks.

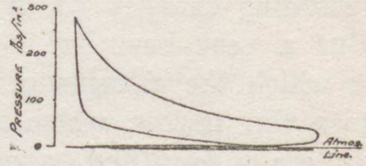


Fig. 178.—Indicator diagram of gas engine

Under various conditions the indicator diagram exhibits curious forms, but every curve and bend in the line corresponds to something which has occurred in the cylinder, and is capable of being interpreted by the engineer. From the information which can be gleaned from it, it is often possible to readjust the valves so that a diagram of larger area is obtained; for if the area can be increased without altering the steam consumption, the power put into the engine is increased in the same ratio.

Exactly the same methods are applied to gas and oil engines as to steam engines, but special springs are used. The diagram of an internal combustion engine is markedly different from that of a steam engine, as will be seen from Fig. 178; but it must be remembered that the lower line represents the rise of pressure during the compression stroke. In the case of very high-speed petrol engines, such as are used on motor-cars and aeroplanes, an indicator diagram is very difficult to obtain. At 1,200 revolutions a minute only one-tenth of a second is available for drawing the diagram, and the mechanism of the ordinary steam engine indicator is incapable of recording changes which occur with such rapidity. But a very beautiful instrument has been devised in which the changes of pressure are communicated to a tiny mirror, which reflects a spot of light upon a piece of sensitised paper fixed on a revolving drum. In this way the indicator diagram is photographed with far greater accuracy than is obtainable in a pencil drawing.

It will be clear that the indicator cannot be used for turbines.

Brake Horse-power

The indicated horse-power, or I.H.P., as it is called, merely tells you at what rate the steam or explosive mixture is doing work in the cylinder, and gives no information as to the rate at which the engine will perform useful work outside. Obviously, this will be less than the I.H.P., because some of the work done by the working fluid, i.e. steam or explosive gases, will be absorbed in driving the engine itself. Thus work is required to start or stop or vary the speed of the reciprocating parts, to vary the speed of the rotating parts, and to overcome the friction of sliding, turning, or rolling between surfaces in contact. In a well-designed and well-made engine these sources of loss will not be more than, say, 10 per cent., so that the I.H.P. does give some idea of the rate at which the engine will perform external work.

As the real test of an engine, however, is in the rate at which it gives out work rather than at which

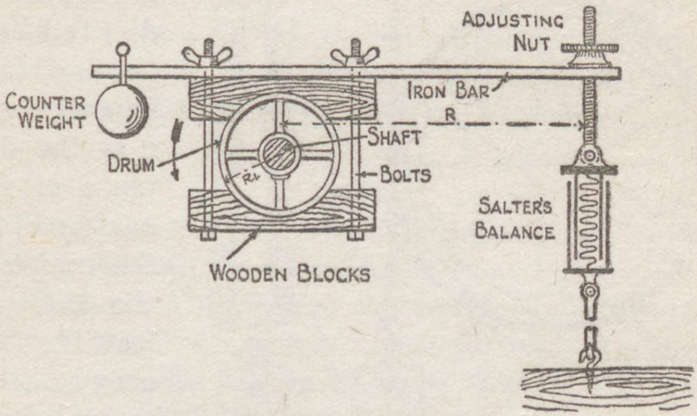


Fig. 179.—Prony brake

it takes work in, it is very necessary to have some means of measuring the output directly; and with an engine of moderate size this is not a difficult matter. Perhaps the simplest piece of apparatus is a Prony brake (Fig. 179). The rim of a small pulley on the engine shaft is gripped by two blocks of wood, held together by two bolts and nuts so that the grip can be adjusted. To the upper block is fixed an iron bar with a spring balance at one end and a small weight at the other to counterbalance the extra length of bar and the weight of the balance on the other side. When the engine is started the pulley tends to carry the blocks round, but is prevented by the spring balance. The speed can be varied by tightening or loosening the nuts. If P is the force indicated on the spring balance and r is the distance of the balance from the centre of the shaft in feet, then the engine is working against a force P applied at the circumference of a circle r feet in diameter. This circumference is $2\pi r$ feet, and if the engine makes n revolutions a minute, the distance over which the force acts per minute is $2\pi r n$, and the work done per minute is $2\pi r n$ P. The horse-power is, therefore,

