199. When uniformity of driving effort or the absence of dead-points is specially important, two independent cylinders are often coupled to the same shaft by cranks at right angles to each other, an arrangement which allows the engine to be started readily from any position. The ordinary locomotive is an example of this form. Among fixed engines of the larger kind, *winding engines*, in which ease of starting, stopping, and reversing is essential, are very generally made by coupling a pair of horizontal cylinders, with cranks at right angles to each other, on opposite sides of the winding-drum, with the link-motion as the means of operating the valves.

Compound horizontal engines.

200. Non-compound engines of so large a size as that of fig. 127 are comparatively uncommon. Horizontal engines of the larger class are generally compounded either (1) by having a high and a low pressure cylinder side by side, working on two cranks at exactly or nearly right angles to each other, or (2) by placing one cylinder behind the other, with the axes of both in the same straight line. The latter is called the *tandem* arrangement. In it one piston-rod is generally common to both cylinders; occasionally, however, the piston-rods are district and are connected to one another by a framing of parallel bars outside of the cylinders. Another construction, rarely followed, is to have parallel cylinders with both piston-rods acting on one crank by being joined to opposite ends of one long crosshead. In some recent compound engines the large cylinder is horizontal, and the other lies above it in an inclined position, with its connecting-rod working on the same crank-pin.

In tandem engines, since the pistons move together, there is no need to provide a receiver between the cylinders. It is practicable to follow the "Woolf" plan of allowing the steam to expand directly from the small into the large cylinder, and in many instances this is done. In point of fact, however, the connecting-pipe and steam-chest form an intermediate receiver of considerable size, which will cause loss by "drop" (§ 113) unless steam be cut off in the large cylinder before the end of the stroke. Hence it is more usual to work with a moderately early cut-off in the low-pressure cylinder than to use the "Woolf" plan of admitting steam to it throughout the whole stroke. Unless it is desired to make the cut-off occur before half-stroke, a common slide-valve will serve to distribute steam to the large cylinder. For an earlier cut-off than this a separate expansion-valve is required on the low-pressure cylinder, to supplement the slide-valve; and in any case, by providing a separate expansion-valve, the point of cut-off is made subject to easy control, and may be adjusted so as to avoid drop or to divide the work as may be desired between the two cylinders.[1] For this reason it is not unusual to find an expansion-valve, as well as a common slide-valve, on the low-pressure cylinder even of tandem engines. In many cases, however, the common slide-valve only is used. On the high-pressure cylinder

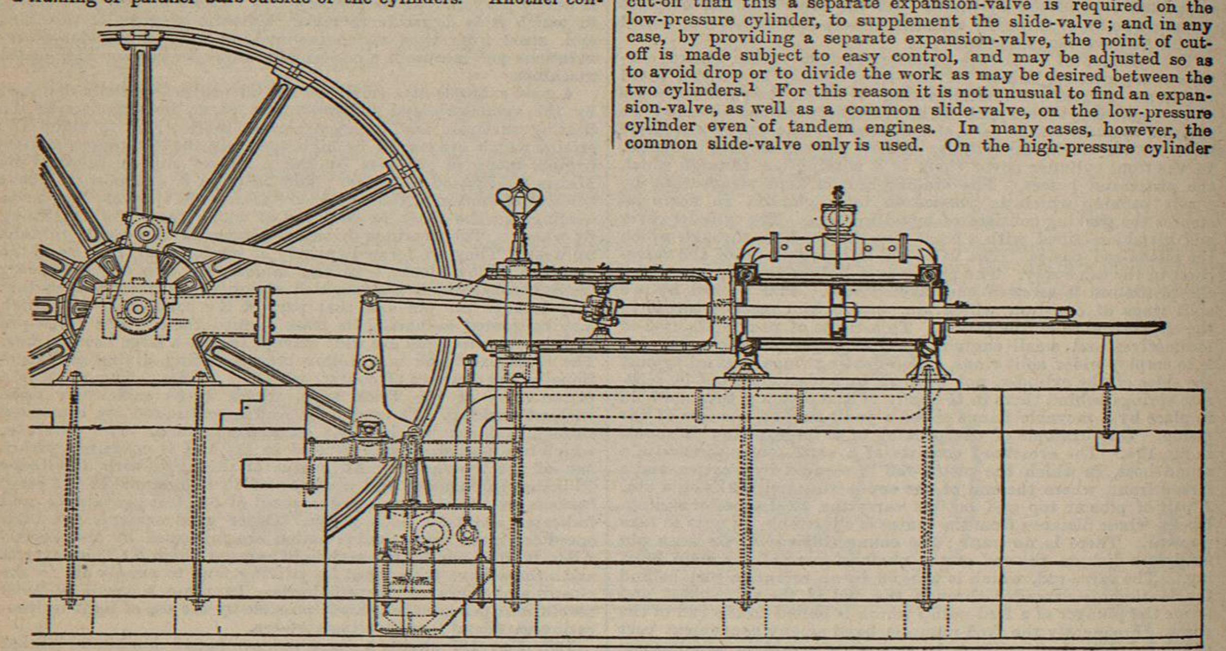

FIG. 127.—Horizontal Corliss Condensing Engine.

of compound engines, the cut-off is usually effected either by an expansion slide-valve or by some form of Corliss or other trip-gear.

For mill engines the compound tandem and compound coupled types are now the most usual, and the high-pressure cylinder is very generally fitted with Corliss gear. In the compound coupled arrangement the cylinders are on separate bedplates, and the fly-wheel is between the cranks.

Direct-acting vertical cylinder engine.

201. The general arrangement of vertical engines differs little from that of horizontal engines. The cylinder is usually supported above the shaft by a cast-iron frame resembling an inverted A, whose sides are kept parallel for a part of their length to serve as guides for the crosshead. Sometimes one side of the frame only is used, and the engine is stiffened by a wrought-iron column between the cylinder and the base on the other side. *Wall-engines* are a vertical form with a flat frame or bedplate, which is made to be bolted against a wall; in these the shaft is generally at the top. Vertical engines are compounded, like horizontal engines, either by coupling parallel cylinders to cranks at right angles (as in the ordinary marine form, which will be illustrated later, § 218), or, tandem fashion, by placing the high-pressure cylinder above the other. In vertical condensing engines the condenser is situated at the base, and the air-pump, which has a vertical stroke, is generally worked by a lever connected by a short link to the crosshead. In some cases the pump is horizontal, and is worked by a crank on the main shaft.

