first cylinder. The equation to the curve may then be taken as $PV^{\frac{10}{9}}=\text{constant}$ (§ 67). In the absence of data regarding the wetness of the steam this assumption may be considered fair.

122. Lastly, fig. 38 shows a pair of diagrams, treated in the same manner, for a two-cylinder compound engine with cranks at right angles to each other, the high-pressure crank being 90° in advance. During the back stroke of the high-pressure piston there is at first compression into the receiver until the large cylinder opens; the high-pressure diagram consequently takes a peculiar form, which should be compared with the diagram already given for a tandem engine (§ 118). In this example there is a considerable amount of drop and also of loss between the two cylinders.

VII. The Production of Steam.—Boilers.

123. The first step in the production of steam is to convert the potential energy of fuel into actual heat; the second step is to transfer the heat to water in the boiler. The efficiency of furnace and boiler is the ratio which the amount of heat taken up by the water bears to the whole potential energy of the fuel. In good boilers this efficiency is about 0·7. The loss is due partly to incomplete combustion of the fuel and partly to incomplete transfer of heat from the products of combustion to the boiler water. Under the first head may be classed—(1) waste of fuel in the solid state by bad stoking, and (2) waste of fuel in the gaseous and smoky states by imperfect combustion. Under the second head are comprised—(1) waste by external radiation and conduction, and (2) waste by heat contained in the hot gases which escape by the chimney, due (*a*) to their still high temperature and (*b*) to the fact that they contain as one of the products of combustion steam-gas which passes away uncondensed. Loss of heat by the hot gases is the most important source of waste. Not only are the actual products of combustion rejected at a high temperature, but along with them goes the nitrogen of the air whose oxygen has been used, and also a quantity of additional air which is needed to dilute the products in order that combustion may be fairly complete. Roughly speaking, about 12 ℔ of air are required to supply oxygen enough for the combustion of 1 ℔ of coal. Over and above this quantity, about 12 ℔ more generally pass through the furnace as air of dilution. In furnaces with forced draught, in which the consumption of coal per square foot of grate surface is much more rapid, the air of dilution may be reduced to half or less than half of this quantity, though to some extent at the expense of completeness in the combustion.

Heating surface. 124. The extent to which heat is taken from the hot gases depends on the *heating surface* through which heat passes into the water. The heating surface is made up of the surface of the furnace or combustion-chamber, so far as that is brought into contact with the water, and of the flues or tubes through which the hot gases pass on their way to the chimney. Its efficiency depends on the conductivity of the metal, on the difference in temperature between the gases on one side and the water on the other, and on the freedom with which steam, when formed, can escape from the surface. Differences in specific conductivity and in thickness of metal affect the result less than might be expected, on account of the resistance which is offered to the passage of heat through the film of scale and also through the film of water vapour which forms on the metallic surface.

By extending the heating surface sufficiently the hot gases may be deprived of heat to an extent which is only limited by the temperature of the boiler water. This temperature, however, need not form a limit, for after leaving the boiler the gases may be further cooled by being brought into contact with a vessel termed a feed-water heater, through which the feed-water passes on its way to the boiler. Even with a feed-water heater, however, the temperature of the hot gases is never, in practice, reduced so low as that of the boiler.

Draught. 125. In nearly all land engines and most marine engines the draught is produced by means of a chimney, which acts in virtue of the column of air within it being specifically lighter than the air outside, so that the pressure within the chimney at its base is less than the atmospheric pressure at the same level outside. The composition of the chimney gases is such that they are heavier than air at the same temperature, and to make them sufficiently lighter to cause a draught they must retain a certain considerable portion of their heat. On the other hand, if they are left too hot the mass of air drawn through the furnace is actually diminished, since then the chimney gases are so much expanded that the increased volume of the draught does not compensate for its diminished density. With a given chimney and furnace the maximum draught is obtained when the gases escape at a temperature about that of melting lead; by making the chimney more capacious a lower temperature will suffice to give the same draught, and this will of course increase the efficiency of the boiler.

126. In place of using a chimney draught depending merely on the temperature of the rejected hot gases, the air required for combustion and dilution may be forced through the furnace either by producing a partial vacuum in the chimney or by supplying air to the grate at a pressure higher than that of the atmosphere. In locomotives, for example, a partial vacuum is produced in the chimney by means of a blast of exhaust steam from the engine; and in many naval and a few mercantile steamers a forced draught is produced by having a closed stokehole or a closed ashpit, which is supplied with air at a pressure above that of the atmosphere by the use of a blowing fan.

If heat were thoroughly extracted from the products of combustion, a forced draught would be more efficient, from the thermodynamic point of view, than a chimney draught, for a chimney is in fact an extremely inefficient heat-engine, and requires a very large amount of heat to be expended in order to effect the comparatively trifling work of maintaining the draught. But where forced draught has been substituted for chimney draught this has hitherto been done for the purpose of increasing not the efficiency but the *power* of boilers. The motive has been to burn more coal per square foot of grate surface and so to evaporate more water with a boiler of given weight. This is incompatible with very high efficiency. When more coal is burnt by forcing the draught it is true that the products of combustion have a higher temperature (since less air is required for dilution) and the effectiveness of the heating surface is therefore increased. But the heating surface has more hot gas to deal with, and the result is that the boiler is less efficient than when the draught is not forced. The same efficiency could be secured, with forced draught, by increasing the heating surface to a sufficient extent; and a still greater efficiency could be realized if the heating surface were still further enlarged so that the gases left the flues at a temperature lower than would be needful if the draught depended on the lightness of the chimney's contents. The most efficient boiler would be one in which the draught was forced by mechanical means, and the gases were then cooled as far as possible by contact with a very extensive heating surface, first in the boiler itself and then in a feed-water heater. None of the forced draught boilers that have hitherto been introduced have a heating surface so large as to make them more efficient than good chimney-draught boilers (in which the rate of combustion is much slower), although the heating surface bears a much larger ratio to the grate area than is usual with chimney draughts.

