surface, leads to a less efficient expenditure of fuel. With a given type of engine there is a certain ratio of expansion which gives a minimum in the ratio of weight to power; when this ratio of expansion is exceeded the engines have to be enlarged to an extent that

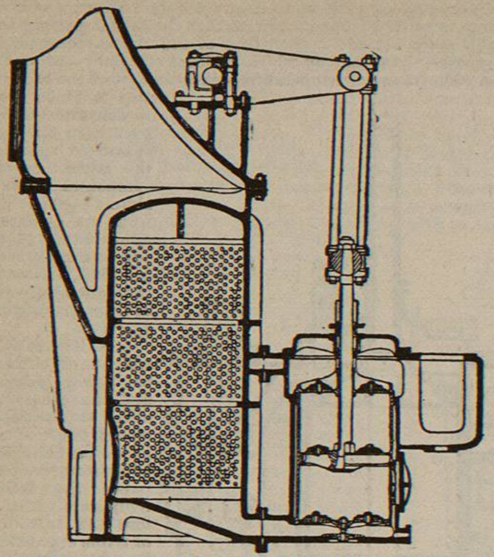

Fig. 137.—Section through Condenser and Air-Pump.

more than counterbalances the saving in boiler weight; when a less ratio of expansion is used the boilers have to be enlarged to an extent that more than counterbalances the reduction of weight in the engine proper.[1]

XIII. Locomotive Engines.

Loco-motive engines.

229. The ordinary locomotive consists of a pair of direct-acting horizontal or nearly horizontal engines, fixed in a rigid frame under the front end of a boiler of the type described in § 133, and coupled to the same shaft by cranks at right angles, each with a single slide-valve worked by a link-motion, or by a form of radial gear. The engine is non-condensing, except in special cases, and the exhaust steam, delivered at the base of the funnel through a blast-pipe, serves to produce a draught of air through the furnace. In some instances a portion of the exhaust steam, amounting to about one-fifth of the whole, is diverted to heat the feed-water. In tank engines the feed-water is carried in tanks on the engine itself; in other engines it is carried behind in a tender.

230. On the shaft are a pair of driving-wheels, whose frictional adhesion to the rails furnishes the necessary tractive force. In some engines a single pair of driving-wheels are used; in many more a greater tractive force is secured by having two equal driving-wheels on each side, connected by a coupling-rod between pins on the outside of the wheels. In goods engines a still greater proportion of the whole weight is utilized to give tractive force by coupling three and even four wheels on each side. These arrangements are distinguished by the terms "four-coupled," "six-coupled," and "eight-coupled" applied to the engines. In *inside-cylinder* engines the cylinders are placed side by side within the frame of the engine, and their connecting-rods work on cranks in the driving shaft. In *outside-cylinder* engines the cylinders are spread apart far enough to lie outside the frame of the engine, and to work on crank-pins on the outsides of the driving wheels. This dispenses with the cranked axle, which is the weakest part of a locomotive engine. Owing to the frequent alternation of strain to which it is subject, a locomotive crank axle is peculiarly liable to rupture, and has to be removed after a certain amount of use.

In some locomotives the leading wheels are coupled to driving wheels behind them, but it is now generally preferred to have under the front of the engine two or four smaller wheels which do not form part of the driving system. These are carried in a *bogie*, that is, a small truck upon which the front end of the boiler rests by a swivel-pin or plate which allows the bogie to turn, so as to adapt itself to curves in the line, and thus obviate the grinding of tyres and danger of derailment which would be caused by using a long rigid wheel-base. The bogie appears to have been of English origin;[2] it was brought into general use in America, and is now common in English as well as in American practice. Instead of a four-wheeled bogie, a single pair of leading wheels are also used, carried by a Bissel *pony* truck, which has a swing-bolster pivoted by a radius bar about a point some distance behind the axis of the wheels. This has the advantage of combining lateral with radial movement of the wheels, both being required if the wheel base is to be properly accommodated to the curve. Another method of getting lateral and radial freedom is the plan used by Mr Webb of carrying the leading axle in a box curved to the arc of a circle, and free to slide laterally for a short distance, under the control of springs, in curved guides.[3]

Pony truck.