High-speed single-acting engines.

202. Engines making 400 to 1600 revolutions per minute have been extensively applied, in recent years, to the driving of dynamos and other high-speed machines. These are for the most part single-acting; steam is admitted to the back of the piston only, and the connecting-rod is in compression throughout the whole revolution. Besides simplifying the valves, this has the important advantage that alternation of strain at the joints may be entirely avoided, with the knocking and wear of the brasses which it is apt to cause. To secure, however, that the connecting-rod shall always push, there must be much cushioning during the back or exhaust stroke. From a point near the middle of the back stroke to the end the piston is being retarded; and, as this must not be done by the rod (which would thereby be required to pull), cushioning must begin there, and the work spent upon the cushion must at every stage be at least as great as the loss of energy on the part of the piston and rod. In some single-acting engines this cushioning is done by compressing a portion of the exhaust steam; in others the rod is kept in compression by help of a supplementary piston, on which steam from the boiler presses; in Mr Willans's engine the cushioning is done by compressing air.

203. A very successful example of the multiple-cylinder single-acting high-speed type is the three-cylinder engine introduced by Mr Brotherhood in 1873, the most recent form of which is shown in figs. 128 and 129. Fig. 128 is a longitudinal and fig. 129 a transverse section. Three cylinders, set at 120° apart, project from a closed casing, the central portion of which forms the exhaust. The pistons are of the trunk type—that is to say, there is a joint in the piston itself which allows the piston-rod to oscillate, and so makes a separate connecting-rod unnecessary. The three rods work on a single crank-pin, which is counterbalanced by masses

[1] Or, alternatively, the adjustment may be made so that the steam undergoes equal changes of temperature in both cylinders.

fixed to the crank cheeks on the other side of the shaft. Steam is admitted to the back of the pistons only. It passes first through a throttle-valve, which is controlled by a centrifugal spring-governor (fig. 128), and is then distributed to the cylinders by three piston-valves A, worked by an eccentric, the sheave of which is made hollow so as to overhang one of the main bearings (fig. 128). Release takes place by the piston itself uncovering exhaust ports in the circumference of the cylinder, and the rocking motion of the piston-rod is taken advantage of to open a supplementary exhaust port (B, fig. 129), which remains open during a sufficient portion of the back stroke. The flexible coupling C shown in fig. 128, in which the twisting moment of the shaft is transmitted through disks of leather, prevents straining of the shaft and bearings through any want of alignment between the shaft of the engine and that of the mechanism it drives. Besides its use as a steam-engine, Mr Brotherhood's pattern has been extensively applied in driving torpedoes by means of compressed air. As a steam-engine it is compounded by placing a high-pressure cylinder outside of and tandem with each low-pressure cylinder.

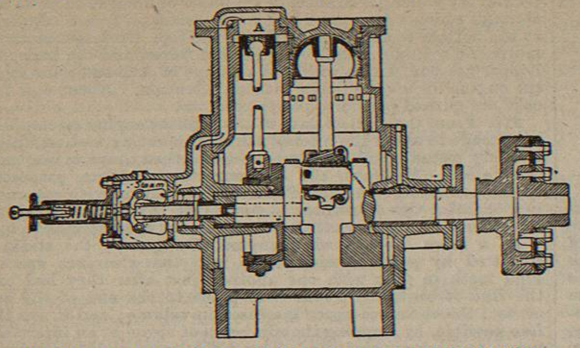

FIG. 128.—Brotherhood's Three-Cylinder Engine: longitudinal section.

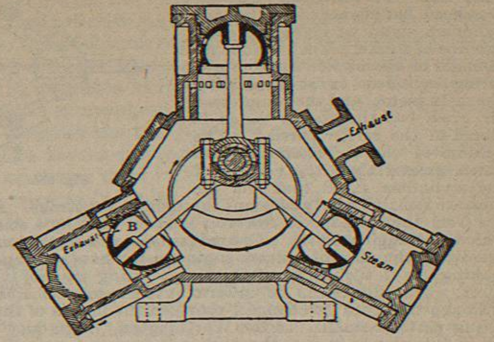

FIG. 129.—Brotherhood's Three-Cylinder Engine: transverse section.

204. In other engines of this type a pair of cylinders, or a high and a low pressure cylinder, are set vertically side by side, to work on cranks opposite each other. The cranks and connecting-rods are completely enclosed, and are lubricated by dipping into a mixture of oil and water with which the lower part of the casing is filled. In the Westinghouse engine, where there are two vertical cylinders to which steam is admitted by a piston-valve, the crank-shaft is situated half a crank's length out of the line of stroke, to reduce the effects of the connecting-rod's obliquity during the working stroke.[1] In Mr Willans's latest form of engine the high and low pressure cylinders are tandem, and the space between the piston forms an intermediate receiver. The piston-rod is hollow, and has a piston-valve in it which controls the admission of steam to the high-pressure cylinder and its transfer to the low-pressure cylinder. The piston-valve within the rod takes its differential motion from an eccentric on the crank-pin. The crosshead is itself a piston working in a cylindrical guide, in which it compresses air as it rises during the back stroke in order to cushion the reciprocating parts.[2]

Pumping engines.

205. In engines for pumping or for blowing air it is not essential to drive a revolving shaft, and in many forms the reciprocating motion of the steam-piston is applied directly or through a beam to produce the reciprocating motion of the pump-piston or plunger. On the other hand, pumping engines are frequently made rotative for the sake of adding a fly-wheel. When the level of the suction water is sufficiently high, horizontal engines, with the pump behind the cylinder and in line with it, are generally preferred; in other cases a beam-engine or vertical direct-acting engine is more common. Horizontal engines are, however, employed to pump water from any depth by using triangular rocking frames, which serve as bell-crank levers between the horizontal piston and vertical pump-rods.[3]

Fig. 130 shows a compound inverted vertical pumping engine of the non-rotative class, by Messrs Hathorn, Davey, & Co. Steam is distributed through lift valves, and the engine is governed by the differential gear illustrated in fig. 107, in conjunction with a cataract, which makes the pistons pause at the end of each stroke. The pistons are in line with two pump-rods, and are coupled by an inverted beam which gives guidance to the crossheads by means of an approximate straight-line motion, which is a modification of that of fig. 120. Surface condensers are frequently used with pumping engines, the water which the engine pumps serving as circulating water.