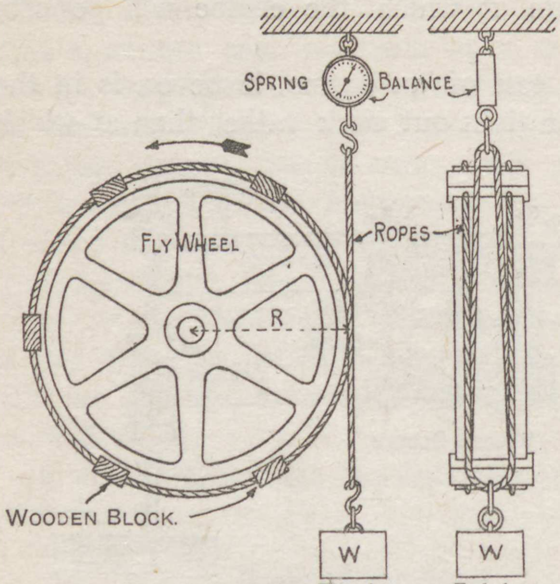


Fig. 180.—Rope brake

$$\frac{2\pi r n P}{33{,}000.}$$

A more usual form of brake consists of a number of wooden blocks strung on a couple of ropes, or sometimes the ropes only are used, as in Fig. 180. The flywheel is gripped by attaching one pair of rope ends to a spring balance and the other pair to a weight or another spring balance. The grip on the flywheel is measured by the difference in the readings of the spring balances or the balance and the weight. When the engine is working this difference is greatly decreased, and the decrease gives the force which the engine is overcoming at the rim of the flywheel. Using the same letters as before—P for the force in pounds and *r* for the radius of the brake circle in feet, the horse-power is given by the formula :

$$\frac{2 \pi r n P}{33,000}$$

Brakes of this kind are called absorption dynamometers, because they absorb the energy given out by the engine. This energy is converted into heat by friction, and if the test is to last for more than a few minutes, or the engine is more than a few horse-power, the flywheel must be water-cooled. For this purpose the inside of the rim is in the form of a channel. Water is continually poured in through a small pipe, carried round by centrifugal force, and scooped out by a wider pipe with a specially shaped end.

If this were not done the brake blocks or ropes would soon catch fire. Special precautions are desirable with four-stroke gas and oil engines, which have flywheels with very heavy rims. It is difficult to cast these without strain being set up while they are cooling in the mould, and the heating in a brake test may cause them to burst. A safer plan, therefore, is to fix a pulley to the other end of the shaft to take the brake.

When one comes to hundreds and thousands of horse-power it is clearly impossible to absorb the energy by friction in this way. Thus if the engine were only of 1,000 horse-power it would raise more than 2 cwt. of water from the freezing point to the boiling point every minute, or it would bring a ton of water from the freezing to the boiling point in nine and a half minutes. But though solid friction is out of the question, liquid friction can be used, and a Froude's hydraulic brake is occasionally employed.

There are, however, other means of testing. Thus a pump is designed to lift a certain amount of water a certain height in a certain time with a certain consumption of coal; and the coal used and the water pumped can be measured without much difficulty. Again, a ship is required to make a certain speed on a certain coal consumption, and this can be tested. Further, an engine for an electric light station is required to produce a certain quantity of electricity for a given consumption of coal or steam, and electrical energy is more easily measured than mechanical energy; so that the power of electric light engines is generally given in "kilowatts" rather than in "horse-power." As a kilowatt is 1,000 watts, and 746 watts correspond to 1 horse-power, the latter can easily be calculated from the electrical output.

The largest and most powerful engines in the world are found in electric light stations, on steam-ships, and, in a few cases, there are large pumping plants. While these cannot be tested by absorbing the energy in an absorption dynamometer, their output can, as we have just seen, be measured fairly easily. Smaller engines, again, can be tested in another way. Instead of absorbing the energy they yield, we can measure the amount transmitted by what is known as a transmission dynamometer. These are usually pieces of apparatus interposed between the engine and the machinery which is being driven ; but as a satisfactory explanation of them would carry us rather more deeply into mechanics than is possible in a book of this kind, no further space need be given to them.