Radial axle-box.

Valves.

231. In inside-cylinder engines the slide-valves are frequently placed back to back in a single valve-chest between the cylinders. The width of the engine within the frame leaves little room for them there, and they are reduced to the flattest possible form, in some cases with split ports, half above and half below a partition in a central horizontal plane. In some of Mr Stroudley's engines the valves are below the cylinders, with faces sloping down towards the front, while the cylinders themselves slope slightly up. In many engines the valves work on horizontal planes above the cylinders; this position is specially suitable when Joy's or some other form of radial gear is used instead of the link-motion. Radial valve-gears have the advantage, which is of considerable moment in inside-cylinder engines, that the part of the shafts' length which would otherwise be needed for eccentrics is available to increase the width of main bearings and crank-pins, and to strengthen the crank-cheeks. Walshaert's gear is very extensively used on Continental locomotives, and Joy's has now been applied to a large number of British engines.

232. In a powerful locomotive of the ordinary type the cylinders are 17 to 19 inches in diameter, with a stroke of about 26 inches. The steam pressure is 130 to 175 ℔. The horse-power ranges up to about 700. A passenger engine for express service has driving-wheels from 7 to 8 feet in diameter, and weighs, without the tender, about 40 tons. Of this nearly 15 tons is borne by each driving axle.[4]

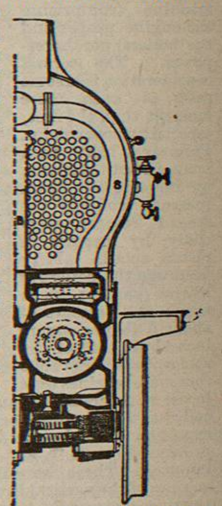

Fig. 138.—Inside-Cylinder Locomotive.

Fig. 138 shows a half section through the smoke-box and one cylinder of an inside-cylinder engine (of the Midland Railway), and illustrates how in an engine of this type the cylinders are situated with regard to the frame, which consists of a single pair of steel plates, extending from end to end and united by other transverse plates, one of which, called the motion-plate, gives support to the guide-bars, and another holds the draw-bar. Another form of frame is built up of two longitudinal plates on each side. In the engine illustrated the valves are above the cylinders, and are worked by Joy's gear. A bogie truck appears in section below the engine. S is the steam-pipe, and B the blast-pipe, which is tapered in the fore-and-aft plane.

[1] On the general subject of marine engines, reference should be made to Mr A. E. Seaton's *Manual of Marine Engineering*; to Mr R. Sennett's *Treatise on the Marine Steam Engine*; and to Mr W. H. Maw's *Recent Practice in Marine Engineering*.

[2] *Min. Proc. Inst. C.E.*, vol. liii. 3, p. 50. [3] *Proc. Inst. Mech. Eng.*, 1883.

[4] For account of many details in recent English practice in locomotive building, reference should be made to a valuable paper by Mr Stroudley, and a discussion upon it (*Min. Proc. Inst. C. E.*, lxxxi.).

233. The outside-cylinder type is adopted by several British makers; in America it is universal. There the cylinders are in castings which are bolted together to form a saddle on which the bottom of the smoke-box sits. The slide-valves are on the tops of the cylinders, and are worked through rocking levers from an ordinary link-motion. Other features by which American practice is distinguished are the use of bars instead of plates for the frames, of cast-iron wheels with chilled rims instead of wrought-iron wheels with steel rims shrunk or forced on, and steel fire-boxes and wrought-iron tubes instead of copper fire-boxes and brass tubes. Fig. 139, which is a half section through one cylinder of an American locomotive, by the Balwin Company of Philadelphia, shows the position of the cylinders and valves.

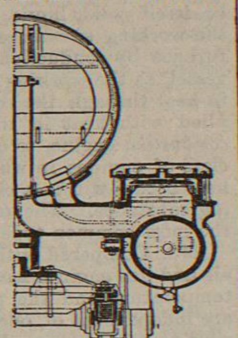

Fig. 139.—American Outside-Cylinder Locomotive.

