h denoting what is called the *specific heat of the saturated vapour*, and c the specific heat of the liquid.

A change of m at constant t will require the addition

$$dQ = \lambda\, dm,$$

λ denoting the latent heat of evaporation at t. Hence the general expression for the heat required for a small change is

$$dQ = \{(h-c)\, m + c\}\, dt + \lambda\, dm; \quad \text{whence}$$

$$d\phi = \frac{(h-c)\, m + c}{t} dt + \frac{\lambda}{t} dm.$$

The principle that the order of differentiation is indifferent gives, as applied to this expression for $d\phi$,

$$\frac{h-c}{t} = \frac{1}{t}\frac{d\lambda}{dt} - \frac{\lambda}{t^2}, \quad \text{whence}$$

$$h = c + \frac{d\lambda}{dt} - \frac{\lambda}{t}.$$

This equation is true whatever unit of heat we employ. We may, therefore, employ for steam the value of λ given in (b) § 140, if we put $t-273$ for T. This gives approximately

$$\lambda = 800 - \cdot 7t.$$

In general if the latent heat of a vapour be expressible as

$$\lambda = a - bt,$$

we have $$\frac{d\lambda}{dt} - \frac{\lambda}{t} = -\frac{a}{t}; \text{ whence } h = c - \frac{a}{t}.$$

For water and steam this gives

$$h = 1 - \frac{800}{t}$$

as the approximate value of the specific heat of saturated steam. It is negative for all values of t that occur in the practical use of steam.

For saturated vapour by itself we must put $m=1$, and if the vapour is to continue just saturated while its volume and temperature change, we must put $dm=0$. The general expression for dQ will then be reduced to

$$dQ = h\, dt.$$

For every vapour the maximum density increases with the temperature, hence increase of temperature with continuance of saturation implies compression. When h is negative and dt positive, dQ will be negative; hence saturated steam when compressed must be allowed to give out heat if it is to remain just saturated. If compressed adiabatically it will be superheated.

CHAPTER XVII.

STEAM AND OTHER HEAT ENGINES.

259. By a heat engine we mean an engine which yields work in virtue of heat supplied to it. The principal heat engines in actual use are the steam-engine and the gas-engine; but air-engines, working by the expansion of air when heated, were at one time in use, and oil-engines in which a spray of oil is converted by heat into vapour are beginning to be employed.

260. Our limits will not permit us to discuss the mechanical details of the various kinds of steam-engine. We must content ourselves with describing the mode in which the pressure of the steam operates to produce mechanical work.

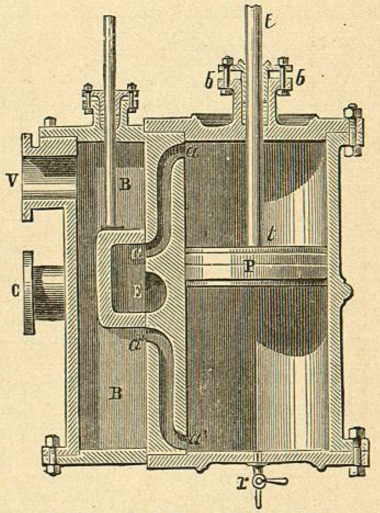
Fig. 135.—Cylinder and Connections.

Figs. 135, 136 illustrate the arrangements by which the steam in an ordinary double-acting engine is made to push the piston alternately in opposite directions. Fig. 135 shows the piston P, which works up and down in the cylinder, and is now nearly in the middle of its stroke, being pushed up by steam, which enters through the lower passage $a'a'$ leading from the steam-chest BB, which is in free communication with the steam-pipe V leading from the boiler. The steam on the upper side of the piston is escaping through the upper passage aa to the open air or to the condenser. E is the opening leading to the escape-pipe C.