CHAPTER XIII

Fuel and Its Problems

WE have repeatedly noticed how the steam engine, the oil engine, and the gas engine have effected a transformation of the habits and customs of the world, and we have seen that each and all of these are merely contrivances for utilising the heat produced by burning fuel. The great problem for all nations, young and old, in the coming years is the supply of fuel, for upon it depends not merely their chances of growth, of increasing prosperity, and the happiness which ought to accompany it, but their very existence. We shall see in this chapter how it is that every nation which desires to make the most of the useful things which lie beneath the soil or grow upon its surface, will have to pay attention first of all to the supply of fuel, and to economy in its use.

What is coal? A geologist will tell you that it is a black rock, combustible or capable of being burnt, found in the ground at varying depths in layers of variable thickness. Some "seams," as they are called, may be no more than a few inches between the incombustible rock above and the incombustible rock below; while others may be 30 feet. Frequently a lump will show distinctly the trace of a leaf, like that of a fern. Others are shaped like branches of trees, while forms like huge tree stumps are found standing vertically in the seams. These and other facts show that it has a vegetable origin—that it is, in fact, composed almost entirely of trees and plants that flourished thousands of years ago, before the vast overlying rocks had been deposited upon them. Of the actual structure—leaf and fruit and stem and branch—few traces remain, and coal is, for the most part, formless. It is not crystalline; it shows no evidence of having been melted or even partially burnt. By some process, the nature of which we can only conjecture, the plants of the carboniferous age have been changed from what is in many respects an unsatisfactory fuel into one more compact, and containing less moisture and ash.

Since plants grow only under the influence of the light and heat of the sun, the world's coalfields contain the stored-up energy of the sun's activities thousands or tens of thousands of years ago. In the engines and boilers of to-day we are using again some of the energy which, in the form of light and heat, enabled the plants of long ago to store up carbon, which is the principal constituent of all forms of fuel. Coal has, therefore, been called, picturesquely, preserved sunshine, and the term is not inappropriate because by suitable means water can be boiled and steam produced by the direct rays of the sun.

The process of coal formation, however, stopped long ago. Nowhere, in no part of the earth where the explorer has yet trod or the prospector searched, is coal being produced. In a few places peat is growing, but it is inferior to coal as a fuel and is being formed in so few places that there is no hope of it ever rendering the same service as coal. So far as scientific men can tell, the quantity of coal in the world is limited ; no more is being produced, and when the known fields are worked out other forms of fuel, if there are any, will have to be used, or the world will be a cold and dreary place indeed. Save for water there may be no source of power left. The hum and buzz of the factory will be hushed, and the great blast furnaces will fall to pieces—a few perhaps remaining like decayed monuments standing amid a scene of desolation and recalling a greatness that has passed away.

To no people in the world is the supply of coal of more importance than it is to those who live in the British Isles. Their commanding position in manufactures and commerce is built upon rich coal-fields, which are slowly but surely becoming exhausted. Before the eighteenth century coal was hardly ever used as a fuel. Charcoal was employed in the manufacture of iron until 1739, and the badly constructed grates rendered timber the only possible domestic fuel. Then the improvements in the manufacture of iron, the steam engine, and the inventions of new textile machinery led to an enormous increase in its consumption. For at least a hundred years we continued to use coal without any thought as to how long it would last. Not until 1857, when Professor Edward Hull published his book on the subject, did anyone attempt to calculate the amount available, and it was three years later when the powerful voice of Professor Stanley Jevons was raised in warning. Ultimately the Government appointed a Royal Commission, which reported in 1870 that the probable amount was 146,480 million tons. And as the amount raised in that year was only 110 million tons there appeared to be sufficient to last 4,000 years.

But the amount raised annually did not stop at 110 million tons. Factories and workshops increased and multiplied; ships became larger, swifter, and more numerous. The population of the towns grew rapidly while, relatively, the population of the country declined. The demand for food exceeded, to a greater and greater extent, the home supply. More and more food had to be imported, and for many of our imports we had to pay directly or indirectly in coal. Consequently the amount raised annually increased as shown in the following table:—

1871 . . .	110 million tons
1898 . . .	202 ,, ,,
1899 . . .	220 ,, ,,

The 4,000 years of possible duration was now reduced to 2,000 years, and there was still no sign of the demand for coal abating. In 1901 another Royal Commission was appointed. They reported in 1905, and came to the conclusion that there was still a store of 140,000 million tons—a result which confirmed the opinion of the Commission which sat thirty years before. They recommended economy; but they did not realise how rapidly the amount raised annually was to increase as the new century wore on. Look at the following figures:—

1903	. . .	230 million tons
1911	. . .	243 ,, ,,
1912	. . .	260 ,, ,,
1913	. . .	287 ,, ,,

In ten years the amount increased by nearly 60 million tons per annum—more than was raised altogether in 1861. If the rate remains constant the duration of 4,000 years in 1870 had fallen to 500 in 1913, and in the absence of some scientific discovery which shall render coal unnecessary, all the industrial activity of Great Britain will be extinguished before 2400. If the rate continues to increase, the land will, under the same conditions, be desolate by 2050, within the lives possibly of the great grandchildren of those who read this book.