127. Most modern boilers are internally fired; that is to say, the furnaces are more or less completely enclosed within the boiler. Externally fired boilers are for the most part much less efficient than internally fired boilers; they are, however, used to a considerable extent where fuel is specially cheap or where the waste heat of other furnaces is to be utilized. Their usual form is that of a horizontal cylinder with convex ends; the strength both of the main shell and the ends is derived from their curvature, and no Boilers for stationary engines.

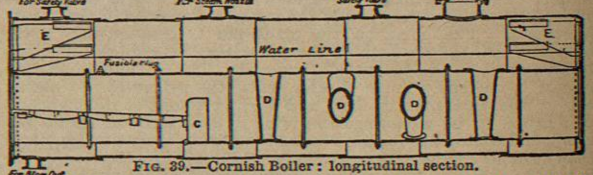


Fig. 39.—Cornish Boiler: longitudinal section.

staying is necessary. The heating surface is entirely external and is of very limited extent.

In large stationary boilers the forms known as the "Lancashire" (or double flue) and the "Cornish" (or single flue) are most common. Figs. 39 and 40 show in section a Cornish boiler by Messrs Galloway, and fig. 41 a Lancashire boiler by the same makers. In both the shell is a round horizontal cylinder with flat ends. In the Cornish boiler there is one internal flue, at the front end of which is the furnace. The hot gases pass through the flue to the back; they then return to the front end by two external side flues Cornish and Lancashire boilers

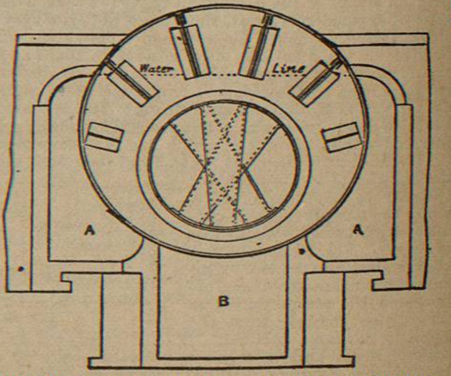


Fig. 40.—Cornish Boiler: transverse section, showing flues.

(A, A, fig. 40), and finally pass to the back again by an underneath flue B. The arrangement in the Lancashire boiler is the same, except that there are two internal flues, each with its own furnace. The shell is made up of rings of riveted plates, larger and smaller in diameter alternately to allow the circumferential seams to be made without bending the edges. The flue is made up of a series of welded rings, joined to each other by a flanged joint with a stiffening ring. This form of joint was introduced by Mr Adamson to stiffen the flue against collapse under external pressure. Other joints, designed with the same object, are shown in figs. 42 and 43. The grate is made up of firebars, sloping down towards the back, where they terminate at the "bridge" of fire-brick (C, fig. 39). Beyond the bridge the flue is crossed by a number of tapered "Galloway" tubes D, D, which increase the heating surface, promote circulation of the water, and stiffen the flue. The end plates are strengthened by gusset stays E, E, riveted to them and to the circumference of the shell by means of angle-irons. The gusset-stays do not extend so far in as to the circumference of the flue (fig. 40), in order that the end plates may retain enough flexibility to allow the flue to expand and contract under change of temperature. To provide for unequal expansion is one of the most important points in the design of boilers; when it is neglected the boiler is subjected to a racking action which induces leakage at joints and tends to rupture the plates. For this reason the flue is attached to the boiler shell at the ends only, so that it may be free to take an upward camber in consequence of the greater heating of the upper side.

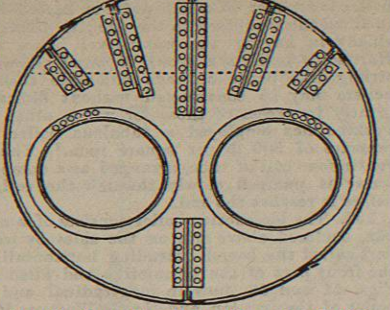
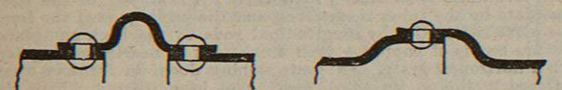


Fig. 41.—Lancashire Boiler: Transverse Section.


Figs. 42 and 43.—Joints for Furnace Tubes.

Mild steel is now very generally used for boiler plates, being superior even to the best Yorkshire iron in the qualities of ductility and tensile strength. The following particulars refer to the Lancashire boiler of fig. 41, which may be taken as representative of a large number of stationary boilers.

128. The shell is 28 feet long and 7 feet in diameter, and is made up of 9 rings, each of two semi-cylindrical plates. The shell plates are $\frac{3}{8}$ inch thick; their edges are planed and fullered, and the rivet holes are drilled. The longitudinal seams, which break joint from ring to ring, are lap-joints double-riveted; the circular seams are single-riveted. Each end plate is a solid piece of steel $\frac{1}{2}$ inch thick; the front plate is attached to the shell by riveting to an angle ring; the back plate is flanged. The flues are each 2 feet $9\frac{1}{2}$ inches in diameter, made up of rings of steel $\frac{3}{8}$ inch thick; the longitudinal joints are welded and the circular joints are flanged and strengthened with stiffening rings. The flues are tapered somewhat at the back end to facilitate expansion, and are attached to the end plates by welded angle-rings. Each flue contains 5 Galloway tubes, tapering from $10\frac{1}{2}$ inches diameter at top to $5\frac{1}{2}$ inches at bottom. On the top of the boiler is the manhole, covered with a cast-iron plate; also a nozzle for the steam-pipe and two others for safety-valves. One of the safety-valves is connected with a float so that it opens if the water-level becomes too low. At the bottom, in front, is another nozzle for the blow-out tap; and in the front plate below the flues is another manhole. Feed-water is supplied by a pipe which enters through the front plate on one side, near the top of the water, and extends for a considerable distance along the boiler, distributing the water by holes throughout the length. A pipe at the same level on the other side serves to collect scum. The fire doors are provided with sliding shutters by means of which the amount of air admitted above the fire may be regulated. On the top of each furnace is fitted a fusible plug which melts if the furnace crown becomes overheated. No separate steam dome is used; the steam is collected by an "anti-priming" pipe shown in fig. 44, which also illustrates the stop-valve by which the delivery of steam from the boiler is started or stopped at will. On the front plate are a pair of glass gauge-tubes for showing the water-level, and a Bourdon pressure-gauge. This last important fitting consists of a bent tube of oval section, one end of which is closed and free to move while the other is open to the steam and is fixed. The pressure within the tube tends to straighten it, and the extent to which this takes place is shown by a pointer which travels over a circular dial. A common lever safety-valve is shown in fig. 45. In other forms the valve is kept down by a weight directly applied to it, or by means of springs. Spring safety-valves are liable to the objection that when the valve opens the load on it increases; to remedy this, forms have been proposed in which the spring acts through a bent lever in such a way that when the strain on it increases the leverage at which it acts is reduced. If the spring is of reasonable length, however, the objection is not serious.