206. In a very numerous class of direct-acting steam-pumps, the steam-piston and the pump-piston or plunger are on the same piston-rod. In some of these a rotative element is introduced, partly to secure uniformity of motion, and partly for convenience of working the valves; a connecting-rod is taken from some point in the piston-rod to a crank-shaft which carries a fly-wheel; or a slotted crosshead fixed to the rod gives rotary motion to a crank-pin gearing into the slot, the line of the slot being perpendicular to that of the stroke. Many other steam-pumps are strictly non-rotative. In some the valve is worked by tappets from the piston-rod. In the Blake steam-pump a tappet worked by the piston as it reaches each end of its stroke throws over an auxiliary steam-valve, which admits steam to one or other side of an auxiliary piston carrying the main slide-valve. In Cameron & Floyd's form one of a pair of tappet-valves at the ends of the cylinder is opened by the piston as it reaches the end of the stroke, and puts one or other side of an auxiliary piston, which carries the slide-valve, into communication with the exhaust, so that it is thrown over. In the Worthington engine—a design which has had much success in America, and is now being introduced in England by Messrs Simpson—two steam cylinders are placed side by side, each working its own pump-piston. The piston-rod of each is connected by a short link to a swinging bar, which actuates the slide-valve of the other steam-cylinder. In this way one piston begins its stroke when the motion of the other is about to cease, and a smooth and continuous action is secured.

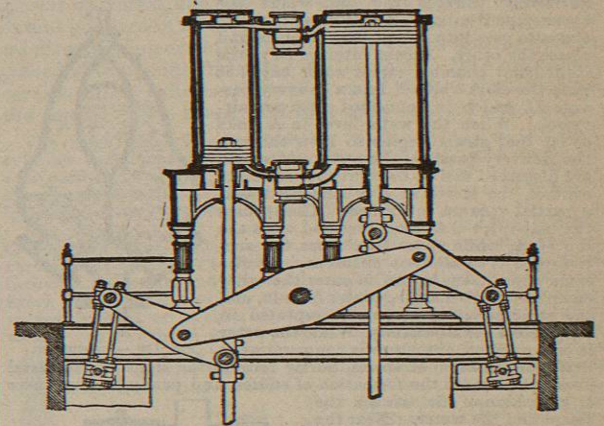

FIG. 130.—Vertical Non-Rotative Pumping Engine.

Worthington engine.

207. The Worthington engine has been extensively applied, on a large scale, to raise water for the supply of towns and to force oil through "pipe-lines" in the United States. In the larger sizes it is made compound, each high-pressure cylinder having a low-pressure cylinder tandem with it on the same rod. Owing to the lightness of the reciprocating masses, and their comparatively slow acceleration, their inertia does not compensate, to any great extent, for the inequality of pressure on the pump-piston that would be caused by an early cut-off in the steam cylinder (see § 186). To meet this difficulty, and make high expansion practicable, an ingenious addition has recently been made to the engine.[4] A crosshead A (fig. 131) fixed to each of the piston-rods is connected to the piston-rods of a pair of oscillating cylinders B, B, which contain water and communicate with a reservoir full of air compressed to a pressure of about 300 lb per square inch. When the stroke (which

[1] See *Engineering*, August 13, 1886.

[2] See "Discussion on High Speed Motors," *Min. Proc. Inst. C.E.*, Nov. 1885.

[3] For an account of beam and other forms of rotative pumping engines, see a paper by Mr Rich, and remarks by Mr J. G. Mair, in *Min. Proc. Inst. C.E.*, April 1884.

[4] *Min. Proc. Inst. C.E.*, 1886, part iv.; *Engineering*, August 20, 1886.

takes place in the direction of the arrow) begins the pistons are at first forced in, and work is at first done by the main piston-rod, through the compensating cylinders B, B, on the compressed air in the reservoir. This continues until the crosshead has advanced so that the cylinders stand at right angles to the line of stroke. Then for the remainder of the stroke the compensating cylinders assist in driving the main piston, and the compressed air gives out the energy which it stored in the earlier portion. The volume of the air reservoir is so much greater than the volume of the cylinders B, B that the air pressure remains nearly constant throughout the stroke. Any leakage from the cylinder or reservoir is made good by a small pump which the engine drives. One advantage which this method of equalizing the effort of a steam-engine piston has (as compared with making use of the inertia of the reciprocating masses) is that the effort, when adjusted to be uniform at one speed, remains uniform although the speed be changed, provided the inertia of the reciprocating parts be small. In the Worthington "high-duty" engine, where this plan is in use, the high and low pressure cylinders are each provided with a separate expansion-valve of the rocking-cylinder type, as well as a slide-valve; the cut-off is early, and the efficiency is as high as in other pumping engines of the best class.

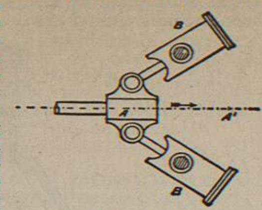

Fig. 131.