In order to push the piston down again, it is necessary to let steam from the steam-chest enter above the piston, and to let the steam below escape. The way in which this is done is exhibited in Fig. 136, which represents only the parts concerned in directing the course of the steam. There is a movable piece called the *slide-valve*, which slides up and down so as to alter the connections. The first figure shows the position which we have just been considering, the steam being admitted below the piston and allowed to escape

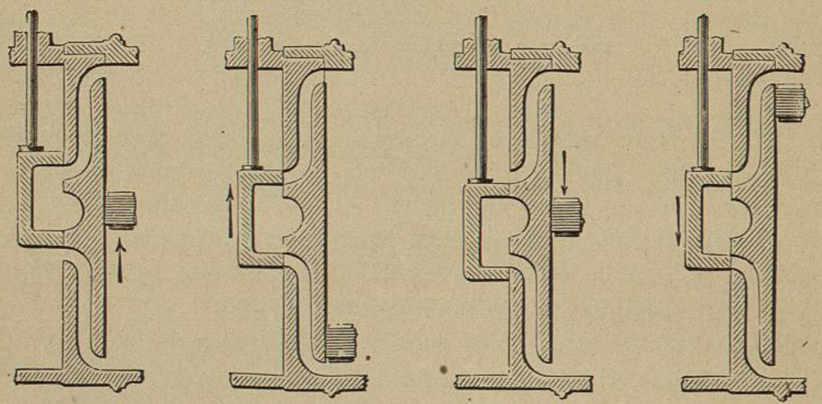

Fig. 136.—Movements of Slide-valve.

above. The second figure shows the slide-valve a little lower down, closing for the instant both passages. The third figure shows the slide-valve still lower; in this position the steam is admitted above the piston and escapes below. In the fourth figure it is again for the instant closing both passages. The slide-valve is in constant motion up and down, being driven by an arrangement (equivalent to a crank) called an *eccentric*, which is shown in duplicate at A, A′, Fig. 138, revolving about the point O as centre.

261. Working Expansively.—If the steam at its full pressure were discharged into the condenser, a great amount of expansive power would obviously be wasted. This power is utilized by what is called *expansive working*. When the piston has performed a part of its stroke, the steam is shut off (or in technical phrase *cut off*) from the cylinder, and the expansive force of the steam already admitted is left to urge the piston through the remainder of its course. The part of the stroke at which the cut-off occurs may be determined at pleasure. It is sometimes at half-stroke, sometimes at quarter-stroke, sometimes at one-fifth of stroke. In the latter case the piston describes the remaining four-fifths of the stroke under the gradually diminishing pressure of the steam which entered the

cylinder during the first fifth; and the work done during these four-fifths is so much work gained by working expansively.

The cutting off of the steam before the end of the stroke is usually effected by the contrivance represented in Fig. 137: *ad*, *a′d′*, are two plates forming part of the slide-valve and of much greater width than the openings L, L′. The excess of width is called *lap*. By this arrangement one of the apertures is kept closed for some time, so that the steam is shut off, and acts only by expansion. The expansion increases with the lap, but not in simple proportion, as equal movements of the slide-valve do not correspond to equal movements of the piston. The amount of expansion can also be regulated by the *link-motion*, which will be described in § 265.

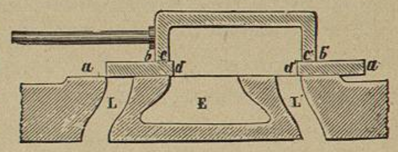

Fig. 137.—Slide-valve for Expansive Working.

262. Compound Engines.—This is the name given to engines in which the steam, instead of escaping from the cylinder into the condenser, or into the open air, escapes into a second cylinder of larger section than the first, in which it drives a second piston.

In triple-expansion engines, which are now in general use for ocean-going steamers, the steam, when it has driven the piston in the second cylinder, escapes into a third cylinder of still larger section, in which it drives a third piston before passing into the condenser. In the boiler and first cylinder the steam is at very high pressure and temperature (the boiler pressure being usually above 10 atmospheres). As it is worked expansively, it escapes into the second cylinder at a more moderate pressure and temperature, and into the third at a still lower pressure and temperature. If the same amount of total expansion occurred in a single cylinder, it would cool the cylinder too far below the temperature of the entering steam, which would thus be chilled on entering, and thereby deprived of a great portion of its pressure.

Expansive working is often combined with the *superheating* of steam, that is to say, heating the steam on its way from the boiler to the cylinder, so as to raise its temperature above the point of saturation.