When you consider this spectacle of a great nation humbled to the dust, its industries decayed, its people forced to emigrate, its towns deserted and in ruins, you will ask, "Is there no means of averting this calamity, or at least of postponing it until scientific discovery shall have shown how to produce power in other ways?" There is. But only a small portion of it lies within the scope of this book. Not a pound of coal should be burnt unnecessarily. But in order to effect this there should be only large engines under men who understand how to get the most out of them. The boilers, steam-pipes, and cylinders of a small engine have larger surfaces in proportion to their volumes than large engines, and they waste more heat even under the most skilful management. An engine working only part time is less efficient than one working full time, and a man that cannot fully employ an engine should not be allowed to have one. He should purchase electrical power or gas power from a large source of supply. (See Fig. 181, Plate 31.)

The average amount of coal used per horse-power per hour in this country is 5 lb. or 6 lb., yet the great turbine built by Messrs. Parsons for Chicago, which was described in Chapter VI., requires less than 1 lb. If the consumption of the average engine is 5 lb. to 6 lb. the consumption of many must be much higher. As about 80 million tons of coal per annum are used for producing power, a reduction of the average consumption to, say, 3 lb. would save about 30 million tons per annum. And at 10s. a ton at the pit mouth this would amount to £15,000,000 a year. Just think, too, of the reduction of wear and tear on the railways, and the saving of wages which are now merely paid for moving stuff which ought not to need moving. If the men engaged in this, and the colliers who would also be liberated, went on the land, more food would be produced at home, we should import less, and we need not export 76 million tons of coal as we did in 1913. We are not so well off that we can afford to let it go unnecessarily. Germany has more than we have, and is raising it at half the rate. We are exhausting our supplies more rapidly than any other country in Europe.

But there are other methods of economising, even in the production of power. Where large engines are impossible and electricity cannot easily be obtained, it is more economical to convert coal into gas in a gas producer, and to use the gas in gas engines than to burn coal under a boiler. It has not hitherto been possible to make gas engines large enough to compete with steam turbines for large powers, and for generating electricity they are not quite so suitable, but for all other purposes up to 1,000 horse-power they are effective and economical. Moreover, the bye-products which can be collected from the producer are valuable in industry and agriculture, so that a double purpose is served by their use.

The advantage of the gas engine, as an engine, lies mainly in the following facts :—

(*a*) The heat is produced in the cylinder, just where it is converted into work. There is no loss, therefore, by radiation from the surface of boilers and long lengths of piping.

(*b*) When air and gas are mixed in proper proportions the combustion is rapid and perfect. There are no unburnt particles like those which pour out of the tops of factory chimneys, which not only represent waste in a direct sense, but lead to an unnecessary expenditure of soap and water, and cast a black pall over every manufacturing town.

(*c*) The stand-by losses are small. Very little coal is used when the engine is not drawing gas from the producer, and when the engine is needed it can be started up in a few minutes, while some time is required to get up steam in boilers.

These advantages were so clear, even in 1880, that the total replacement of steam by gas within fifty years was prophesied by eminent engineers. What they did not foresee, however, was the difficulty of building very large gas engines, the invention of the turbine with its economy of steam and its evenness of effort, and the need for this evenness of effort in driving electrical machinery. Moreover, the enormous growth in the demand for power destroyed real competition even for small sizes, and kept engineers busy making both classes of engine. The cheapness of coal and the small proportion which the cost of power bears to the cost of manufacture, also prevented manufacturers from exerting themselves in the direction of economy.

