CHAPTER IX.

FUEL—COMBUSTION—THE GENERATION OF STEAM—BOILERS AND THEIR FITTINGS.

Combustion—Combination of oxygen with carbon—Combination of oxygen with compounds of carbon and hydrogen—Chemical symbols and atomic weights of constituents of fuel—Principal compounds of carbon, hydrogen, and oxygen—Constituents of fuel—Heat of combustion of carbon and hydrogen with oxygen—Description of fuels in common use—Table of the chemical constituents and evaporative power of various fuels—Weight and temperature of the products of combustion—Waste of fuel by splintering, distillation, insufficient air supply—Smoke forming—Draught creation, radiation, and conduction—Conduction of heat through the plates of furnaces—Importance of preventing an over-supply of air to fuel—The various types of boilers—Cylindrical boiler with external firing—Cornish boiler—Tubulous boilers—Lancashire boiler—Galloway tubes—The stiffening of internal flues—Locomotive boilers—Marine boilers for low-pressure steam—Marine boilers for high-pressure steam—Proportions of parts of boilers—Firegrate area—Evaporative power of fuel in various types of boilers—Consumption of fuel per square foot of firegrate area—Efficiency of heating surface—Cubic capacities of boilers of different types—Steam room—Strength of boilers—Hollow cylinder pressed from within: 1st, longitudinal strain; 2nd, transverse strain—Strength of riveted joints—Hollow cylinder pressed from without—Flat stayed surfaces—Effects of unequal heating in straining boilers—Materials of construction—Boiler fittings—Safety valves—Pressure gauges—Feed pumps—Injectors—Water gauges.

WE have hitherto considered chiefly the nature and the laws of heat, and the details of the engine which is employed to convert the heat into mechanical work; but of the source of heat—viz. the fuel, and the medium by means of which it is conveyed to the engine, viz. water, and the apparatus by which the heat of the fuel is transferred to the water, viz. the boiler—we have up till now said but little.

The source of heat which is always employed is fuel, such as coal, wood, peat, or mineral oil, the principal calorific

constituents of which are carbon and hydrogen. The chemical combination of these elements with oxygen produces intense heat, which, for the purposes of the steam-engine, is transmitted to the water contained in the boiler in a manner to be hereafter described.

The amount of heat which can be generated by the chemical combination of fuel and oxygen, commonly called combustion, depends upon the relative proportions of carbon and hydrogen which the fuel contains, as well as on the amount of oxygen which is supplied to it. It is well known that chemical elements combine with each other in certain definite proportions only; that is to say, for instance, a certain definite weight of carbon—viz. twelve units—will combine with a certain other definite weight of oxygen—viz. sixteen units—to form the compound called carbonic oxide, and these two elements will only combine in these proportions or in certain simple multiples of them. Thus, for example, no chemical combinations can be formed out of seven parts by weight of carbon to five parts by weight of oxygen; but, on the other hand, twelve parts of carbon will combine with twice sixteen parts of oxygen, forming the compound called carbonic acid or carbonic anhydride, which is the term applied to the product of the complete combustion of carbon in oxygen.

The numbers 12 and 16 applied to carbon and oxygen are called the atomic weights of these two substances, and it is supposed that the ultimate atoms of which they are composed have to each other the relative weights of 12 to 16. These numbers are also called the *chemical equivalents* of the substances.

If, instead of pure elementary substances, such as carbon and oxygen, we had to deal with the combination of a compound with a simple element, we should find that the chemical equivalent of the compound would be the sum of the equivalents of its constituents; thus, for example, a pound of olefiant gas, which is composed of carbon and hydrogen in the proportion of six parts by weight of carbon to one of hydrogen, would, in order to effect its combustion, require a quantity of oxygen computed as follows. The carbon weighs $\frac{6}{7}$ of a pound, and would require $\frac{16}{12} \times 2$ of its own weight of oxygen in order to form carbonic acid. The hydrogen weighs $\frac{1}{7}$ of a pound; its chemical equivalent or atomic weight is 1, and it combines with oxygen in the proportion of two parts by weight to sixteen of the oxygen. That is to say, the weight of oxygen required is $\frac{1}{7} \times \frac{16}{2}$ of a pound. Consequently for the pound of olefiant gas we shall want $(\frac{6}{7} \times \frac{16}{12} \times 2) + (\frac{1}{7} \times \frac{16}{2}) = 3\frac{3}{7}$ lbs. of oxygen.

The following are the chemical symbols and atomic weights of the principal elementary constituents of fuel.