208. Mr Hall's "pulsometer" is a peculiar pumping engine without cylinder or piston, which may be regarded as the modern representative of the engine of Savery (§ 6). The sectional view, fig. 132, shows its principal parts. There are two chambers A, A', narrowing towards the top, where the steam-pipe B enters. A ball-valve C allows steam to pass into one of the chambers and closes the other. Steam entering (say) the right-hand chamber forces water out of it past the clack-valve V into a delivery passage D, which is connected with an air-vessel. When the water-level in A sinks so far that steam begins to blow through the delivery-passage, the water and steam are disturbed and so brought into intimate contact, the steam in A is condensed, and a partial vacuum is formed. This causes the ball-valve C to rock over and close the top of A, while water rises from the suction-pipe E to fill that chamber. At the same time steam begins to enter the other chamber A', discharging water from it, and the same series of actions is repeated in either chamber alternately. While the water is being driven out there is comparatively little condensation of steam, partly because the shape of the vessel does not promote the formation of eddies, and partly because there is a cushion of air between the steam and the water. Near the top of each chamber is a small air-valve opening inwards, which allows a little air to enter each time a vacuum is formed. When any steam is condensed, the air mixed with it remains on the cold surface and forms a non-conducting layer. The pulsometer is, of course, far from efficient as a thermodynamic engine, but its suitability for situations where other steam-pumps cannot be used, and the extreme simplicity of its working parts, make it valuable in certain cases.

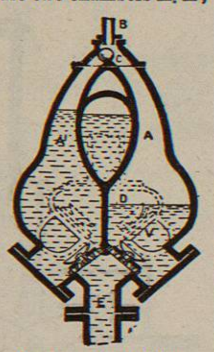

Fig. 132.—Pulsometer.

209. We have seen that the tendency of modern steam practice is towards higher pressures, and that this means a gain both in efficiency and in power for a given weight of engine. High pressure, or indeed any pressure materially above that of the atmosphere, is out of the question when engine and boiler are to work without the regular presence of an attendant. Mr Davey has recently introduced a domestic motor which deserves notice from the fact that it employs steam at atmospheric pressure. One form of this successful little engine is shown in fig. 133. The boiler—which serves as the frame of the engine—is of cast-iron, and is fitted with a cast-iron internal fire-box, with a vertical flue which is traversed by a water-bridge. The cylinder, which is enclosed within the upper part of the boiler, and the piston are of gun-metal, and work without lubrication. Steam is admitted by an ordinary slide-valve, also of gun-metal, worked by an eccentric in the usual way. The condenser stands behind the boiler; it consists of a number of upright tubes in a box, through which a current of cold water circulates from a supply-pipe at the bottom to an overflow-pipe at the top. In larger sizes of the motor the cylinder stands on a distinct frame, and the boiler has a hopper fire-box, which will take a charge of coke sufficient to drive the engine for several hours without attention. About 6 or 7 lb of coke are burned per horse-power per hour.

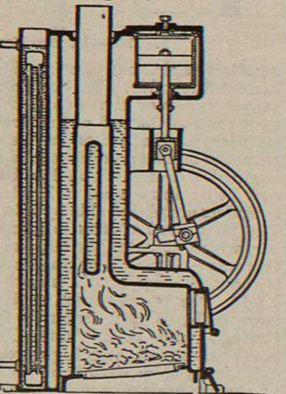
Fig. 133.—Davey Motor.

210. From the earliest days of the rotative engine attempts have been made to avoid the intermittent reciprocating motion which an ordinary piston-engine first produces and then converts into motion of rotation. Murdoch, the contemporary of Watt, proposed an engine consisting of a pair of spur-wheels gearing with one another in a chamber through which steam passed by being carried round the outer sides of the wheels in the spaces between successive teeth.[1]

In a more modern wheel-engine (Dudgeon's) the steam was admitted by ports in side-plates into the clearance space behind teeth in gear with one another, just after they had passed the line of centres. From that point to the end of the arc of contact the clearance space increased in volume; and it was therefore possible, by stopping the admission of steam at an intermediate point, to work expansively. The difficulty of maintaining steam-tight connexion between the teeth and the side-plates on which the faces of the wheels slide is obvious; and the same difficulty has prevented the success of many other forms of rotary engine. These have been devised in immense variety, in many cases, it would seem, with the idea that a distinct mechanical advantage was to be secured by avoiding the reciprocating motion of a piston.[2] In point of fact, however, very few forms entirely escape having pieces with reciprocating motion. In all rotary engines, with the exception of steam turbines,—where work is done by the kinetic impulse of steam,—there are steam chambers which alternately expand and contract in volume, and this action usually takes place through a more or less veiled reciprocation of working parts. So long as engines work at a moderate speed there is little advantage in avoiding reciprocation; the alternate starting and stopping of piston and piston-rod does not affect materially the frictional efficiency, throws no deleterious strain on the joints, and need not disturb the equilibrium of the machine as a whole. The case is different when very high speeds are concerned; it is then desirable as far as possible to limit the amount of reciprocating motion and to reduce the masses that partake in it.

211. A recent interesting and successful example of the rotary type is the spherical engine of Mr Beauchamp Tower,[3] which, like several of its predecessors,[4] is based on the kinematic relations of the moving pieces in a Hooke's joint. Imagine a Hooke's joint, uniting two shafts set obliquely to one another, to be made up of a central disk to which the two shafts are hinged by semicircular plates, each plate working in a hinge which forms a diameter of the central disk, the two hinges being on opposite sides of the disk and at right angles to one another. Further, let the disk and the hinged pieces be enclosed in a spherical chamber through whose walls the shafts project. As the shafts revolve each of the four spaces bounded by the disk, a hinged piece, and the chamber wall will suffer a periodic increase and diminution of volume, between limits which depend on the angle at which the shafts are set. In Mr Tower's engine this arrangement is modified by using spherical sectors, each a quarter sphere, in place of semicircular plates, for the pieces in which the shafts terminate. The shafts are set at 135°. Each of the four enclosed cavities then alters in volume from zero to a quarter sphere, back to zero, again to a quarter sphere, and again back to zero, in a complete revolution of the shafts. In practice the central disk is a plate of finite thickness, whose edge is kept steam-tight in the enclosing chamber by spring-packing, and the sectors are reduced to an extent corresponding to the thickness of the central disk. One shaft is a dummy and runs free, the other is the driving-shaft. Steam is admitted and exhausted by ports in the spherical sectors, whose backs serve as revolving slide-valves. It is admitted to each cavity during the first part of each periodical increase of the cavity's volume. It is then cut off and allowed to expand as the cavity further enlarges, and is exhausted as the cavity contracts. If the working shaft, to which the driven mechanism serves as a fly-wheel, revolves uniformly, the dummy shaft is alternately accelerated and retarded. Apart from this, the only reciprocating motion is the small amount of oscillation which the comparatively light central disk undergoes. Tower's spherical engines.