Gas can, of course, be burnt in other ways than in the cylinder of an engine. It is used very extensively, not only for domestic heating, but also for furnaces in the factory. But until recently attempts to use it for raising steam have not been very successful. The amount of heat obtainable from any fuel is proportional to the weight burnt, and gases are so light in comparison with solids that they require a large furnace. The fierce flame playing directly upon the plates is also objectionable because it leads to overheating. But within the last two years a new process has been devised which is interesting because it has arisen out of investigations in pure science, and because it enables a greater proportion of the heat produced by the burning fuel to be communicated to the water in the boiler.

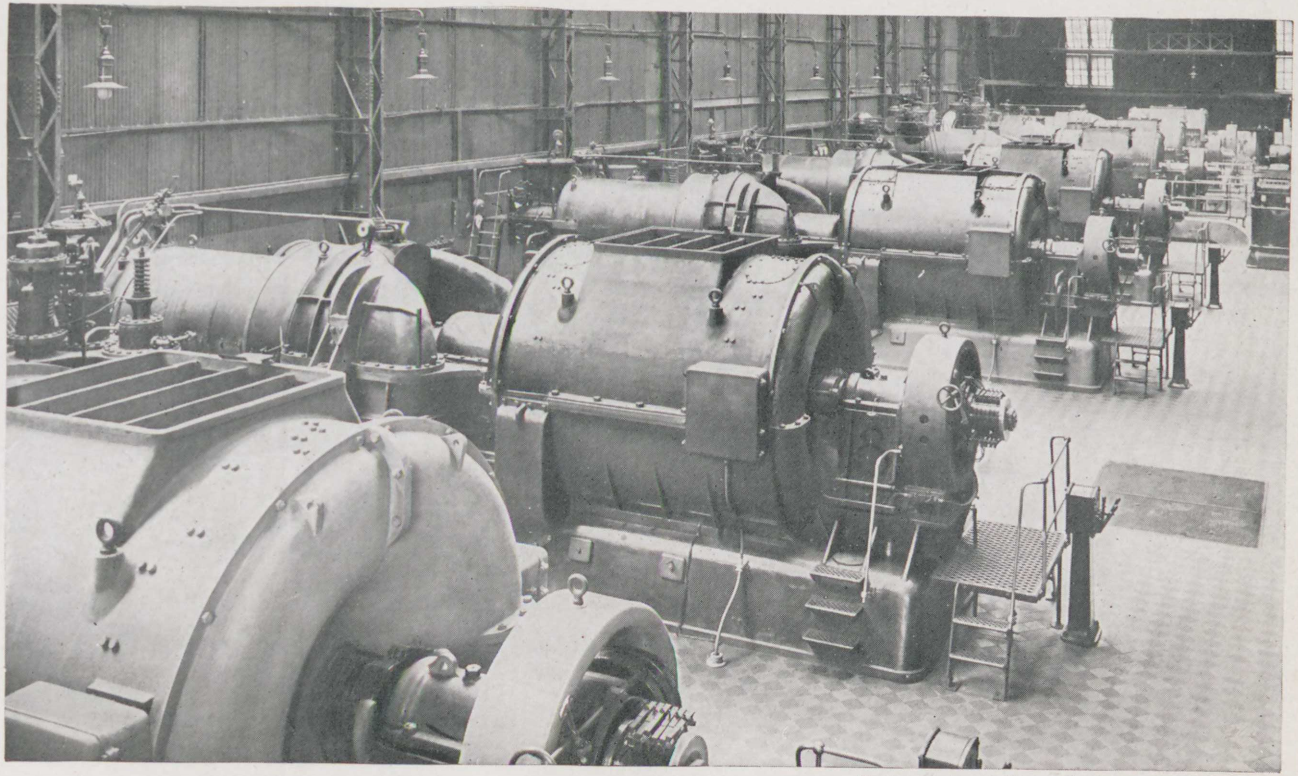
In order to understand this invention let us consider two facts. Two gases, such as hydrogen, coal gas, or producer gas, or Mond gas, or blast-furnace gas, and air or oxygen, can be exploded by means of a flame, or a spark, or a hot wire, but a certain temperature is necessary to effect this. Slow combustion, however, goes on at temperatures below that at which explosion takes place, and the rate at which this slow combustion goes on depends upon the nature of the surface of the vessel in which the gases are enclosed, or upon the presence of certain substances in the mixture. In the presence of certain (generally porous) substances, combination may be so rapid on the surface of the material that the heat produced causes explosion. The first fact, then, is that certain substances promote extremely rapid combustion.