263. In the construction of the boiler it is important to afford the greatest possible facility for the communication of heat from the furnace to the water. In the locomotive and in many other modern engines this is effected by making the hot gases on their way from the furnace to the chimney pass through a large number of parallel tubes of copper or other good conductor, which traverse the boiler from end to end and are surrounded by the water. A very large heating surface is thus obtained, and the transmission of heat is proportionally rapid.

264. **Surface Condensation.**—In many modern engines, the condenser consists of a number of vertical tubes of about half an inch diameter, connected at their ends, and kept cool by the external contact of cold water. The steam, on escaping from the cylinder, enters these tubes at their upper ends, and becomes condensed in its passage through them, thus yielding distilled water, which is pumped back to feed the boiler. The same water can thus be put through the engine many times in succession, and the waste which occurs is usually repaired by adding from time to time a little distilled water prepared by a separate apparatus.

The old method of condensing is by a jet of cold water playing into the interior of the condenser.

265. **Apparatus for Reversing: Link-motion.**—The method usually employed for reversing engines is known as Stephenson's link-motion, having been first employed in locomotives constructed by Robert Stephenson, son of the maker of the "Rocket." The merit of the invention belongs to one or both of two workmen in his employ—Williams, a draughtsman, who first designed it, and Howe, a pattern-maker, who, being employed by Williams to construct a model of his invention, introduced some important improvements.

The link-motion, which is represented in Fig. 138, serves two purposes: first, to make the engine travel forwards or backwards at pleasure; and, secondly, to regulate the amount of expansion which shall take place in the cylinder. Two oppositely placed eccentrics, A and A′, have their connecting-rods jointed to the two extremities of the *link* B B′, which is a curved bar, having a slit, of uniform width, extending along nearly its whole length. In this slit travels a stud or button C, forming part of a lever, which turns about a fixed point E. The end D of the lever D E is jointed to the connecting-rod D N, which moves the rod P of the slide-valve. The link itself is connected with an arrangement of rods L I K H,[1] which enables the

[1] I is a fixed centre of motion, and the rods K I, M L are rigidly connected at right angles to each other. M is a heavy piece, serving to counterpoise the link and eccentric rods.

engine-driver to raise or lower it at pleasure by means of the handle G H F. When the link is lowered to the fullest extent, the end B of the connecting-rod, driven by the eccentric A, is very near the runner C which governs the movement of the slide-valve; this valve accordingly, which can only move in a straight line, obeys the eccentric A almost exclusively. When the link is raised as much as possible, the slide-valve obeys the other eccentric A′, and this change

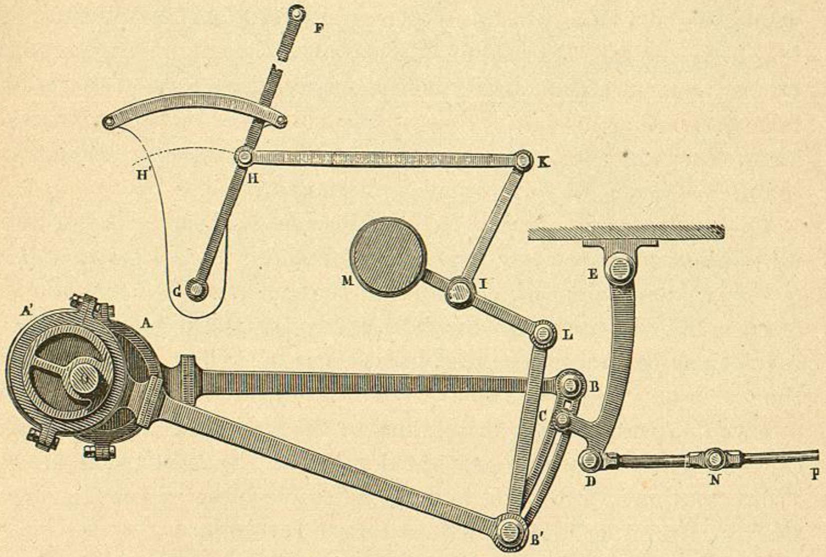

Fig. 138.—Link-motion.

reverses the engine. When the link is exactly midway between the two extreme positions, the slide-valve is influenced by both eccentrics equally, and consequently remains nearly stationary in its middle position, so that no steam is admitted to the cylinder, and the engine stops. By keeping the link near the middle position, steam is admitted during only a small part of the stroke, and consequently undergoes large expansion. By moving it nearer to one of its extreme positions, the travel of the slide-valve is increased, the ports are opened wider and kept open longer, and the engine will accordingly be driven faster, but with less expansion of the steam. As a means of regulating expansion, the link-motion is far from perfect, but its general advantages are such that it has come into very extensive use, not only for locomotives but for all engines which need reversal.