Carbon . . .	C . .	12
Hydrogen . .	H . .	1
Oxygen . . .	O . .	16

The following are the principal chemical combinations of the foregoing.

Name	Chemical composition	Chemical symbol
Carbonic oxide	Formed of carbon and oxygen, in the proportion of twelve parts by weight of the former to sixteen of the latter, or $C_{12} + O_{16}$.	CO
Carbonic acid or carbonic anhydride.	Formed of carbon and oxygen, in the proportion of twelve parts by weight of the former to thirty-two of the latter, or $C_{12} + O_{32}$.	CO_2

The above are the products of the combustion of carbon in oxygen, the former being the result of imperfect, the latter of perfect combustion.

Name	Chemical composition	Chemical symbol
Water . .	Formed of hydrogen and oxygen, in the proportion of two parts by weight of the former to sixteen of the latter, or $H_2 + O_{16}$.	H_2O

The above is the product of the combustion of hydrogen in oxygen.

Name	Chemical composition	Chemical symbol
Olefiant gas .	Formed of carbon and hydrogen, in the proportion of twelve parts by weight of carbon two of hydrogen, or $C_{12} + H_2$.	CH_2
Marsh gas .	Formed of carbon and hydrogen, in the proportion of twelve parts by weight of carbon to four of hydrogen, or $C_{12} + H_4$.	CH_4

The two above are gaseous forms of the large family of hydrocarbons, which exist largely in fuel in the solid and liquid states also. To this category belong the vegetable and mineral oils, animal fats, and the bituminous portions of coal.

Fuel.—Ordinary fuel is composed chiefly of carbon, hydrogen, oxygen, and mineral matters, or of chemical combinations of these three elements. Its heating power, as before mentioned, depends on the relative proportions of the two first elements, and on the manner in which they are supplied with oxygen.

The heat evolved by a pound of hydrogen when burnt with oxygen so as to form water is 62,032 thermal units, which is sufficient to evaporate 64·2 lbs. of water from and at 212°. It requires for its combustion 8 lbs. of oxygen.

The heat evolved by a pound of carbon when burnt completely is 14,500 thermal units, which is sufficient to evaporate 15 lbs. of water from and at 212°. The amount of oxygen required to effect the combustion is $2\frac{2}{3}$ lbs.

When imperfectly burned so as to form carbonic oxide the quantity of heat evolved is only 4,400 units, equivalent to an evaporative power of 4·55 lbs. of water from and at 212°. The amount of oxygen required is $1\frac{1}{3}$ lbs.

In every case the oxygen is obtained from the air, which is a mechanical mixture of nitrogen and oxygen in the proportion of 77 parts by weight of the former to 23 of the latter. The nitrogen plays no part in the combustion, except that it mingles with the products of combustion, and reduces their temperature.

It will be noticed that the heat of combustion of hydrogen is about four times as great as that of carbon, and consequently those fuels which contain a relatively large quantity of hydrogen, such as the hydrocarbons, possess the greatest evaporative power; for the heating power of a compound of these two elements is *in most cases* nearly equal to the sum of the heating powers of the constituents.

In making an exact estimate of the calorific value of fuel, it is necessary to take account of the heat lost by breaking up any existing chemical compounds; for, just as the chemical union of carbon and oxygen, or of carbon and hydrogen, produces heat, so the separation of, say carbon from hydrogen, requires the expenditure of heat. If, then, a fuel contains hydrocarbons, which, during the combustion, are broken up into their constituent proportions of carbon and hydrogen, and each of these latter then combined with oxygen so as to form carbonic acid and water, we must not calculate the heat produced by the combination as being the same as if equal quantities of *free* carbon and *free* hydrogen were so combined. The proper way to proceed is to calculate first the heat that would be produced supposing the substances were all originally in the free or uncombined state, and then to subtract from this quantity the heat required in order to dissociate the hydrogen from the carbon. The latter quantity is always equal to the heat which would be produced by the combination of the equivalent quantities of free carbon and hydrogen. Thus, for example, one pound of marsh gas consists of three-quarters of a pound of carbon and one-quarter of a pound of hydrogen. If these constituents were in the uncombined state their combustion with oxygen would yield the following quantities of heat:—

Carbon, $\frac{3}{4}$ lb. . .	$14{,}500 \times \frac{3}{4} = 10{,}875$	thermal units.
Hydrogen, $\frac{1}{4}$ lb. . .	$62{,}032 \times \frac{1}{4} = 15{,}508$	,,
Total . . .	$= 26{,}383$	,,