The second fact is best illustrated by an ordinary Bunsen burner, or a gas stove, or any gas burner in which some air is mixed with the gas before burning. In these burners the air openings are always so proportioned that the air which enters at the base is insufficient for complete combustion, the remainder being obtained by the flame from the atmosphere above the burner. If the air holes be stopped up gradually, the mixture becomes more and more nearly in the correct proportion for an explosion. The flame grows smaller, a sharply defined inner blue cone makes its appearance, and, finally, the flame "strikes back," producing an ordinary luminous gas flame starting from the small orifice through which the gas enters. Before this occurs the velocity of the gases passing out of the burner has always been at least as great as the rate at which the flame tends to pass down the tube. When it does occur, when the flame "strikes back," the velocity of combustion exceeds the velocity with which mixture flows upward. An explosion has not occurred, but the rate of combustion has been greatly increased.

Now, Professor W. A. Bone found that if he closed the end of a tube with a disc of porous material something like fireclay, passed an explosive mixture of gases into the open end, and applied a light at the other, combustion went on in the pores of the disc, causing it to glow brightly. This was a case of surface action. The gases will not pass through the disc rapidly enough in either direction to allow of a flame on the outside, or an explosion inside, but combustion proceeds rapidly just within the surface of the material itself.

As a result of this discovery we have the Bonecourt Boiler, and Figure 182 on Plate 32 illustrates one of several forms the apparatus takes. The boiler is fitted with tubes, 6 inches in diameter, and each tube is packed with blocks of special material upon the surface of which the mixed gases burn. The combustion takes place mainly in the first third of the length of the tube, and so much heat is abstracted from the gases by the material with which the tube is packed in the last two-thirds, that the temperature at the point of exit is only 30° higher than that of the steam in the boiler. More than 92 per cent. of the total heat produced is communicated to the water, as compared with 75 per cent. in the case of the best type of ordinary boiler, and it can be made in sizes to compete with the largest of them. The Bonecourt Boiler Co., moreover, claim that it occupies less than one-ninth of the space required by Lancashire boilers evaporating the same quantity of water per hour, though this does not allow for the space required if producers had to be installed. A single tube only 6 inches in diameter will burn over 900 cubic feet of town's gas per hour and produce 400 lb. of steam from and at 212° F. in the same time.

The saving, as compared with ordinary boilers, depends upon the nature of the fuel used. Town's gas is generally expensive, gas from blast furnaces and coke ovens is cheap and would otherwise run to waste, and Mond gas is cheap if the bye-products are recovered. So that there are many cases in which the full advantage of 15 per cent. to 18 per cent. in the efficiency of these boilers would be gained. It is not possible, however, for manufacturers to scrap their plant every time an improvement is placed on the market, and these boilers will be more readily adopted in iron and steel works which have an ample



By permission of Messrs. A. C. Parsons & Co., Ltd.

Fig. 181.—Inside a Power Station: The Carville Power Station, showing Parsons Turbo-Alternator sets

PLATE 32

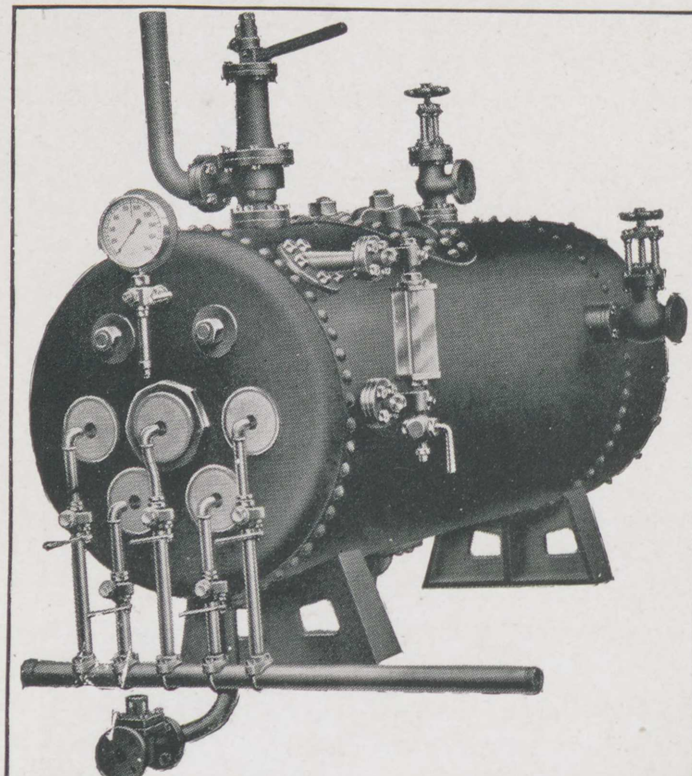


Photo by permission of the Bonecourt Waste Heat Boiler Co., Ltd.