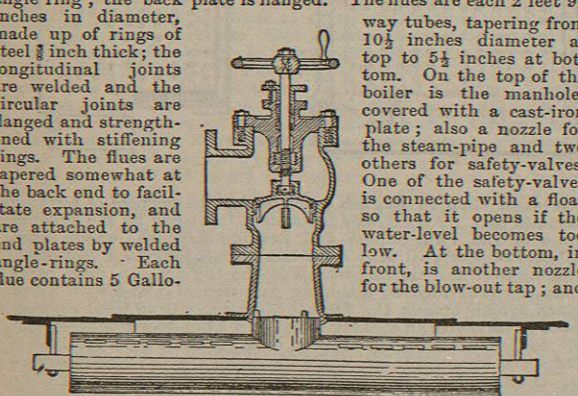


Fig. 44.—Anti-Priming Pipe and Stop-Valve.

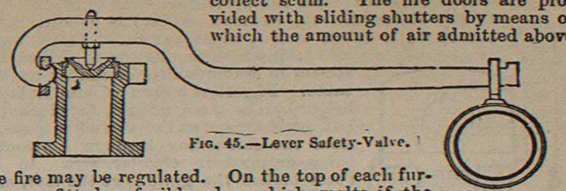


Fig. 45.—Lever Safety-Valve.

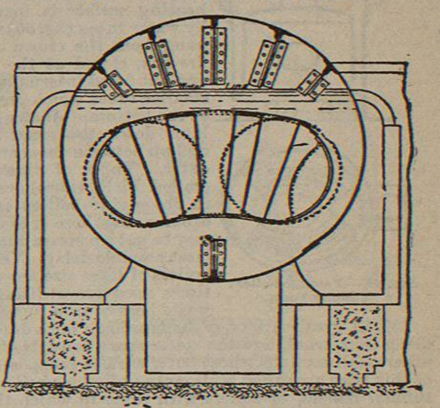


Fig. 46.—Galloway Boiler: Section beyond the Bridge.

129. A modification of the Lancashire type—the "Galloway" boiler—is shown in sectional elevation in fig. 46. In it the two flues are joined beyond the bridge into a single flue, of the form shown in the figure, which is traversed by numerous Galloway tubes and is also fitted with water-pockets at its sides.

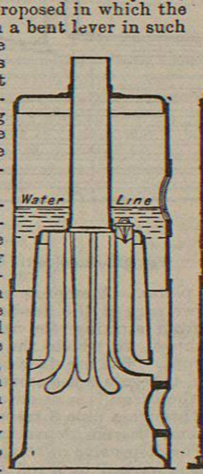


Fig. 47.—Vertical Boiler with Vertical Water Tubes.

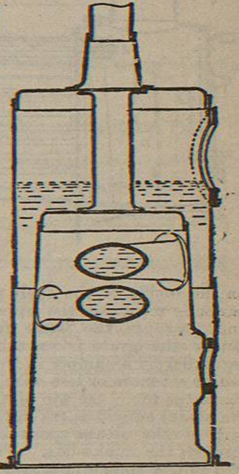


Fig. 48.—Vertical Boiler with Horizontal Water Tubes.

130. In other types of boiler an extensive heating surface is obtained by the use of a large number of small tubes through which the hot gases pass. This construction is universal in locomotive and marine boilers. It is applied in some instances to boilers of the ordinary cylindrical form by making small tubes take the place of that part of the flue or flues which lies behind the bridge, or by using small tubes as channels through which the gases return from back to front after passing through the main flue. Another form of tubular boiler is an externally fired horizontal cylinder fitted with tubes which carry the hot gases from the back to the front.

131. Vertical boilers are extensively used in connexion with small engines. Examples are shown in figs. 47–49. Fig. 48 is an ordinary vertical boiler filled with cross tubes of the Galloway type. Fig. 47 (by Messrs Davey, Paxman, & Co.) is a boiler with curved water tubes, each of which has fitted in the top a loose cap whose function is to deflect the stream of water which circulates up the tubes. Fig. 49 is a form of multitubular boiler by the same makers, in which the hot gases escape at the side after passing from the smoke-box through horizontal tubes grouped in circular arcs. In all these boilers the grate is at the foot, and the fire-door is at a mouthpiece in the side of the boiler near the base. In other forms of vertical boiler the heating surface is increased by water tubes (fig. 50) which hang from the crown of the fire-box, closed at the lower end but fitted internally with smaller tubes which are open at the bottom. Water circulates down the inner tubes and up between them and the outer. Tubes of this kind (called Field tubes) are used in fire-engine boilers and in other cases where it is necessary to get up steam with the least possible delay. Vertical boilers of large size are sometimes used for utilizing the waste heat of iron furnaces.

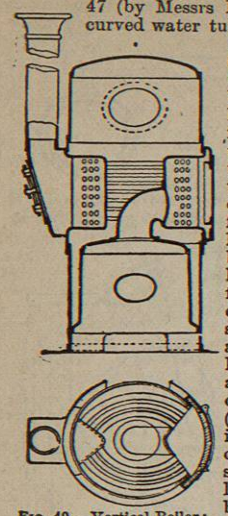


Fig. 49.—Vertical Boiler: Tubular Form.

Fig. 50.—Field Tube.

Sectional or tubulous boilers.