234. Locomotive engines have been compounded in several ways. In 1876 M. A. Mallet[1] introduced, on the Bayonne and Biarritz Railway, a type of compound locomotive in which one small high-pressure cylinder and one large low-pressure cylinder were used in place of the two equal cylinders of a common locomotive. Outside cylinders were used in the first instance, but Mallet's system is also applied to inside-cylinder engines. The pipe from the high to the low-pressure cylinder takes a winding course through the smoke-box; this gives a sufficient volume of intermediate receiver, and also dries the steam before it enters the large cylinder. A reducing valve is provided through which steam of a pressure lower than that of the boiler can be admitted direct to the low-pressure cylinder to facilitate starting. The reversing gear is arranged to act on both cylinders by one movement, and also to permit a separate adjustment of the cut-off in each. Engines on Mallet's system have been successfully used on other Continental railways and in India, in some instances by conversion from the non-compound form.[2] His plan has the advantage of permitting this (in certain cases), and of requiring scarcely any more working parts than are needed in a common locomotive; but it gives an unsymmetrical engine. He has also proposed an engine with four cylinders,—one high-pressure cylinder tandem with one low-pressure cylinder on each side. Another symmetrical form has been used, in which a pair of outside high-pressure cylinders are compounded with a pair of inside low-pressure cylinders.

235. The most important experiment yet made in the compounding of locomotives is that which Mr F. W. Webb, of the London and North-Western Railway, has been conducting on a large scale since 1881.[3] In Mr Webb's system three cylinders are used. Two equal high-pressure Webb's system.

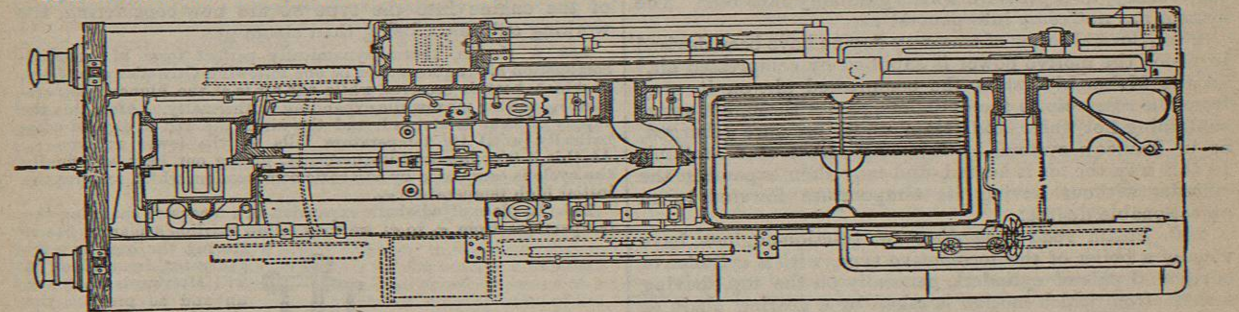

Fig. 140.—Webb's Compound Locomotive.

cylinders are fixed outside the frames, and drive the rear driving axle by crank-pins at right angles to one another. A single low-pressure cylinder of very large size is set beneath the smoke-box, and drives a crank in the middle of the forward driving axle. The driving axles are not coupled, and the phase-relation of the low-pressure to the high-pressure stroke is liable to alter through unequal slip on the part of the wheels. This, however, is of no material consequence, on account of the large size of the intermediate receiver and the uniformity with which the two high-pressure cylinders deliver steam to it. The receiver is formed, as in M. Mallet's arrangement, by leading long connecting pipes through the smoke-box. All three slide-valves are worked by Joy's gear. Those of the low-pressure cylinders are placed below the cylinders (an arrangement which has the advantage of letting the valve fall away from the port-face when the engine is running down hill with the steam-valve closed); the valve of the large cylinder is above it. The arrangement is completely symmetrical; it has the important mechanical advantage of dispensing with coupling rods, while retaining the greater tractive power of four drivers; only one axle is cranked, and that with a single crank in the centre, which leaves ample room for long bearings. A plan of Mr Webb's engine, half in section, is given in fig. 140. The results of Mr Webb's experiments have been, in his judgment, so satisfactory that for express passenger service he is now building engines only of the compound type. In some recent examples the small cylinders are 14 inches, and the large cylinder 30 inches in diameter, with a stroke of 24 inches, and the boiler pressure is 175 ℔. Engines of the same type are also being introduced in India, South America, and the continent of Europe.