Another rotary engine of the Hooke's-joint family is Mr Field-

[1] See Farey's *Treatise on the Steam Engine*, p. 676.
[2] A large number of proposed rotary engines are described, and their kinematic relations to one another are discussed, in Reuleaux's *Kinematics of Machinery*, translated by Prof. Kennedy.
[3] *Proc. Inst. Mech. Eng.*, March 1885.
[4] One of these, the disk-engine of Bishop, was used for a time in the printing office of *The Times*, but was discarded in 1857.

ing's,[1] in which a gimbal-ring and four curved pistons take the place of the disk. Two curved pistons are fixed on each side of the gimbal-ring, and as the shafts revolve these work in a corresponding pair of cavities, which may be called curved cylinders, fixed to each shaft.

212 Attempts have been made from time to time to devise steam-engines of the turbine class, where rotation of a wheel is produced either by reaction from a jet of escaping steam or by impact of a jet upon revolving blades. A revolving piece which is to extract even a respectable fraction of the kinetic energy of a steam jet must move with excessive velocity. In Mr C. A. Parsons's steam-turbine this difficulty is overcome and a moderate degree of efficiency is secured by using a series of central-flow turbine wheels, in the form of perforated disks all on one shaft, with fixed disks between which are perforated to serve as guide-blades. Steam passes from end to end of the series, giving up a small portion of its energy to each, but retaining little at the end.

XII. Marine Engines.

Types of marine engines. 213. The early steamers were fitted with paddle-wheels, and the engines used to drive them were for the most part modified beam-engines. Bell's "Comet" (§ 21) was driven by a species of inverted beam-engine, and another form of inverted beam, known as the side-lever engine, was for long a favourite with marine engineers. Side-lever engines. In the side-lever engine the cylinder was vertical, and the piston-rod projected through the top. From a crosshead on the rod a pair of links, one on each side of the cylinder, led down to the ends of a pair of horizontal beams or levers below, which oscillated about a fixed gudgeon at or near the middle of their length. The two levers were joined at their other ends by a crosstail, from which a connecting-rod was taken to the crank above. The side-lever engine is now obsolete.

Beam-engines. In American practice, engines of the beam type, with a braced-beam supported on A-frames above the deck, are still common in river-steamers and coasters.

Steeple-engines. 214. An old form of direct-acting paddle-engine was the steeple-engine, in which the cylinder was set vertically below the crank. Two piston-rods projected through the top of the cylinder, one on each side of the shaft and of the crank. They were united by a crosshead sliding in vertical guides, and from this a return-connecting-rod led to the crank.

215. Modern paddle-wheel engines are usually of one of the following types. (1) In *oscillating cylinder engines* the cylinders are set under the crank-shaft, and the piston-rods are directly connected to the cranks. The cylinders are supported on trunnions which give them the necessary freedom of oscillation to follow the movement of the crank. Steam is admitted through the trunnions to slide-valves on the sides of the cylinders. In some instances the mean position of the cylinders is inclined instead of vertical; and oscillating engines have been arranged with one cylinder before and another behind the shaft, both pistons working on one crank. The oscillating cylinder type is best adapted for what would now be considered comparatively low pressures of steam. (2) *Diagonal engines* are direct-acting engines of the ordinary connecting-rod type, with the cylinders fixed on an inclined bed and the guides sloping up towards the shaft.

216 When the screw-propeller began to take the place of paddle-wheels in ocean-steamers, the increased speed which it required was at first supplied by using spur-wheel gearing in conjunction with one of the forms of engines then usual in paddle steamers. After a time types of engine better suited to the screw were introduced, and were driven fast enough to be connected directly to the screw shaft. The smallness of the horizontal space on either side of the shaft formed an obstacle to the use of horizontal engines, but this difficulty was overcome in several ways. In Penn's trunk-engine, still used in the navy, the engine is shortened by attaching the connecting-rod directly to the piston, and using a hollow piston-rod, called a trunk, large enough to allow the connecting-rod to oscillate inside it. The trunk extends through both ends of the cylinder and forms a guide for the piston. It has the drawback of requiring very large stuffing-boxes, of wasting cylinder space, and of presenting a large surface of metal to alternate heating by steam and cooling by contact with the atmosphere. The use of high-pressure steam is likely to make the trunk-engine obsolete.

217. The return-connecting-rod engine is another horizontal form much used in the navy. It is a steeple-engine placed horizontally, with two, and in some cases four, piston-rods in each cylinder. The piston-rods pass clear of the shaft and the crank, and are joined beyond it in a guided crosshead, from which a connecting-rod returns.

Ordinary horizontal direct-acting engines with a short stroke and a short connecting-rod are also common in war-ships, where the horizontal is frequently preferred to the vertical type of engine for the sake of keeping the machinery below the water-line. In horizontal marine engines the air-pump and condenser are generally placed on the opposite side of the shaft from the cylinder, which balances the weight and allows the air-pump to be driven direct.

218. In merchant ocean-steamers one general type of engine is universal, and the same type is now to an increasing extent adopted in naval practice. This is the inverted vertical direct-acting engine, generally with two or more cylinders placed side by side directly over the shaft. In exceptional cases a single cylinder has been used, with a fly-wheel on the shaft. Two, three, and four cylinders are common.

The most usual form of existing marine engine is the two-cylinder compound arrangement, with cranks at right angles or nearly at right angles, of which figs. 135, 136, 137 (pp. 518–20) show a characteristic example (the engines of the s.s. "Tartar," by Messrs John & James Thomson, Glasgow).