132. A great variety of boilers have been designed in which the firing is external, and the water space consists of groups of tubes or other small sections whose outer surface is exposed to heat. Boilers of this type are called sectional or tubulous boilers, in distinction to tubular boilers, or boilers with tubes in which the hot gases circulate. A successful example of the tubulous or sectional type is the Babcock & Wilcox water-tube boiler, which consists of a series of inclined welded tubes up which water circulates. These are joined at their ends by cast-iron connecting boxes to one another and to a horizontal drum on the top in which the mixture of steam and water which rises from the tube undergoes separation. At the lowest point of the boiler is another drum for the collection of sediment. Root's boiler is another in which water is heated by circulating through inclined tubes exposed to the fire; it differs from the above form chiefly in having the water-level below the top of the tube. Harrison's boiler is a group of small globular vessels of cast-iron strung like beads on rods which tie them together. Sectional boilers may be constructed without difficulty to bear pressures greatly in excess of those for which other types are suited. Mr Perkins has employed a tubulous boiler to deliver steam at a pressure of 500 ℔ per square inch.[1] The Herreshof boiler is a continuous coil of tube, arranged as a dome over the fire. Feed-water is pumped slowly through the coil, and turns to steam before it reaches the end.

133. The locomotive boiler consists of a nearly rectangular fire-box, enclosed above and on the sides by water, and a cylindrical part called the barrel extending horizontally from the fire-box to the front part of the locomotive and filled with numerous tubes. Figs. 51 and 52 show in longitudinal and transverse section a boiler of the London and North Western Railway, which may be taken as typical of modern English practice.

The barrel is 10 feet long and a little more than 4 feet in diameter, and is made up of three rings of steel plates, $\frac{13}{32}$ inch thick, arranged telescopically. It contains 198 brass tubes, each $1\frac{7}{8}$ inches in external diameter. The front tube-plate in which the tubes terminate is of steel $\frac{3}{4}$ inch thick; it is stayed to the back tube-plate by the tubes themselves, and the upper part of the front tube-plate is also tied by longitudinal rods to the back end-plate. The fire-box is of copper $\frac{1}{2}$ inch thick. It is nearly rectangular, with a horizontal grate. (A grate sloping down in front is often preferred.) Round its sides, front, and back (except where the fire-door interrupts) is a water space about 3 inches wide, which narrows slightly towards the bottom. The flat sides of the fire-box are tied to the flat sides of the shell by copper stay-bolts, 4 inches apart, which are secured by screwing them into both plates and riveting over the ends. The roof of the fire-box is stiffened by a number of girders on the top, to which the plates are secured by short bolts. The girders are themselves hung from the top of the shell above them by slings which are secured to angle-irons riveted on the inside of the shell plates. A sloping bridge of fire-brick partially separates the upper part of the fire-box from the lower and prevents the flame from striking the tubes too directly. Under the grate is an ashpan, to which the supply of air is regulated by a damper in front. The fire-door opens inwards, and can be set more or less open, to regulate the amount of air admitted above the fire. On top of the barrel is a steam-dome, from which the steam supply is taken through a pipe S traversing the forward part of the steam space and passing down to the valve-chest through the smoke-box. The stop-valve or "regulator" R is situated in the smoke-box, and is worked by a rod through the boiler from the cab at the back. Above the fire-box end of the shell are a pair of Ramsbottom safety-valves, V, V—two valves pressed down by a single spring attached to the middle of a cross bar, which is prolonged to form a hand lever by which the valves may be lifted. In front of the forward tube-plate is the smoke-box, containing the blast-pipe B by which the exhaust steam is used to produce a partial vacuum and so force a draught through the furnace.

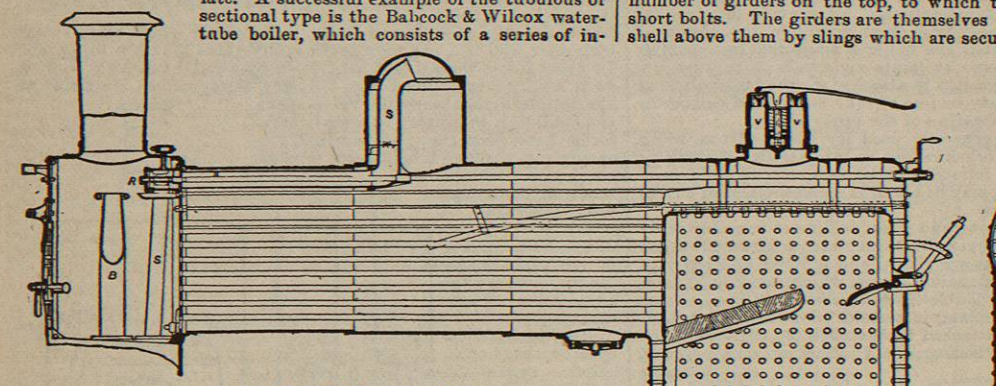


Fig. 51.—Locomotive Boiler.

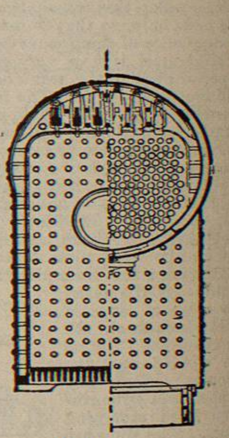


Fig. 52.

134. Instead of stiffening the fire-box roof by the use of girder stays, the plan is sometimes followed of staying it directly to the shell above. The outer shell above the fire-box is generally cylindrical; but to facilitate this method of staying it is sometimes made flat. This construction is not unusual in American locomotive boilers, another feature of which is that the grate is made much larger than in English practice, for the purpose of burning anthracite coal. An extreme instance is furnished by the Wooton engines of the Philadelphia and Reading Railroad, which burn small coal of poor quality in a fire-box $9\frac{1}{2}$ feet long by 8 feet wide, extending over the trailing wheels of the engine. In some cases the fire-box is divided by a sloping partition of plates with water between, which crosses the fire-box diagonally from front to back and has in its centre an opening resembling a fire-door mouthpiece to allow the products of combustion to pass. In others the fire-bridge is supported by water tubes, and water tubes are also used as grate-bars. This is done rather to promote circulation of the water than to give heating surface. The practice of American and English locomotive engineers differs widely as regards the materials of construction. American shells are of mild steel, English shells generally of mild steel but often of wrought-iron. In English practice the fire-boxes are of copper and the tubes of brass; in America the fire-boxes are of mild steel and the tubes of wrought-iron.[1]

[1] *Proc. Inst. Mech. Eng.*, 1877. See also a paper by Mr Flannery, "On High-Pressure Steam Boilers," *Min. Proc. Inst. C.E.*, 1878.