236. Experiments on the saving of fuel by compounding locomotives point to an economy of from 10 to 20 per cent. It may be expected, for reasons which have been discussed above, that a compound engine, even when working at the high speed of a locomotive, will have a somewhat higher efficiency than a non-compound engine.

[1] *Proc. Inst. Mech. Eng.*, 1879.

[2] Von Borries, *Ztschr. des Ver. deutscher Ingenieure*, 1880; Sandiford, *Proc. Inst. Mech. Eng.*, 1886.

[3] See *Proc. Inst. Mech. Eng.*, 1883; also *Engineering*, May 1885.

But, apart from this, an important merit of the compound system is that, while it absolutely prevents the grade of expansion from being reduced below a certain minimum, depending on the ratio of cylinder volumes, it also permits a comparatively high degree of expansion, which in an ordinary locomotive would involve the use of specially large cylinders and a separate cut-off valve. Experiments on the steam-jacketing of locomotive cylinders have not hitherto been attended by success.

237. *Tramway locomotives* for the most part resemble railway locomotives in the general features of their design. The boiler is of the usual locomotive type. A pair of cylinders in front, either inside or outside the frames, are connected directly to the hindmost of two coupled driving axles. Owing to the smallness of the driving-wheels, the axles lie near the road, and the cylinders are set sloping at a considerable angle upwards to keep them clear of dirt. To prevent the discharge of steam into the atmosphere, the exhaust steam is often led into an atmospheric condenser, consisting of a large number of pipes set on the top of the engine, and exposed to free contact with the air. In some instances the common locomotive type is widely departed from: a mixed vertical and horizontal boiler is used, and the engine is connected to the driving axle by worm-wheel or other gear, or by a rocking lever between the connecting-rod and the crank.[1]

Fireless locomotive.

238. In the "fireless" tramway locomotive of M. Léon Francq, a reservoir which takes the place of an ordinary boiler is charged at the beginning of the journey with water heated under pressure by injecting steam from stationary boilers at a pressure of 15 atmospheres. The thermal capacity of the water is sufficient—without further addition of heat—to supply steam to the engine during the journey, at a pressure which gradually falls off.[2] The system has not come into general use.

239. Several forms of tramway engine have been devised in which the motive power is supplied by compressed air.[3] In the Mekarski system the compressed air, on its way from the reservoir to the cylinders, passes through a vessel containing hot water and steam under pressure (charged, as in Francq's system, by injecting steam at a station). In this way the air is heated, and may then expand in the cylinder without having its temperature lowered to an objectionable degree.

240. Steam *road-locomotives* or traction-engines have usually a boiler of the locomotive type, with a cylinder or compound pair of cylinders, generally on the top, driving a shaft from which motion is taken by a gearing chain or spur-wheels to a single driving axle at the fire-box end. The engine is steered by means of a leading axle, whose direction is controlled by a hand-wheel and chain-gear. To facilitate rapid turning the driving-wheels are connected to their axle by a differential or compensating gear which allows them to revolve at different speeds. This is a set of four bevel-wheels like White's dynamometer coupling: the outside bevel-wheels are attached to the driving-wheels; the intermediate ones, which gear with these, turn in bearings in a revolving wheel driven by the engine. So long as both driving-wheels are equally resisted both are driven at the same speed, but if one is retarded (as the inner wheel is in turning a curve) it acts to some extent as a fulcrum to the bevel gear, and the outer wheel takes a greater share of the motion. An important feature in traction engines is the elasticity of the driving-wheels. Many devices have been employed, partly to give the wheels an extended tread, or arc of contact with the ground, and partly to avoid shocks in passing over rough ground. Both objects are accomplished by Mr R. W. Thomson's plan of surrounding each wheel with a thick tyre of india-rubber, protected on the outside by an armour of small plates. In most modern traction-engines the rim is itself rigid, but is connected to the nave through a system of springs which allow it to take up an eccentric position, and the tyres have skew bars on the surface to increase their adhesion to the road.