But experiments prove that the heat developed by the combustion of one pound of marsh gas in oxygen is only 23,582 thermal units, thus leaving a deficiency of 2,801 units due to the heat absorbed in splitting up the chemical compound of carbon and hydrogen. In those compounds of carbon and hydrogen in which only two equivalents of hydrogen are combined with one of carbon, the heat of combination is so little that it is not necessary to take account of it in computing theoretically the calorific value of fuel. When a fuel contains oxygen, in addition to carbon and hydrogen, it is found that so much of the hydrogen as would be required to combine with the oxygen present in order to form water, must be left out of account in calculating the calorific effect. Any excess of hydrogen above this quantity must, however, be taken into consideration.

The fuels in most common use are coal, coke, peat, wood, and in some countries, such as South Russia, mineral oils. Of these coal is by far the most important; it is therefore the only kind of fuel which will be considered in detail in this chapter.

There are numerous varieties of coal found in this country, which differ from each other in appearance, in chemical constitution, and in their behaviour when undergoing combustion. Of these the principal varieties are anthracite, dry bituminous, and caking bituminous coals. Anthracite is found chiefly in South Wales. Chemically it consists almost entirely of pure carbon. It burns without flame or smoke. It is a very difficult coal to ignite, and unless gradually heated it splits up, when thrown on the fire, into small pieces.

Dry bituminous coal is the most useful fuel for steam generation. It consists chemically of carbon, hydrogen, oxygen, and mineral matter which forms ash. It is lighter than anthracite, and burns easily with very little smoke.

Caking bituminous coal contains less carbon than the foregoing, and more hydrogen and oxygen. It is called caking because it softens when exposed to heat. It burns easily with a good deal of smoke. The following table[1] gives the chemical composition and theoretical heating power of various kinds of coal. The theoretical heating power is calculated in the manner already explained. The practical heating power differs very considerably from the

Name of fuel	Chemical constituents			Heat of combustion of fuel in thermal units	Evaporative power of one pound of the fuel in pounds of water from and at 212°
	C	H	O		
I. Charcoal from wood	0·93	—	—	13,500	14
,, peat.	—	—	—	11,600	12
II. Coke, good . .	0·94	—	—	13,620	14
,, middling .	0·88	—	—	12,760	13·2
,, bad . .	0·82	—	—	11,890	12·3
III. Coal:					
1. Anthracite . .	0·915	0·035	0·026	15,225	15·75
2. Dry bituminous .	0·90	0·04	0·02	15,370	15·9
3. ,, .	0·87	0·04	0·03	14,860	15·4
4. ,, .	0·80	0·054	0·016	14,790	15·3
5. ,, .	0·77	0·05	0·06	13,775	14·25
6. Caking . .	0·88	0·052	0·054	15,837	16·0
7. ,, . . .	0·81	0·052	0·04	14,645	15·15
8. Cannel. . .	0·84	0·056	0·08	15,080	15·6
9. Dry long flaming .	0·77	0·052	0·15	13,195	13·65
10. Lignite . .	0·70	0·05	0·20	11,745	12·15
IV. Peat, dry . .	0·58	0·06	0·31	9,660	10·0
Peat containing 25 per cent. moisture	—	—	—	7,000	7·25
V. Wood, dry . .	0·50	—	—	7,245	7·5
Wood containing 20 per cent. moisture	—	—	—	5,600	5·8
VI. Mineral oil from .	0·84	0·16	0·	21,930	22·7
,, to .	0·85	0·15	0·	21,735	22·5

[1] Taken from the *Journal of the Royal United Service Institution.* Vol. XI.

theoretical, and depends chiefly on the stoking, and on the furnace being suitably made to develope complete combustion. The proper method of designing furnaces will be explained later on, but it may here be mentioned that with the best of fuel and the most suitable of furnaces it is possible by bad stoking to obtain the most indifferent results. For instance, if the fuel is laid on in such a manner that air in sufficient quantities cannot reach it, the coal will be partly distilled instead of being burnt; the more volatile constituents, such as the hydrocarbons, will be driven off in the shape of unburnt gas, and a large proportion of the carbon proper will burn incompletely, forming carbonic oxide instead of carbonic acid, its heating power being thus reduced by more than 70 per cent.

The heating powers in the above table are calculated on the supposition that one pound of pure carbon is capable of evaporating fifteen pounds of water from 212°. This is an experimental result arrived at by chemists, and is greatly in excess of anything that has yet been realised in steam boilers.