The locomotive type of boiler is used for stationary engines of the portable, semi-portable, and semi-fixed types, and also to a limited extent for marine engines in cases were lightness is of special advantage.

Marine boilers.

135. So long as marine engines used steam of a pressure less than about 35 ℔ per square inch the marine boiler was generally a box with flat sides, elaborately stayed, with a row of internal furnaces near the bottom opening into a spacious combustion-chamber enclosed within the boiler at the back, and a set of return tubes leading from the upper part of the chamber to the front of the boiler, where the products of combustion entered the uptake and passed off to the funnel. The use of higher pressures has made this form entirely obsolete. The normal marine boiler is now a short circular horizontal cylinder of steel with flat ends, with internal furnaces in cylindrical flues, internal combustion-chambers, and return tubes above the flues. In one variety, called the double-ended boiler, there are furnaces at both ends of the shell, each pair leading to a combustion-chamber in the centre that is common to both, or to separate central chambers with a water space between them.

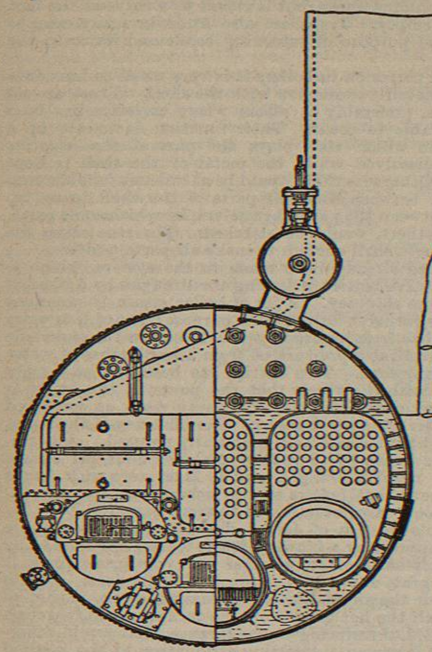


Fig. 53.

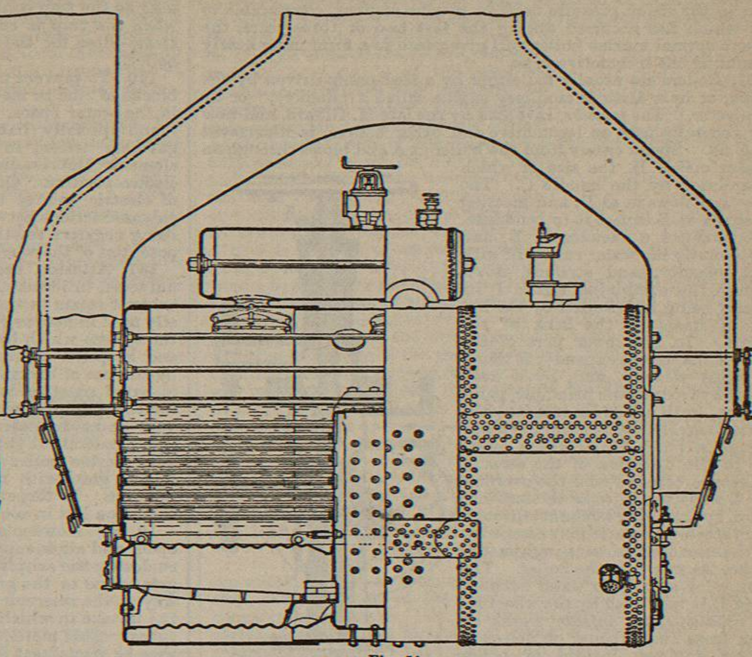


Fig. 54.

Figs. 53, 54.—Double-Ended Marine Boiler.

Details of double-ended marine boiler.

Figs. 53 and 54 show with some completeness a double-ended marine boiler of the most modern construction for high-pressure steam. At each end there are three furnaces in flues made of welded corrugated steel plates. The use of corrugated plates for flues, introduced by Mr Fox, makes thin flues able to resist collapse, and allows the flues to accommodate themselves easily to changes of temperature. One combustion-chamber is common to each pair of furnaces. It is strengthened on the top by girder stays and on the sides by stay-bolts to the neighbouring chamber and to the shell. The tubes are of iron, and a certain number of them are fitted with nuts so that they serve as stays between the tube-plate of the combustion-chamber and the front of the boiler. The upper part of the front plate is tied to the opposite end of the boiler by long stays. The uptakes from both ends converge to the funnel base above the centre of the boiler's length. The boiler shown is one of a pair, which lie side by side in the vessel, the uptake at each end being common to both. Each boiler has a steam-dome, from which the steam-pipe leads to the engine; this consists of a small cylindrical vessel, with flat ends tied together by a central stay. Short pipes connect the dome near each end with the steam space of the main shell. The boilers of figs. 53 and 54, which are by Messrs Gourlay Brothers of Dundee, work at a pressure of 165 ℔ per square inch above the atmosphere, and are used with triple expansion engines. The shell is $12\frac{1}{4}$ feet in diameter, and $16\frac{1}{2}$ feet long. The plates are of mild steel $1\frac{1}{8}$ inches thick round the shell and 1 inch in the ends. The tube plates are $\frac{7}{8}$ inch and $\frac{13}{16}$ inch thick, and the corrugated flues $\frac{1}{2}$ inch. The longitudinal seams are treble-riveted, with inside and outside covering plates. The circumferential seams are lap-joints double-riveted. There are 127 tubes at each end, 46 of which are stay-tubes. The tubes are of iron, $3\frac{1}{2}$ inches in external diameter. Above these are 18 longitudinal steel stays $2\frac{3}{4}$ inches in diameter. The steam-dome is a cylinder $2\frac{1}{2}$ feet in diameter and 8 feet long, stayed by a central $3\frac{1}{2}$-inch rod of steel. The short fire-box stays are also of steel $1\frac{1}{2}$ inches in diameter, of $7\frac{3}{4}$ inches pitch, and are secured by nuts and washers at both ends. The central combustion-chamber has a round and unstayed roof. The top of each side combustion-chamber is stayed by three steel girders $8\frac{3}{8}$ inches × $2\frac{1}{4}$ inches in section, secured by four bolts to the roof-plate below. A single-ended marine boiler by the same makers is shown in fig. 55. Boilers of this class are in some instances set athwartship instead of longitudinally, and bevelled on the bottom, at the back, to accommodate them to the shape of the hull. A modification of the cylindrical form is occasionally used, in which the section is an oval, with round top and bottom and flat sides. The combustion-chambers are sometimes made with rounded tops, which are tied to the back plate by gusset-stays and angle-irons. In naval practice the tubes are frequently of Muntz metal in place of iron. Another form of boiler, used to a considerable extent in the British navy, is a long horizontal cylinder with two