Fig. 135 is an end elevation, fig. 136 a longitudinal section through the centre of the engines, and fig. 137 a thwart-ship section through the condenser and air-pump. The cylinders are 50 and 94 inches in diameter, and the stroke is 5 feet. Both cylinders are fitted with liners, and are steam-jacketed. Double-ported slide valves are used on both, and the high-pressure valve has a relief ring. The crosshead guides are fitted on the side on which the crosshead bears when the engines are going ahead, with a hollow box behind the guiding surface, and cold water is kept circulating in this to prevent the guides from heating. The crank-shaft is of Vicker's steel, 17½ inches in diameter. The condenser is in the place it usually has in engines of this type,—in the lower part of the back frame, with its tubes running horizontally from end to end of the engine. There are 1400 tubes, of 1 inch diameter and 1½ inch pitch. The air-pumps are of the single-acting bucket kind, and are driven by a lever from the crosshead.

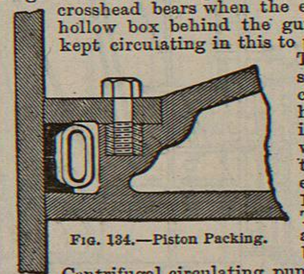
Fig. 134.—Piston Packing.

Centrifugal circulating pumps are used, driven by a pair of independent small vertical engines. The link-motion is worked by steam starting and reversing gear, which appears on the left side of the engine in fig. 135. These engines work with a boiler pressure of 90 lb, and indicate 3560 horse-power. Fig. 134 shows, on a larger scale, the piston packing, which consists of a pair of floating rings, pressed out by a spiral spring behind them.

219. Two other arrangements of double compound (as distinguished from triple-expansion) marine engines of the inverted vertical type require notice. One is the tandem arrangement, largely adopted in the steamers of the "White Star" line. In these each crank is operated by an independent pair of compound cylinders, the high-pressure cylinder being on top of the low-pressure cylinder, with one piston-rod common to both. The valves of both are worked by a single pair of eccentrics with a link-motion; the valve-rod of the low-pressure cylinder extends through the top of its valve-chest, and is joined either directly or by a short lever with the valve-rod of the high-pressure cylinder. Generally two pairs of tandem cylinders are placed side by side, one pair abaft the other, to work on cranks at right angles. In exceptionally large engines three pairs have been used, working on

[1] *Min. Proc. Inst. C.E.*, November 1885.

cranks 120 apart,[1] an arrangement greatly superior to that of two cranks in uniformity of effort on the shaft. To facilitate removing the pistons from the cylinders, the large cylinder has in some cases been set above the other.

220. The other arrangement of double compound marine engine has three cylinders set in line fore and aft. The middle one is the high-pressure cylinder; the other two receive steam from it, and form together the equivalent of one large low-pressure cylinder. The three work on cranks at 120° apart. Besides securing the advantage in uniformity of effort which three cranks have over two, this form avoids the use, in very powerful engines, of a low-pressure cylinder of excessive size. On the other hand, the three-cylinder form takes up more space, and has a larger number of working parts. In the most powerful engines that have yet been constructed this three-cylinder arrangement is followed. The "Umbria" and "Etruria" have a 71-inch high-pressure cylinder between two 105-inch low-pressure cylinders, with a stroke of 6 feet. These engines, which were built just before the introduction of triple expansion, are supplied with steam at a pressure of 110 lb by gauge, and indicate 14,300 horse-power.

In this and in the ordinary two-cylinder form of marine engine, the low-pressure valve-chest and the casing of the engine between the cylinders form an intermediate receiver for the steam.

Triple-expansion engines. 221. During the last two or three years a great advance has taken place in marine engineering by the general introduction of triple-expansion engines, and by an increase in steam pressure which the system of triple expansion makes practicable. In 1874 the steamer "Propontis" was fitted with a set of three-crank triple-expansion engines, designed by Mr A. C. Kirk. The experiment was prevented from being fully successful by the failure of the boilers, which were of a special type. Another experiment with triple engines in the yacht "Isa" in 1877 prepared the way for their application to regular ocean service. In 1882 the steamship "Aberdeen," with triple engines, designed by Mr Kirk, to work with steam of 125 lb pressure, supplied from double-ended steel boilers of the ordinary marine type, demonstrated the advantage and safety of the system. Since then its use has become general in new steamers, and in many cases the older double engines are being removed to give place to engines of the triple-expansion type, with the effect of reducing the consumption of coal by about 25 per cent.[2]

222. In the most common arrangement of triple-expansion engines three cylinders are ranged in line, fore and aft, working on cranks at 120° apart. Piston-valves are generally preferred, and these are not uncommonly worked by some form of radial valve-gear instead of the ordinary link-motion. An advantage of this is that the space which would be taken up by eccentrics upon the shaft is saved, and longer main bearings are in consequence possible, without spreading the engines in the fore-and-aft direction. An objectionable feature of the three-cylinder triple engine is its length; on the other hand, the high speed and high pressure which are features of modern practice make long bearings indispensable.

223. To avoid the length of the three-crank engine, Mr Brock and others have made engines of the triple-expansion type with two cranks, by putting the high and the intermediate pressure cylinders above and tandem with two low-pressure cylinders. Mr Brock has also built four-cylinder *quadruple*-expansion engines of a similar form (with two cranks), and estimates that they show an economy in coal consumption of 5 per cent. as compared with triple-expansion engines working with the same pressure of steam.

224. Steam-jackets are retained by some but not by all builders; where they are employed the boiler steam is usually reduced in pressure before admission to the intermediate and low-pressure cylinder jackets and to the receiver-jackets. The feed-water is frequently heated to about 200° F. by Weir's plan of condensing in it, by common injection, a quantity of steam taken from the second receiver; this has the advantage of freeing it of air, and of preventing local chilling in the boiler. In present-day practice the boiler pressure, for a triple-expansion engine, ranges from 120 to 170 lb per square inch (by gauge), and it does not appear that any material increase of this is possible without a complete departure from the present type of marine boiler. On the other hand, without a material increase of pressure there is little advantage in quadruple expansion.