Weight and temperature of the products of combustion.—The temperature of the products of combustion of fuel depends upon their weight and specific heat. The weight of the products of combustion depends upon the quantity of air which is supplied to the fuel. As stated above, one pound of carbon requires for its perfect combustion two and two-thirds pounds of oxygen, or about twelve pounds of air. When imperfectly burned it requires one and one-third pounds of oxygen, or six pounds of air. One pound of hydrogen gas consumes eight pounds of oxygen, or thirty-six pounds of air.

It is found, however, that in practice more air than the above quantities must be supplied to the fuel in order to effect complete combustion. The extra quantity required depends upon the nature of the draught. Thus when the draught is produced by a chimney it is usual to estimate that twice the theoretical quantity is required, *i.e.* twenty-four pounds of air per pound of carbon. When the draught is artificial, such as that produced by a blower, or by a fan, or by the blast-pipe, one and a half times the theoretical quantity, or eighteen pounds of air per pound of carbon, is usually required. Although common coal is a complicated mixture of carbon, hydrogen, and oxygen, no serious error will be committed by estimating the quantity of air required for its combustion on the supposition that it is pure carbon.

From the above it will be evident that, even with the same fuel, the temperature of the products of combustion will vary according to the nature of the draught. Thus taking, again, the case of pure carbon, burnt under an artificial blast, and, therefore, requiring eighteen pounds of air per pound of fuel, we have the total weight of the products of combustion $=18+1=19$ pounds. The total heat of combustion is, as stated above, 14,500 units. The mean specific heat of the products is, according to Rankine, ·237 for constant pressure, and the temperature is found by dividing the total heat of combustion by the weight multiplied by the specific heat. Thus, in the present instance, the temperature $=\frac{14500}{19 \times \cdot 237}$

If the draught were produced by means of a chimney, so that twenty-four pounds of air would be required, instead of eighteen, the temperature would only be $\frac{14500}{25 \times \cdot 237}=2,440°$. On the other hand, if it were possible to burn the fuel completely with only the theoretical quantity of air necessary, viz. twelve pounds, the weight of the products of combustion would be only thirteen pounds, and the temperature $\frac{14500}{13 \times \cdot 237}=4,580°$, or very nearly double the temperature which is usually obtained in practice. It will be seen presently, when considering the waste of fuel in the gaseous state, that this question of initial temperature and weight of the products of combustion assumes an important aspect.

In practice it is found that a pound of coal falls very far short of the evaporative power stated in the table. The reasons for this are twofold. First, the fuel is wasted in various ways, which will presently be enumerated; and second, the boiler is unable to abstract from the fuel all the heat which actually is generated and to convey it to the water, so the residue passes up the chimney unutilised.

Waste of fuel.—The ways in which fuel is wasted are various. Many kinds of coal, such as anthracite and dry steam coal, are extremely brittle when exposed suddenly to great heat, and small splinters are broken off which fall through between the bars of the grate into the ashpit. In the majority of cases, however, the great waste takes place not so much in the solid as in the gaseous state. In an ordinary coal fire, kindled from below, the upper layers of fuel are heated through long before they become incandescent. When thus warmed, the coal is partially distilled, instead of being burnt, and many of its most valuable constituents are driven off in a gaseous state, and escape up the chimney unburnt, unless special provision is made to mingle fresh air with the gases as they arise, and to burn them, as it were, above the fuel.

An insufficient supply of air to the fuel itself is often a source of very great waste. It has been stated before that if only enough oxygen be present to burn the carbon into carbonic oxide, instead of into carbonic acid, the units of heat so generated will be only 4,400 per pound of carbon, instead of 14,500. Carbonic oxide is a perfectly colourless gas, and its formation in very large quantities may easily escape detection. If mingled, however, with a sufficient supply of fresh air, and suitably ignited, it will burn into carbonic acid, and in so doing will give out the missing 10,100 units of heat.

The formation of smoke is also a most fruitful, as it is one of the most common sources of waste. Smoke is pure unburnt carbon in a finely divided state which floats about in the hot gases and air proceeding from the fire, so that whenever we see dense volumes of smoke escaping from a chimney, we know that it represents so much valuable fuel absolutely thrown away, beyond the reach of recovery. Smoke when once formed is extremely difficult to ignite, and the greatest art of good firing consists in its prevention. Coals which are rich in hydrocarbons are also the most fruitful smoke producers. It is supposed that these volatile hydrocarbons when driven off at a considerable temperature, in the manner described, evolve free carbon before they are mingled with the air above the fuel, and becoming cooled down by contact with the air, the suspended particles of carbon show themselves in the form of smoke. Many arrangements have been contrived for mingling fresh air with the gases arising from the fuel in order to effect their combustion. Some of these will be referred to hereafter, when the practical details of boilers come under consideration.