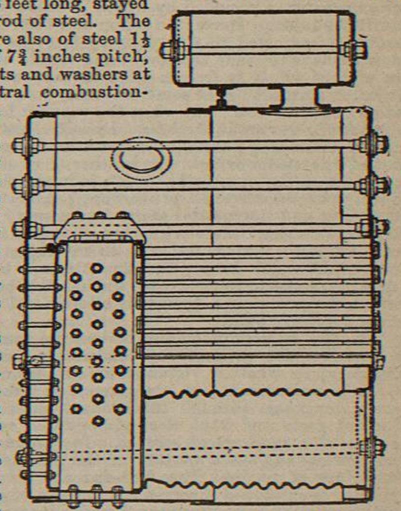


Fig. 55.—Single-Ended Marine Boiler.

[1] See a paper by Mr Fernie, *Min. Proc. Inst. C.E*, 1883.

internal furnaces opening into a large combustion-chamber about the middle of the length. From this a set of tubes distributed over nearly the whole water space extend to the back, where the uptake is situated.

136. The locomotive type of boiler has been successfully adapted to marine use by Mr Thornycroft and others, especially for torpedo boats. This form gives much greater heating surface than others in proportion to its weight, and allows, especially when worked with forced draught, a large amount of power to be got from a small boiler. It is probable that, if any further rise is to occur in the steam pressure used in marine engines, comparable to that which has occurred during the last two or three years, the present normal marine boiler will give place to a form more nearly resembling the locomotive type.

137. Boilers are usually fed either by a feed-pump driven by the engine, or by a distinct auxiliary engine called a "donkey," or by an injector. The *injector*, invented by the late M. Giffard, and now very generally used on locomotive and other boilers, is illustrated in fig. 56. Steam enters from the boiler at A and blows through an annular orifice B, the size of which is regulated by the handle C. The feed-water flows in at D, and meeting the steam at B causes it to condense. This produces a vacuum at B, and consequently the water rushes in with great velocity, and streams down through the combining nozzle I, its velocity being augmented by the impact of steam on the back of the column. In the lower part of the nozzle E the stream expands; it therefore loses velocity, and, by a well-known hydrodynamic principle, gains pressure, until at the bottom its pressure is so great that it enters the boiler through a check-valve which opens only in the direction of the stream. The escape orifice F and the overflow pipe G allow the injector to start into action, by providing a channel through which steam and water may escape before the stream acquires enough energy to force its way into the boiler. The opening for admitting water between D and B is regulated by the wheel H. The *exhaust-steam injector* works by steam from the exhaust of non-condensing engines, instead of boiler steam. The steam orifice is then larger in proportion to the other parts, and the steam supply more liberal. In *self-starting injectors* an arrangement is provided by which overflow will take place freely until the injector starts into action and then the openings are automatically adjusted to suit delivery into the boiler. One plan of doing this is to make the combining nozzle under the steam orifice in a piece which is free to slide in the outer casing. Until the injector starts it lies at some distance from the steam orifice, and allows free overflow; but when the vacuum forms it rises, in consequence of pressure at the base. In self-adjusting injectors this rise of the combining nozzle is made use of to contract the water-way round the steam orifice. In another form of self-starting injector one side of the combining nozzle is in the form of a hinged flap, opening backwards to allow overflow, but closing up when a vacuum is formed and the injector starts into action.[1] Weir's *hydrokineter* for large marine boilers is another apparatus in which the principle of the injector is made use of, with the object of promoting circulation of the water during the time steam is being raised. It consists of a series of nozzles, with water-inlets between them, through which water is drawn by means of a central jet of steam supplied from a donkey boiler.

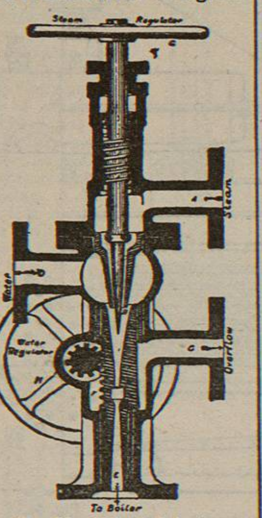


FIG. 56.—Giffard's Injector.

138. In stationary engine boilers the feed-water is frequently heated by the products of combustion before these reach the chimney, in what is virtually an extension of the boiler itself. Green's economizer is a contrivance for this purpose, in which the water passes through tubes whose outer surface is exposed to the hot gases and kept clear of deposited soot by the continuous action of a mechanical scraper. In locomotives and other non-condensing engines a portion of the exhaust steam is frequently made use of to heat the feed-water. When an exhaust-steam injector is employed it serves the purpose of a feed-water heater as well as that of a feed-pump. Besides increasing the efficiency of the boiler by utilizing what would otherwise be waste heat, a feed-water heater has the advantage that by raising the temperature of the water it removes air, and also, in the case of hard water, causes lime and other substances held in solution to be deposited in the heater instead of being carried into the boiler, where they would form scale. In Weir's feed-heater for marine engines the temperature of the feed-water is raised to about 200° Fahr. by injecting steam from the intermediate receiver.

[1] See papers in *Proc. Inst. Mech. Eng.*, 1860, 1866, 1884.