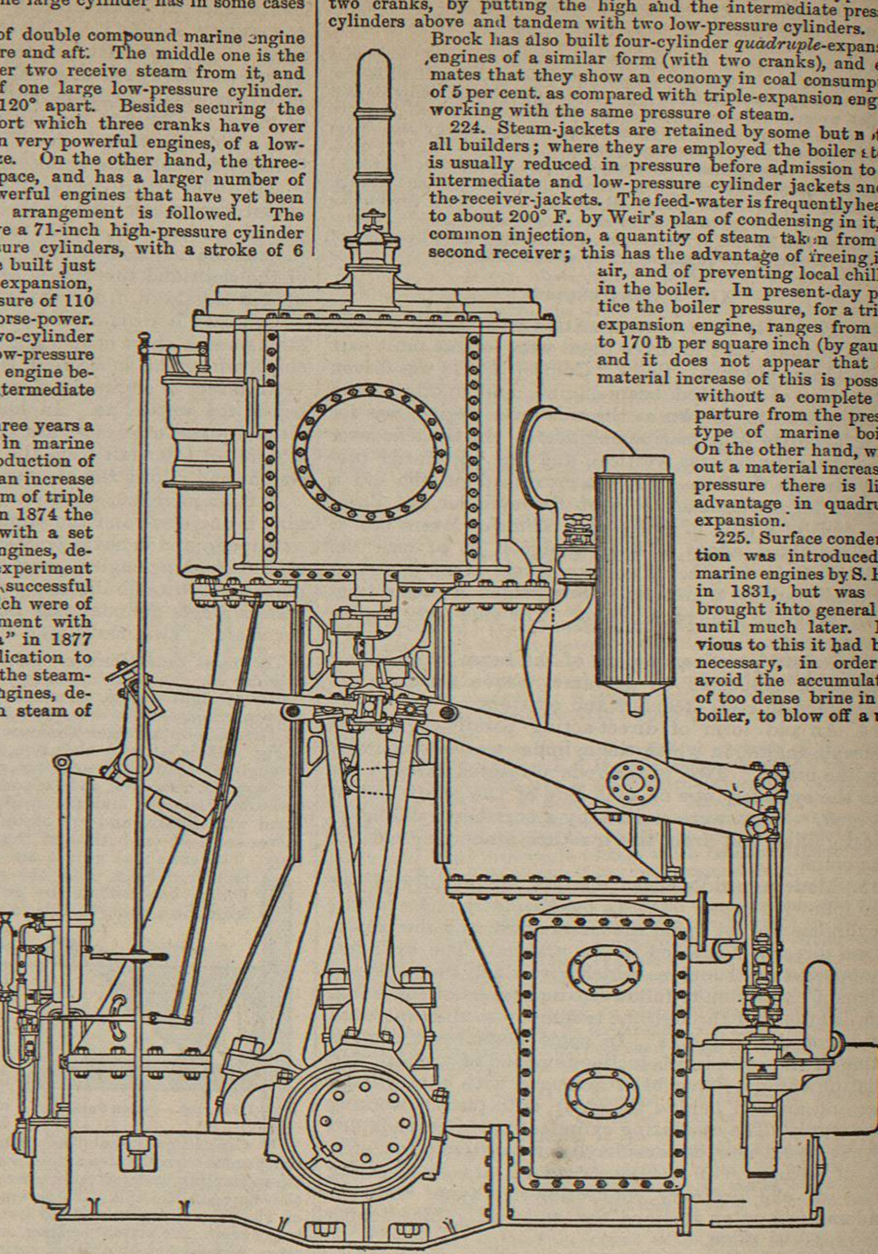

Fig. 135.—End Elevation of Marine Engine.

225. Surface condensation was introduced in marine engines by S. Hall in 1831, but was not brought into general use until much later. Previous to this it had been necessary, in order to avoid the accumulation of too dense brine in the boiler, to blow off a portion of the brine at short intervals and replace it by sea water, a process which of course involved much waste of heat. By the use of surface condensers it became possible to use the same portion of water over and over again. The very freedom of the condensed water from dissolved mineral substances was for a time an obstacle to the adoption of surface condensers, for it was found that the boiler, no longer protected by a deposit of scale, became rapidly corroded through the action of acids formed by the decomposition of the lubricating oil. This objection was overcome by introducing a sufficient amount of salt water to allow some scale to form, and the use of surface condensers soon became universal on steamers plying in sea water. The marine condenser consists of a multitude

[1] See description of the engines of the "City of Rome," with three 46-inch and three 86-inch cylinders, with a stroke of 6 feet, working up to 11,890 I. H. P., *Proc. Inst. Mech. Eng.*, 1880.

[2] The rapid progress of the system of triple expansion may be judged from the fact mentioned by Mr W. Parker of Lloyds in a recent paper (*Engineering*, July 30, 1886), that, out of 199 engines then being built for merchant steamers, 128 sets were of the triple-expansion type. For war-ships also triple engines are being built of sizes up to 13,000 horse-power. For a discussion of several important points in the design of triple-expansion engines, see a paper by R. Wyllie, *Proc. Inst. Mech. Eng.*, Oct. 1886.

of tubes, generally of brass, about ¾ of an inch in diameter. Through these cold sea-water is made to circulate, while the steam is brought into contact with their outside surfaces. In some cases, especially in Admiralty practice, cold water circulates outside the tubes and the steam passes inside.

226. The ordinary marine engine has four pumps:—the air-pump, which is made large enough to serve in case injection instead of surface-condensation should at any time be resorted to; the feed-pump; the circulating-pump, which maintains a current of sea-water through the tubes of the condenser; and the bilge-pump, which discharges any water accumulated by leakage or otherwise in the bilge of the ship. The pumps are so arranged that in the event of a serious leak the circulating-pump can also draw its supply from the bilge. In most engines, especially those of less recent construction, the four pumps are placed behind the condenser, and are worked by a single crosshead driven by a lever, the other end of which is connected by a short link with one of the crossheads of the engine. It is now becoming common to use a small engine, distinct from the main engine, to drive the feed-pump, and to supply circulating water by a centrifugal pump also driven by a separate engine.