Fig. 182.—Waste Heat Boiler

supply of blast furnace and coke oven gas available.

Whenever this question of the supply of fuel is raised people ask at once, "What about oil?" The medium oil engine, the petrol engine, and the Diesel engine are so familiar that the mind at once travels to the possibility of securing power without using boilers or gas producers at all, and few people other than engineers, chemists, and geologists have any idea of the magnitude of the oil supply or to what extent it is comparable with that of coal. The broad facts of the case, however, can be put very briefly. The total production of oil *in the world*, in 1913, was 57 million tons—30 millions in the United States, 10 millions in Russia, and the rest in Roumania, Persia, Mexico, and the Far East. On the other hand, the production of coal *in Great Britain alone* in the same year was 287 million tons. The world's production of coal is probably about 1,000 million tons, and there seems no reason to believe that oil will ever be able to provide for more than one-twentieth of the world's power.

But when we speak of oil in this way we refer to petroleum, which is obtained by sinking wells into layers of earth far below the surface, which are saturated with it. Frequently this is under pressure, so that when the borehole reaches the oil it is forced up in a fountain. Hundreds of thousands of barrels a day are obtained from "gushers" without the trouble of pumping. But oilfields seem to be more quickly worked out than coalfields, so that active exploration for fresh fields has to be carried on if the supply is to be kept up.

So far as those fuels which are derived from petroleum are concerned, the gradually rising prices will put a limit to their use, and the people in the countries in which they occur will have an advantage over those in the countries to which they have to be conveyed. Manufactures must, as a rule, be carried on in close proximity to the source of raw material or fuel, and if we in Great Britain had to import fuel our export trade would dwindle to insignificant proportions. Our greatest need of oil is for the Navy, unless that era of certain peace which is the hope of so many people shall begin in earnest. The submarine depends upon the Diesel engine, and the fastest vessels of other types are wholly or partially dependent upon oil fuel for raising steam. An adequate supply for the protection of our trade and the defence of the Empire will, ere long, be obtainable from British Colonies and Dependencies, but it is unlikely that this will be sufficiently plentiful or cheap to be used in providing power for manufactures. For this we shall have to rely upon the bountiful but not inexhaustible provision of Nature beneath our own soil.

Now while there is no vast natural store of liquid fuel in Great Britain, it does not follow that since we cannot get all we want from other countries we must go seriously short. For many years oil has been obtained by distilling certain shales in Scotland, and some, at present of inferior quality, is obtainable from certain clays in England. Again, benzol obtained from coal tar can, as we have seen, be used in place of petrol in the smaller internal combustion engines. There are also Diesel engines running quite satisfactorily on the heavier oils obtained from tar. So that by distilling some of our coal we can provide the amount of gaseous and liquid fuels we require. Since not only fuel in its different forms, but many other substances essential to manufacture, are obtainable from coal, it is clear that one of the great problems of the future for this country is to secure that coal shall be burnt or distilled in just those proportions which satisfy our various needs, and that the processes should be carried on in such a way that not a pound of the precious rock is wasted.

We are not doing this now, because few people know the facts or understand the principles involved. It is nobody's business to see that fuel is not wasted, and everybody plays for his own hand. And yet the action of a few thousand people and the prejudices or ignorance or indifference of a few million are hurrying the whole nation towards industrial bankruptcy. Within the next hundred years—perhaps even sooner—matters to which no one will listen today will, in all probability, overshadow in their magnitude and their menace every other topic of human interest.

Let us now take a rather wider view of the fuel question and look at it as it affects the world and its distant future. The same process of exhaustion which has gone on and is going on in Great Britain will be repeated in other lands. They may learn from our experience, but the process of exhaustion, though slower, is inevitable. Are the resources of human knowledge equally limited? Has man struggled all these years to master Nature only to be beaten in the end? When he has swept bare the forests, won the last seam of coal, drained the last oilfield of its precious liquid, will he then be reduced to his former dependence upon the sun for light and warmth, and upon muscle and nerve for things of use and beauty which are not found ready made? By no means. So long as the sun shines, and the wind blows, and the rain falls he can wring a sustenance from the soil and hold at bay the savagery which would otherwise enfold him. But for this he must have power. How, then, is he to obtain it?