[1] See *Min. Proc. Inst. C.E.*, vol. xxix., 1884; also *Proc. Inst. Mech. Eng.*, 1880.
[2] *Proc. Inst. Mech. Eng.*, 1879.
[3] *Proc. Inst. Mech. Eng.*, 1878, 1881.

XIV. Air and Gas Engines.

241. Under this head we may include all heat-engines in which the working substance is air, or the gaseous products of the combustion of fuel and air, whether the fuel be itself solid, liquid, or gaseous. When air alone forms the working substance, it receives heat from an external furnace by conduction through the walls of a containing vessel, as the working substance in the steam-engine takes in heat through the shell of the boiler. An engine supplied with heat in this way may be called an *external-combustion* engine, to distinguish it from a very important class of engines in which the combustion which supplies heat occurs within a closed chamber containing the working substance. The ordinary coal-gas explosive engine is the most common type of *internal-combustion* engine.

242. Compared with an engine using saturated steam, air and gas engines have the important advantage that the temperature and the pressure of the working substance are independent of one another. Hence it becomes possible to use an upper limit of temperature greatly higher than in the ordinary steam-engine, and if the lower limit is not correspondingly raised an increase of thermodynamic efficiency results. It is true that the same advantage might be obtained in the case of steam, by excessive superheating; but this would mean substantially the conversion of the engine into the type we are now considering, the working substance being then steam gas.

243. A simple, thermodynamically perfect form of external-combustion air-engine would be one following Carnot's cycle (§ 40), in which heat is received while the air is at the highest temperature τ_1, the air meanwhile expanding isothermally. After this the supply of heat is stopped, and the air is allowed to expand adiabatically until its temperature falls to the lower extreme τ_2. At this it is compressed isothermally, giving out heat, and finally the cycle is completed by adiabatic compression, which restores the initial high temperature τ_1.

244. In place of adiabatic expansion as a means of changing the temperature from τ_1 to τ_2 we may follow Stirling's plan (§ 54) of storing the heat in a regenerator, from which it will afterwards be taken up and so produce the elevation of temperature from τ_2 to τ_1 which in the above cycle was performed by adiabatic compression.

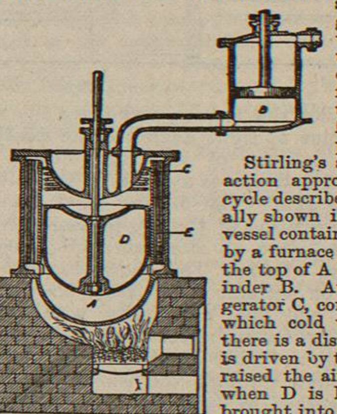
Fig. 141.—Stirling's Air-Engine.

Stirling's air-engine, in which the action approximated to the perfect cycle described in § 54, is diagramatically shown in fig. 141. A is a closed vessel containing air, externally heated by a furnace beneath it. A pipe from the top of A leads to the working cylinder B. At the top of A is a refrigerator C, consisting of pipes through which cold water circulates. In A there is a displacer plunger D, which is driven by the engine; when this is raised the air in A is heated, whereas when D is lowered the air in A is brought into contact with the refrigerator and cooled. On its way from the bottom to the top of A, or *vice versa*, the air must pass through an annular lining of wire-gauze E. This is the regenerator. At the beginning of the cycle D is up. The air is then receiving heat at τ_1, and is expanding isothermally; this is the first stage in § 54. Then the plunger D descends. The air is driven through the regenerator, where it deposits heat, and its temperature on emerging at the top is τ_2. Next, the working

piston makes its down-stroke (in the actual engine the working cylinder was double-acting, another heating vessel, precisely like A, being connected with the cylinder B above the piston); this compresses the air isothermally, the heat produced by compression being taken up by C. Finally the plunger is raised, and the working air again passes through the regenerator, taking up the heat it left there, and rising to τ_1. The theoretical indicator diagram has been given in fig. 13.