227. In the improvement of the marine engine two points are noteworthy,—reduction in the rate of consumption of coal per horse-power, and reduction in the weight of the machine (comprising the engine proper and the boilers) per horse-power. The second consideration is in some cases of even more moment than the first, especially in war-ships. Progress has been made, in both respects, by increase of steam pressure, and, in the second respect especially, by increase of piston speed. Fifty years ago the boilers of marine engines made steam at a pressure of about 5 lb per square inch above that of the atmosphere. By 1860 compound engines were in use with pressures ranging from 25 to 40 lb. In 1872 statistics collected for nineteen ocean steamers showed that the average consumption of coal was then 2·11 lb per H.P. per hour, the boiler-pressure 45 to 60 lb, and the mean piston speed about 375 feet per minute.[1] These were for the most part two-cylinder compound engines of the vertical inverted type. Nine years later statistics for thirty engines of the same type showed a consumption of 1·83 lb of coal, a mean boiler pressure of 77½ lb, and a mean piston speed of 467 feet per minute.[2] In recent triple-expansion engines the pressure is as high as 165 lb; a piston speed of 700 or 800 feet per minute is not uncommon in naval engines, and in some cases it has risen to over 1000 feet per minute.[3] The economy in coal consumption brought about by the change from double-expansion engines working at (say) 80 lb to triple engines at 160 lb or more is variously estimated at from 18 to 25 per cent. Much of this is due simply to the increased range of temperature through which the working substance is carried; but it appears that the actual performance of the triple engine is better than that of the double compound in a ratio greater than that by which its ideal efficiency—as an engine using a wider range of temperature—exceeds that of the other; and this is to be ascribed to the same causes as have been already discussed in speaking of the advantage of the compound over the simple engine. Apart from its greater economy of coal, the triple engine owes some of its practical success to the mechanical superiority of three driving cranks over two.

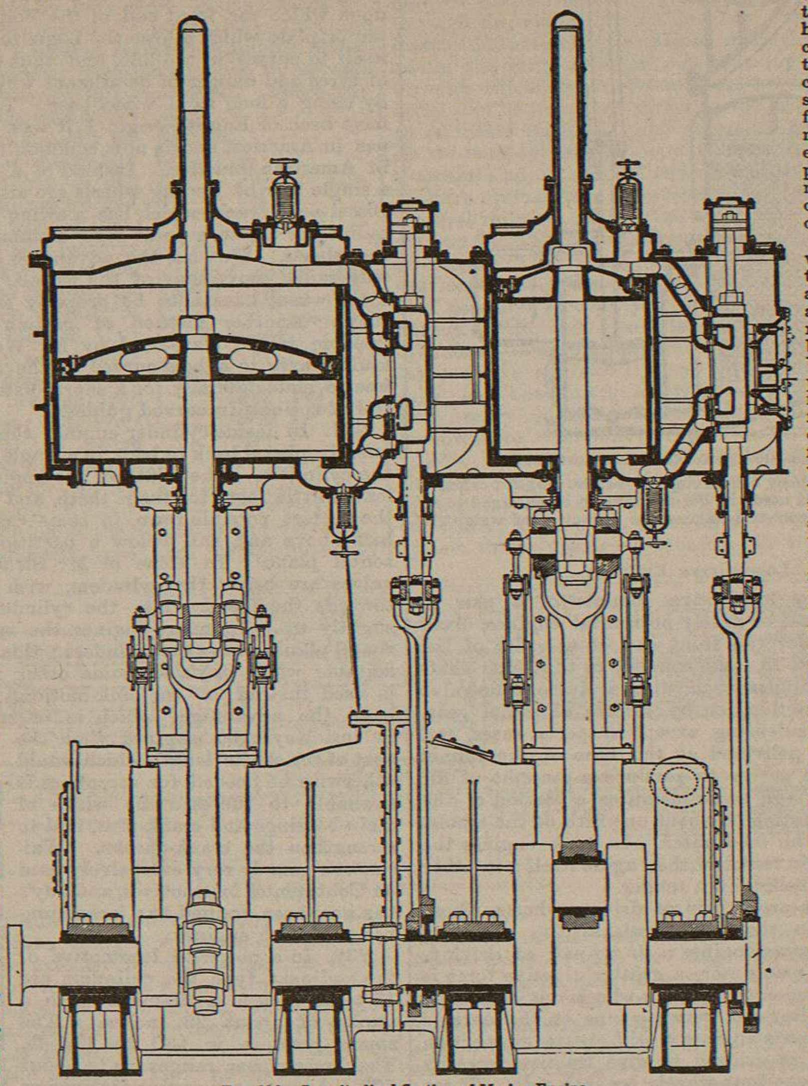

Fig. 136.—Longitudinal Section of Marine Engine.

Relation of weight to power. 228. The relation of weight of machinery to power developed, and the causes which affect this ratio, have recently been discussed by Messrs Marshall and Weighton,[4] from whose paper the following figures are taken. Before the introduction of triple expansion and forced draught the weight of engines in the mercantile marine, including the boilers and the water in them, was 480 lb per I.H.P. In the navy this was reduced, chiefly by the use of lighter framing, with the object of minimizing weight, to 360 lb. Triple-engines of the merchant type, without forced draught, are only slightly lighter than double engines; but in naval practice, where forced draught, greatly increased speed, and the use of steel for frames and working parts have combined to reduce the ratio of weight to power, a marked reduction in weight is apparent. A recent set of vertical triple engines, which with natural draught indicate 2200 H.P., and with a draught forced by pressure in the stokehole equal to 2 inches of water indicate 4000 H.P., weigh under the latter condition (along with the boilers) only 155 lb per I.H.P. In another set, in which the draught is forced by a pressure of 3 inches, and the cylinders are only 15½, 24, and 37 inches in diameter, with a stroke of 16 inches, the indicated horse-power is 4200, and the weight of engines and boilers is 136 lb per I.H.P. In these the boilers are of the locomotive type, and the mean piston speed is 1066 feet per minute. Even these light weights are surpassed in smaller engines, such as those of torpedo boats. In so far as this immense development of power from a small weight of machinery is due to high piston speed, it is secured without loss—indeed with some gain—of thermodynamic efficiency; forced draught, however, without a corresponding extension of the heating

[1] Sir F. J. Bramwell, *Proc. Inst. Mech. Eng.*, 1872.

[2] F. C. Marshall, *Proc. Inst. Mech. Eng.*, 1881.

[3] Marshall and Weighton, *Proc. North-East Coast Inst. Engineers and Ship-builders*, 1886.

Loc. cit.