Fuel is often largely wasted in forming the draught which feeds the furnaces with air. The draught is produced either by means of a chimney or by some more artificial blower, such as the steam blast-pipe or the revolving fan. In the case of a chimney it is found that the best temperature for the ascending gases is about 600°, whereas the temperature of the fire is about 2,440° above that of the outside air. Consequently about one-fourth of the total heat of combustion is wasted in forming the draught. Hence it appears that a chimney is a most wasteful expedient, for it involves the necessity of supplying the fuel with a double allowance of air, and in order to maintain the draught efficiently it carries off this air at a high temperature. With a blast-pipe or fan it is not necessary, as far as the draught is concerned, that the escaping gases should have any higher temperature than that of the atmosphere, and, moreover, the quantity of air which must be supplied to the fuel is one fourth less than when a chimney is employed.

Radiation and conduction are usually set down among the causes of waste of heat, but when the fire is properly enclosed, and the boiler surrounded with non-conducting materials, losses from this cause may be rendered extremely small.

The inability of the boiler to abstract all the heat which the fuel gives out is a consequence of the nature of the conduction of heat through the plates which separate the water in the boiler from the fire. The rate at which conduction takes place between the plates depends, first, upon the difference in temperature between the two sides of the plate; the greater the difference the quicker being the rate of conduction; second, upon the conductivity of the metal which forms the plate; and third, upon the thickness of the plate.

As regards the difference in temperature between the sides of the plate, it is evident that when the temperature on each side is the same no conduction of heat can take place. If, for example, a boiler be used to form steam of 100 lbs. pressure to the square inch, the temperature of this steam and of the water from which it is formed is 337·5°; consequently the hot gases coming from the fire cannot be cooled down below this point, and must at the least escape up the chimney at this temperature; and therefore all the heat due to the difference between this temperature and that of the atmosphere is of necessity wasted. As a matter of fact, it is impossible to retain the hot gases long enough in contact with the plates to allow of their temperature dropping to that of the steam, and consequently the waste from this source is considerably greater than what has been stated above. This evil may be reduced, to a certain extent, by introducing the comparatively cold feed water at that part of the boiler where the gases are coldest, an arrangement which is always carried out in carefully designed boilers.

From the above it will be readily understood how important it is to reduce the supply of air to the fuel to the minimum which is consistent with perfect combustion. Any excess quantity of air, in the first place, reduces the temperature within the furnace, and thus diminishes the rate of conduction through the heating surface; and, in the next place, it augments the bulk of the gaseous products of combustion, and thus makes it more difficult than it otherwise would be for the heating surface to reduce the temperature of the products to that of the steam and water within the boiler; for it is self-evident that a given area of heating surface is more efficient in abstracting the heat from a small than from a large bulk of gases.

Description of various Types of Boilers.

The essential parts of all boilers are as follows:—

A furnace, which contains the fuel to be burnt; a water receptacle, which contains the water to be evaporated; a steam space to hold the steam when generated; heating surface to transmit the heat from the burning fuel to the water; a chimney, or other apparatus to cause a draught to the furnace and to carry away the products of combustion; and various fittings for supplying the boiler with water, for carrying away the steam, when formed, to the engine in which it is used; for allowing steam to escape into the open air when it forms faster than it can be used; for ascertaining the quantity of water in the boiler; for ascertaining the pressure of the steam, &c.

The forms of steam generators are most numerous, and depend chiefly upon the purposes for which they are required. They may all be divided into three principal categories; viz. stationary, locomotive, and marine boilers.

In stationary boilers the size and weight are of secondary consideration, whereas for locomotive purposes, they are paramount.

The great majority of stationary boliers are cylindrical in shape, because the cylinder is the best practical form for strength as against internal pressure; the ends are either flat or else segments of spheres. It would be impossible within the limits of this short work to describe all the varieties of stationary boilers which have been contrived in various countries, but a few representative types will be considered.

Stationary Land Boilers.