139. In stationary and marine boilers the steam, after leaving the boiler, is frequently taken through a *separator*, the function of which is to separate the dry steam from particles of water held in suspension. Steam is led round a sharp corner, and the water particles thrown off by centrifugal force collect in a *trap* below, from which they are discharged by a pipe which is kept open so long as the trap contains water, but is closed by a valve at the foot when the trap is empty. Traps are also fitted in many cases to steam-pipes for the purpose of returning condensed water to the boiler.

140. To prevent corrosion in boilers it is very usual to introduce blocks of zinc in metallic connexion with the shell. These are set in the water space, preferably at places where corrosion has been found specially liable to occur. Their function is to set up a galvanic action, in which zinc plays the part of the negative element, and is dissolved while the metal of the shell is kept electro-positive. Otherwise there would be a tendency for difference of electric quality between different parts of the shell to set up galvanic actions between the parts themselves, by which some parts, being negative to others, would be attacked. The zinc raises the potential of the whole shell enough to make all parts positive.

141. Allusion has already been made to the system which is universal in locomotive boilers of forcing the draught by a blast of exhaust steam in the chimney. Forced draught. A jet of boiler steam is occasionally used in marine furnaces for the same purpose; but of late years the system which has found most favour is to box in the stokehole and keep the air in it at a pressure of from 1 to 3 inches of water by the use of blowing fans. This system has been applied largely in naval practice, with the result that the power of the boiler is increased in the ratio of about 3 to 2, or even more, as compared with its power under chimney draught. The efficiency of the boiler is, in general, slightly but not very materially reduced. An ordinary marine boiler burns 16 to 20 lb of coal per hour per square foot of grate with natural draught, and 30 lb or more with forced draught. In torpedo-boat boilers of the locomotive type the consumption has in some cases been forced to more than 100 lb.

In Mr Howden's system of forced draught the stokehole is open, and air is supplied by a blowing fan to a reservoir formed by enclosing the ashpit and also to another reservoir from which it gets access to the grate above and through the fire-door. On its way to the reservoir the air is heated by passing across a part of the uptake in which the hot gases from the furnace are led through tubes. This method of restoring to the furnace what would otherwise be waste heat forms an interesting alternative to the method of restoring heat to the boiler by passing the hot gases through a feed-water heater; it is in fact an application to boiler furnaces of the regenerative principle alluded to in chap. II.[2]

142. Many appliances have been devised for the mechanical supply of coal to boiler furnaces, but these have hitherto taken the place of hand-firing to only a very limited extent. Mechanical stokers. In Juckes's furnace the fire-bars are in short lengths, jointed by pins to form a continuous chain or web, which rests on rollers and is caused to travel slowly in the direction of the furnace's length by pin-wheels round which the web is carried at the front and back. Coal is allowed to drop continually on the travelling grate from a hopper in front of the furnace. A more usual form of mechanical stoker is a reciprocating shovel or ram, supplied from a coal-hopper, which throws or pushes a small quantity of coal into the fire at each stroke. Along with this devices are employed for making the grate self-cleansing, by giving alternate fire-bars a rocking or sliding motion through a limited range. In Mr Crampton's dust-fuel furnace the coal is ground to powder and fed by rollers into a pipe from which it is blown into the furnace by an air-blast. Dust fuel. The mixture of fuel and air is so intimate that the excess of air required for dilution is only one-fifth of the amount required for combustion.[3] A similar advantage attends the use of gaseous fuel, and of liquid fuel that is blown into the furnace in the form of spray.

143. The use of liquid fuel for boilers has of late acquired considerable importance in connexion with the discovery of crude petroleum, in large quantity, at Baku on the Caspian Sea. The petroleum refuse which is left after distilling paraffin from the crude oil forms an exceedingly cheap fuel, with a calorific value per lb about one-third greater than that of coal. It has now superseded coal in the steamers of the Caspian, and has been largely employed for locomotives in the south-eastern part of Russia. The oil is injected in the form of spray near the foot of the fire-box by a steam jet arranged in such a way that air will be drawn into the furnace along with the petroleum. In the arrangement for burning petroleum used in Russian locomotives by Mr T. Urquhart the flame impinges on a structure of fire-brick, built in the fire-box with numerous openings to allow the products of combustion to diffuse themselves throughout the combustion-chamber. This guards against too intense action on the metallic surfaces, and at the same time serves as a reservoir of heat to rekindle the flame if combustion is intermittent. In getting up steam an auxiliary boiler is used to supply the jet.[1]

[2] The methods and results of these systems of forcing draught are described in papers read before the Institution of Naval Architects, April 1886.

[3] *Proc. Inst. Mech. Eng.*, 1869.

VIII. The Distribution of Steam.—Valves and Valve Motions.

144. In early steam-engines the distribution of steam was effected by means of conical valves, worked by tappets from a rod which hung from the beam. The slide-valve, the invention of which in the form now known as the long D-slide is credited to Murdoch, an assistant of Watt, came into general use with the introduction of locomotives, and is now employed, in one or other of many forms, in the great majority of engines.

The common or locomotive slide-valve is illustrated in fig. 57. The seat, or surface on which the valve slides, is a plane surface formed on or fixed to the side of the cylinder, with three ports or openings, which extend across the greater part of the cylinder's width. The central opening is the exhaust-port through which the steam escapes; the others, or steam ports, which are narrower, lead to the two ends of the cylinder respectively. The valve is a box-shaped cover which slides over the seat, and the whole is enclosed in a chamber called the valve-chest, to which steam from the boiler is admitted. When the valve moves a sufficient distance to either side of the central position, steam enters one end of the cylinder from the valve-chest and escapes from the other end of the cylinder through the cavity of the valve into the exhaust-port. The valve is generally moved by an eccentric on the engine-shaft (fig. 58), which is mechanically equivalent to a crank whose radius is equal to the eccentricity, or distance of O, the centre of the shaft, from P, the centre of the eccentric sheave. The sheave is encircled by a strap forming the end of the eccentric rod, and the rod is connected by a pin-joint to the valve-rod, which comes out of the valve-chest through a steam-tight stuffing-box. The eccentric rod is generally so long that the motion of the valve is sensibly the same as that which it would receive were the rod infinitely long. Thus if a circle (fig. 59) be drawn to represent the path of the eccentric centre during a revolution of the engine, and a perpendicular PM be drawn from any point P on a diameter AB, the distance CM is the displacement of the valve from its middle position at the time when the eccentric centre is at P. AB is the whole travel of the valve.