245. The actual forms in which Stirling's engine was used are described in two patents by R. & J. Stirling (1827 and 1840[1]). An important feature in them was that the air was compressed (by means of a pump) to a pressure greatly above that of the atmosphere. Stirling's cycle is theoretically perfect whatever the density of the working air, and compression did not in his case increase what may be called the theoretical thermodynamic efficiency. It did, however, very greatly increase the mechanical efficiency, and also, what is of special importance, it increased the amount of power yielded by an engine of given size. To see this it is sufficient to consider that with compressed air a greater amount of heat was dealt with in each stroke of the engine, and therefore a greater amount of work was produced. Practically it also increased the thermodynamic efficiency by reducing the ratio of the heat wasted by external conduction and radiation to the whole heat.

A double-acting Stirling engine of 50 I.H.P., used in 1843 at the Dundee foundry, appears to have realized an efficiency of 0·3, and, notwithstanding very inadequate means of heating the air, consumed only 1·7 ℔ of coal per I.H.P. per hour.[2] This engine remained at work for three years, but was finally abandoned on account of the failure of the heating vessels. In some forms of Stirling's engine the regenerator was a separate vessel; in others the plunger D was itself constructed to serve as regenerator by filling it with wire-gauze and leaving holes at top and bottom for the passage of the air through it.

Ericsson's air engine.

246. Another mode of using the regenerator was introduced in America by Ericsson, in an engine which also failed, partly because the heating surfaces became burnt, and partly because their area was insufficient. In Ericsson's engine the temperature of the working substance is changed (by passing through the regenerator) while the pressure remains constant. Cold air is compressed by a pump into a receiver, from which it passes through a regenerator into the working cylinder. In so passing it absorbs heat from the regenerator and expands. The air in the cylinder is then further expanded by taking in heat from a furnace under the cylinder. The cycle is completed by the discharge of the air through the regenerator. The indicator diagram approximates to a form bounded by two isothermals and two lines of constant pressure.[3]

247. Externally-heated air-engines are now employed only for very small powers—from a fraction of 1 H.P. up to about 3 H.P. Powerful engines of this type are impracticable on account of their relatively enormous bulk. Those that are now manufactured resemble the original Stirling engine very closely in the main features of their action, and comprise essentially the same organs.[4]

Internal combustion engines.

248. *Internal-combustion* engines form a far more important class of motors. The earliest example of this class appears to have been the hot-air engine of Sir George Cayley,[5] of which Wenham's[6] and Buckett's[7] engines are recent forms. In these engines coal or coke is burnt under pressure in a closed chamber, to which the fuel is fed through a species of air-lock. Air for combustion is supplied by a compressing pump, and the engine is governed by means of a distributing valve which supplies a greater or less proportion of the air below the fire as the engine runs slow or fast. The products of combustion, whose volume is increased by their rise in temperature, pass into a working cylinder, raising the piston. When a certain fraction of the stroke is over the supply of hot gas is stopped, and the gases in the cylinder expand, doing more work and becoming reduced in temperature. During the return stroke they are discharged into the atmosphere, and the pump takes in a fresh supply of air. Fig. 142 is a diagram section of the Buckett engine. A is the working piston, the form of which is such as to protect the tight sliding surface (at the top) from contact with the hot gases; B is the compressing pump, C the valve by which the governor regulates the rate at which fuel is consumed, and D the air-lock through which fuel is supplied.

249. In engines of this class the degree to which the action is thermodynamically efficient depends very largely on the amount of cooling the gases undergo by adiabatic or nearly adiabatic expansion under the working piston. Without a large ratio of expansion the thermodynamic advantage of a high initial temperature is lost; but, as the gases have to be discharged at atmospheric pressure, a large ratio of expansion is possible only when there is much initial compression. Compression is therefore an

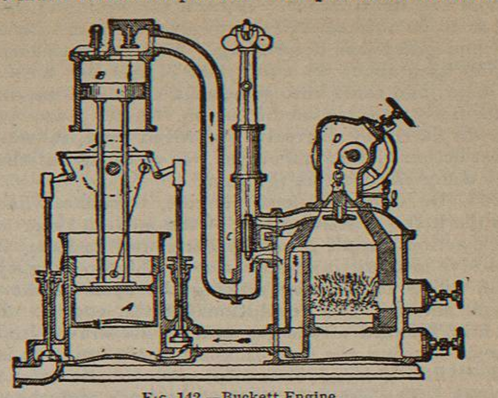
Fig. 142.—Buckett Engine.

essential condition, without which a heat-engine of this type cannot be made efficient. It is also, as has already been pointed out, essential in all air-engines to the development of a fair amount of power by an engine of moderate bulk.