Cylindrical boiler with external firing.—The simplest of all steam generators, and one which is now but seldom used

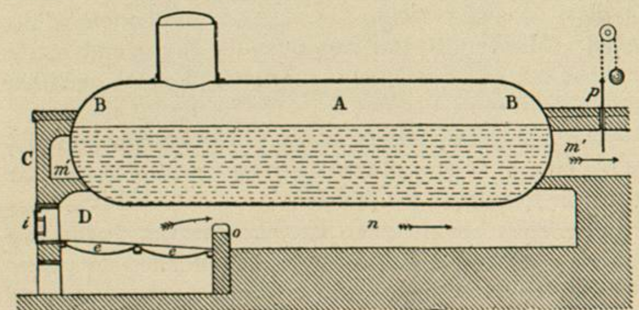

Fig. 151.

in this country, is illustrated in longitudinal and transverse section in figs. 151, 152. It consists of a cylinder A, formed of iron plate with hemispherical ends BB, set horizontally in brickwork C. The lower part of this cylinder contains the water, the upper part the steam. The furnace D is external to the cylinder, being underneath one end. It consists simply of a series

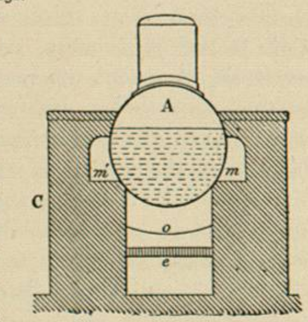

Fig. 152.

of grate bars *e e* set in the brickwork at a convenient distance below the bottom of the boiler.

The sides and front of the furnace are walls of brickwork, which, being continued upwards, support the end of the cylinder. The fuel is thrown on to the bars through the furnace door *i*, which is set in the front brickwork. The air enters between the grate bars from below. The portion beneath the bars is called the ashpit. The flame and hot gases, when formed, first impinge on the bottom of the boiler, and are then carried forward by the draught to the so-called bridge *o*, which is a projecting piece of brickwork, which contracts the area of the flue *n*, and forces all the products of combustion to keep close to the bottom of the boiler. Thence the gases pass along the flue *n*, and return past one side of the cylinder in the flue *m* (fig. 152), and back again by the other side flue *m'* to the far end of the boiler, whence they escape up the chimney. This latter is provided with a door or damper *p*, which can be closed or opened at will, so as to regulate the draught.

This boiler has two great defects. The first is that the area of heating surface, which is represented by those portions of the flues which are bounded by the surface of the cylindrical shell, is too small in proportion to the bulk of the boiler. The second is that if the water contains solid matter in solution, as nearly all water does to a greater or less extent, this matter becomes deposited on the bottom of the boiler, just where the greatest evaporation takes place. The deposit, being a non-conductor, prevents the heat of the fuel from reaching the water in sufficient quantities, thus rendering the heating surface inefficient; and further, by preventing the heat from escaping to the water, it causes the plates to become unduly heated, and quickly burnt out. This defect is sometimes obviated by placing within the shell of the cylinder a segment shaped trough, shown in transverse section in fig. 153. The trough *a* is fixed a few inches from the bottom of the boiler.

In the water space below it the ebullition is most violent, and the circulation of the water so rapid, that no deposit can take place; while within the trough the water is com-

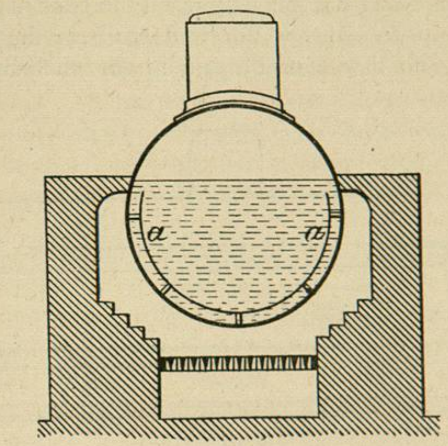

Fig. 153.

paratively quiet, and the mud consequently deposits itself here and does no harm, and can easily be removed periodically.

There is another defect belonging to this system of boiler to which many engineers attach great importance, viz. that the temperature in each of the three flues *n*, *m*, *m'* is very different, and consequently the metal of which the shell of the boiler is composed expands very unequally in each of the flues, and cracks are very likely to take place where the effects of the changes of temperature are most felt.

Cornish boiler.—The Cornish boiler obviates most of the defects of the system just described. It consists also of a cylindrical shell A (figs. 154, 155), with flat or semi-circular ends. The furnace, however, instead of being situated underneath the front end of the shell, is enclosed within it in a second cylinder B, having usually a diameter rather