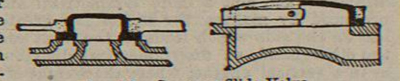


FIG. 57.—Common Slide-Valve.

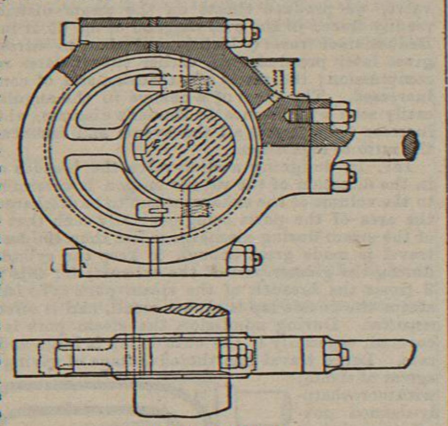


FIG. 58.—Eccentric.

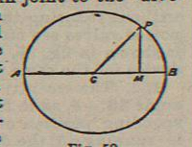


Fig. 59.

145. If the valve when in its middle position did not overlap the steam ports (fig. 60), any movement to the right or the left would admit steam, and the admission would continue until the valve had returned to its middle position, or, in other words, for half a revolution of the engine. Such a valve would not serve for expansive working, and as regards the relative position of the crank and eccentric it would have to be set so that its middle position coincided with the extreme position of the piston; in other words, the eccentric radius would make a right angle with the crank. Expansive working, however, becomes possible when we give the valve what is called "lap," by making it project over the edges of the steam ports, as in fig. 61, where o is the "outside lap" and i is the "inside lap." Admission of steam (to either side) then begins only when the displacement of the valve from its middle position exceeds the amount of the outside lap, and continues only until the valve has returned to the same distance from its middle position. Further, exhaust begins only when the valve has moved past the middle by a distance equal to i, and continues until the valve has again returned to a distance i from its middle position. Thus on the diagram of the eccentric's travel (fig. 62) we find, by setting off o and i on the two sides of the centre, the positions a, b, c, and d of the eccentric radius at which the four events of admission, cut-off, release, and compression occur for one side of the piston. As to the other side of the piston, it is only necessary to set off o to the right and i to the left of the centre, but for the sake of clearness we may confine our attention to one of the two sides. Of the whole revolution, the part from a to b is the arc of steam admission, from b to c is the arc of expansion, from c to d the arc of exhaust, and from d to a the arc of compression. The relation of these, however, to the piston's motion is still undefined. If the eccentric were set in advance of the crank by an angle equal to ACa, the opening of the valve would be coincident with the beginning of the piston's stroke. It is, however, desirable, in order to allow the steam free entry, that the valve be already some way open when the piston stroke begins, and thus the eccentric may be set to have a position Ca' at the beginning of the stroke. In that case the valve is open at the beginning of the stroke to the extent mm', which is called the "lead." The amount by which the angle between Ca' (the eccentric) and CA (the crank) exceeds a right angle is called the *angular advance*, this being the angle by which the eccentric is set in advance of the position it would occupy if the primitive arrangement without lap were adopted. The quantities lap, lead, and angular advance (θ) are connected by the equation


FIG. 60.—Slide-Valve without Lap.

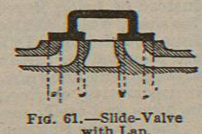


FIG. 61.—Slide-Valve with Lap.

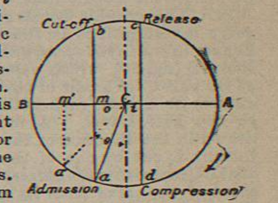


Fig. 62.

$$\text{outside lap} + \text{lead} = \text{half travel} \times \cos\theta.$$

An effect of lead is to cause *preadmission*, that is to say, admission before the end of the back stroke, which, together with the compression of steam left in the cylinder when the exhaust port closes, produces the mechanical effect of "cushioning," to which reference has already been made. Graphic method of finding the distribution of steam. To examine the distribution of steam throughout the piston's stroke, we may now draw a circle to represent the path of the crank pin (fig. 63, where the dotted lines have been added to show the assumed configuration of piston, connecting-rod, and crank) and transfer to it from the former diagram the angular positions a, b, c, and d at which the four events occur. To facilitate this transfer the diagrams of eccentric path and of crank-pin path may by a suitable choice of scales be drawn of the same actual size. Then by projecting these points on a diameter which represents the piston's path, by circular arcs drawn with a radius equal to the length of the connecting-rod, we find p, the position of the piston at which admission occurs during the back stroke, also q and r, the position at cut-off and release, during the stroke which takes place in the direction of the arrow, and s, the point at which compression begins. It is obviously unnecessary to draw the two circles of figs. 62 and 63 separately; the single diagram (fig. 64) contains the solution of the steam distribution with a slide-valve whose laps, travel, and angular advance are known, the same circle serving, on two scales, to show the motion of the crank and of the eccentric.

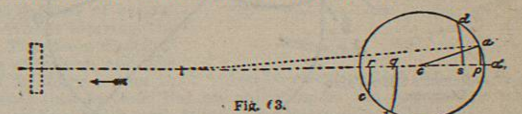


Fig. 63.

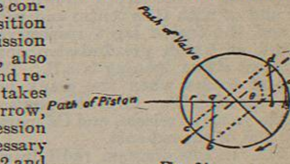


Fig. 64.

146. A method of representing graphically the relations of valve and piston motion, sometimes convenient in dealing with valve-gears of a more complex character than the single eccentric, is to set off the valve's and the piston's simultaneous displacement at right angles to each other, as in fig. 65, the valve's motion being exaggerated by using a coarser scale for it than for that of the piston. The result is an oval curve, from which the events in the

[1] See a paper by Mr T. Urquhart, *Min. Proc. Inst. C.E.*, 1884; also *Engineering*, June 11–25, 1886.