266. Gas-engines.—In Otto's "Silent Gas-engine," the earliest type of the class of engine now employed, a dilute mixture of gas and air (about one part in twelve being gas) is admitted into the cylinder, and, after being compressed to about three atmospheres, is ignited by instantaneous communication with a small jet of gas kept constantly burning. The effect is something intermediate between ignition and explosion; the maximum pressure in the early part of the stroke being 10 or 12 atmospheres, and the mean pressure in the whole stroke 4 or 5. In the return stroke, the products of combustion escape at atmospheric pressure, this return stroke being effected by the momentum of the fly-wheel, which also carries the piston through another forward stroke during which the charge of gas and air is admitted; and through another backward stroke in which it is compressed previous to ignition as above described.

This is the ordinary cycle of operations when the engine is working up to the full power for which it is intended; but a centrifugal governor is provided which prevents the gas from being admitted oftener than is necessary for keeping up the standard number of revolutions per minute; so that in working far below its full power the gas is only admitted at every third, fourth, or fifth stroke, the intervening strokes being maintained by the fly-wheel. The governor can be regulated to give any speed required, the most usual being 170 revolutions per minute; and the difference of speed between full work and running idle is only one or two revolutions.

The general appearance of the engine is shown in Fig. 139. A is the cylinder, with a jacket round it through which a convective circulation of water is maintained by means of two pipes, not shown in the figure, connecting it with a tank at a higher level. This is necessary to prevent overheating. C is the centrifugal governor. B, D are two vessels containing oil with automatic lubricators, B lubricates the piston, and D the slide which controls the ignition of the charge. E is a chimney, in the lower part of which the gas jet is kept burning. F is a spring fastening, which keeps the slide strongly pressed home so as to prevent leakage. The connecting-rod, crank, and heavy fly-wheel speak for themselves.

Gas-engines have a great advantage in being constantly ready for use without the tedious process of getting up steam. They are started by lighting the gas jet and giving a few quick turns to the fly-wheel; and are stopped by turning out the jet. The usual sizes are from ½ to 20 horse-power. They are easily kept in order,

the principal trouble consisting in the removal of a hard deposit of carbon which forms in certain places.

Gas-engines and triple-expansion steam-engines resemble each other in having a very high initial temperature of the expanding

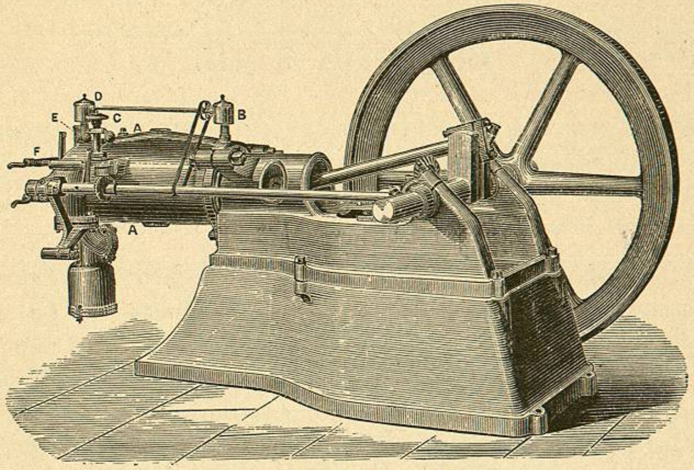

Fig. 139.—Otto's Silent Gas-engine.

fluid which drives the piston, and they resemble each other also in possessing a high degree of "efficiency;" that is to say, they convert a much larger fraction of the heat received into mechanical effect than the simpler forms of steam-engine. But even in the most favourable circumstances this fraction has never, we believe, exceeded one-seventh or thereabouts; so that, from a theoretical point of view, there is still large scope for improvement.