Petroleum engines.

250. Internal-combustion engines using solid fuel have hitherto been little used, and that only for small powers. Several small engines employ liquid fuel (namely, petroleum) injected in a state of spray, or even vaporized before entering the combustion-chamber. In some forms, of which the Brayton petroleum engine is a type, combustion occurs as the fuel is injected; in others the action approaches closely that of *gas-engines*, that is to say, of engines in which fuel (generally coal-gas) is supplied in a perfectly gaseous state, and is burnt in a more or less explosive manner. These last are the only heat-engines that have as yet entered into serious competition with steam-engines.

Gas engines.

Lenoir.

251. The earliest gas-engine to be brought into practical use was that of Lenoir (1860). During the first part of the stroke air and gas, in proportions suitable for combustion, were drawn into the cylinder. At about half-stroke the inlet valve closed, and the mixture was immediately exploded by an electric spark. The heated products of combustion then did work on the piston during the remainder of the forward stroke, and were expelled during the back stroke. The engine was double-acting, and the cylinder was prevented from becoming excessively heated by a casing through which water was kept circulating. The water-jacket has been retained in nearly all later gas-engines.

An indicator diagram from a Lenoir engine is shown in fig. 143.[8] After explosion the line falls, partly from expansion, and partly from the cooling action of the cylinder walls; on the other hand, its level is to some extent maintained by the phenomenon of after-burning, which will be discussed later. In this engine, chiefly because there was no compression, the heat removed by the water-jacket bore an exceedingly large proportion to the whole heat, and the efficiency was comparatively low; about 95 cubic feet of gas were used per horse-power per hour. Hugon's engine, introduced five years later, was a non-compressive engine very similar to Lenoir's. A novel feature in it was the injection of a jet of cold water to keep the cylinder from becoming too hot. These engines are now obsolete; the type they belonged to, in which the mixture is not compressed before explosion, is now represented by one small engine—Bischoff's—the mechanical simplicity of which atones for its comparatively wasteful action in certain cases where but little power is required.

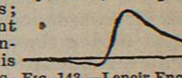
Fig. 143.—Lenoir Engine Diagram.

252. In 1866 Otto and Langen introduced a curious engine,[9] which, as to economy of gas, was distinctly superior to its predecessors. Like them it did not use compression. The explosion occurred early in the stroke, in a vertical cylinder, under a piston which was free to rise without doing work on the engine shaft. The piston rose with great velocity, so that the expansion was much more nearly adiabatic than in earlier engines. Then after the piston had reached the top of its range the gases cooled, and their pressure fell below that of the atmosphere; the piston consequently

[1] The 1827 patent is reproduced in F. Jenkin's Lecture on Gas and Caloric Engines, *Inst. Civ. Eng.*, Heat Lectures, 1883–84. See also *Min. Proc. Inst. C.E.*, 1845 and 1854.
[2] See Rankine's *Steam Engine*, p. 367. The consumption per brake H.P. was much greater.
[3] For a diagram of Ericsson's engine see Rankine's *Steam Engine*, or *Proc. Inst. Mech. Eng.*, 1873.
[4] For description of Robinson's, Bailey's, and Rider's hot-air engines see F. Jenkin's lecture, *loc. cit.*
[5] *Nicholson's Art Journal*, 1807.
[6] *Proc. Inst. Mech. Eng.*, 1873.
[7] F. Jenkin, *loc. cit.* Fig. 142 is taken from this paper.
[8] Slade, *Jour. Franklin Inst.*, 1866.
[9] *Proc. Inst. Mech. Eng.*, 1875.