The exact way in which petroleum has been formed in Nature's vast manufactory is not fully understood, but all solid fuel is of vegetable origin. So long as plants will grow there will be a source of fuel.

It does not follow, however, that it will be of timber. Forest trees are of slow growth, and half the world devoted to forestry would fail to keep the factories of the other half going. But all plants contain cellulose, which they build up out of the carbon dioxide and moisture of the air. When cellulose is fermented it forms ultimately sugar as one of its products; when sugar is fermented it forms alcohol;

and alcohol can, as we have seen, be used as a fuel for internal combustion engines. Probably the most suitable substance to grow for this purpose would be beet, because the plant itself in the course of its growth produces a large quantity of sugar and shortens the process which would be necessary if cellulose were the starting point.

But it is very doubtful whether the demand for power could be wholly met in this way, though it is a striking fact that before the war the beer and wine produced annually in the world contained about 5 million tons of alcohol. It would be curious indeed if what a man takes to warm his interior should prove to be more valuable for warming his exterior; and still more curious if the motor cyclist of the future should stop at a wayside inn to beg a glass of water for himself and purchase a drink for his engine!

It may be, indeed, that water will ultimately turn out to be the salvation of both. Dame Nature is not so bad a mother, after all, for in many parts of the earth she has provided a source of power which is inexhaustible—a source which may be a little capricious and uncertain, but which, so long as the sun shines and the wind blows and the rain falls will never fail. For under the influence of the sun the air takes up moisture from the great oceans, and the wind carries it towards the land. Local variations of temperature arising from atmospheric circulation cause some of this to be thrown out as rain on land and sea alike; but the main precipitation occurs when the moist winds blow over mountain ranges.

Here, in regions of lower atmospheric pressure, the air expands, and, in expanding, cools. And as the quantity of water vapour that air can carry depends upon the temperature, the seaward slopes of mountain ranges are bathed with moisture.

The rain which falls upon the land becomes separated, generally speaking, into three portions. The first sinks deeply into the earth's crust, forming underground waters which feed springs and wells, and often form the source of streams and rivers. The second remains for a time on the surface and is re-evaporated directly or through the breathing of plants. The third runs off the surface, feeds streamlet and river, and finally reaches the sea.

It is a wonderful fact, that in this great cycle there is no waste. The water circulates continuously from sea to air and down to earth, and back again to air or sea. It is the third portion of which man makes use to produce power. He builds great walls or dams across the valleys, and prevents the water running away until it has paid toll. From these reservoirs he conducts it through pipes or channels to water wheels or turbines, so that in falling from a higher to a lower level it may do the work of which he stands in need. A cubic foot of water weighs 62·5 lb., and leaving friction out of account, every cubic foot falling from a height of 10 feet will perform 625 ft.-lb. of work. This work may be used to drive dynamos, and the electric current generated may be used for heat and light and power as well as for processes of manufacture which cannot be dealt with here.

Just as the sun enabled the plants of bygone ages to grow, and in this way provided us with vast stores of coal, so the same sun furnishes another means by which man can increase his power and lighten toil.

But while the special conditions which were necessary to the formation of coal have long since passed away, the conveyance of water from sea level to high ground seems likely to go on as long as the earth remains habitable by man. It is a wonderful world, and though perhaps some of what has been written in this chapter has little to do with engines, you will see how important the matter is, and will agree, I think, that the engineer who cannot see beyond the whirling wheels and moving rods of his machine is not worthy of the name. And not he alone. For his work is merely one small division of that intellectual struggle by which the human race has risen from savagery to civilisation. Nations rise and fall because human nature is frail and men are prone to error.

But from the first crude efforts in the far distant past the control over natural forces has been gradually widened and extended. Let us who to-day enjoy the fruits of ten thousand years of strenuous endeavour honour the memory of the pioneers, and look with reverence, but without fear, upon those gigantic forces which have been brought under our control.

And, above all, let us realise that our debt to the past and our obligations to the future lay upon us the duty of guarding those gifts which Nature has bestowed upon us, and of exercising economy in their use.

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